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Transactions

15th World Congress of Soil Science
15 Bodenkundlicher Weltkongress
15ème Congrès Mondial de la Science du Sol
15º Congreso Mundial de la Ciencia del Suelo
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TRANSACTIONS

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Commission V: Symposia

International Society of Soil Science
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# Utilization of Soil Information in Systems Modelling for Sustainable Agriculture and Global Climate Change

**Convener:** Friedrich H. Beinroth. *(Puerto Rico)*  
**Co-convener:** Valentino Sorani. *(Mexico)*

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FOREWORD

The consequences of the accelerating deterioration the natural environment indisputably threaten the future of humanity. The urgency of these concerns prompted the nations of the world to hold the U.N. Conference on Environment and Development in Rio de Janeiro, Brazil, in June of 1992. The principal outcome of the conference was AGENDA 21, an action plan elaborating strategies to halt and reverse environmental degradation and promote environmentally sound and sustainable development worldwide. What, then, can soil scientists contribute to accomplishing the goals and objectives of AGENDA 21?

The environment, concurrent with economic growth, democracy, and population and health, is one of the four pillars that together support and make sustainable development possible. Since the soil and land resource base is an essential component of the environment and its integrity a conditio sine qua non for the sustainability of many managed and natural biophysical systems, the active involvement of soil scientists in development issues is imperative. Soil scientists must participate prominently in the development of integrated approaches to the planning and management of land resources that consider all environmental factors as well as social and economic aspects. Soil scientists must also contribute to the development of the techniques, processes, and regulatory policies and frameworks that can be combined to facilitate systems-based, holistic approaches. And they should also play a pivotal role in enhancing the scientific understanding of land resource systems and ecosystemic interactions. Basic to these endeavors, however, is the availability of adequate soil data, either amassed over the years in conventional ways or generated by the nontraditional methods of the information age. Propitiously, the tools and techniques of information science make it now possible to utilize the wealth of soil information in exciting new ways. Indeed, the resulting demand for massive amounts of spatial, descriptive and analytical soil data of high quality may well precipitate a renaissance of pedology.

In the context of this perspective, the symposium was convened to address some of the issues that will be central to the soil science agenda of the future. As many of these issues and problems transcend national boundaries and their solution therefore require concerted action and global partnerships, it is commendable that the International Society of Soil Science selected this timely topic for a symposium.

The symposium papers present a philosophical framework, discuss the state-of-the-art of information technology, address the status quo of soil data availability, describe current efforts to generate these data, demonstrate their use in agricultural and environmental scenarios, and explore the implication of these developments and paradigm shifts for soil resource inventory and characterization programs. It is hoped that this symposium will create awareness of the new frontiers of soil science, promote interdisciplinary and cross-sectorial collaboration, help the international soil science community recognize its societal obligations and responsibilities, and set it on a course of action that will secure a healthy future of the land.

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Modelling Agroecosystems Performance to Deal with Climate Change and Sustainable Agriculture

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Abstract. Climate change can bring about rapid changes that take unexpected directions. Such changes imply that what was true in the past will no longer apply, and warns us that the site-specific, empirical knowledge acquired through generations of trial and error can no longer be used with confidence to prepare for the future. The rapid obsolescence of empirical knowledge further suggests that to secure agricultural sustainability, we should invest more in the acquisition of process-based knowledge. The advantage of process-based knowledge is that it can be used repeatedly to diagnose problems and prescribe alternative ways to improve agroecosystem performance wherever and whenever the processes in question govern its behavior and performance. Process-based knowledge also enables sustainability to be measured and quantified in terms of the productivity, stability, resiliency and equitability of agroecosystems. The quantitative assessment of sustainable performance is achieved through simulation models that capture and organize our understanding of processes so that agroecosystems can be studied by simulating outcomes of alternative practices and policies. This approach is based on the premise that it is more convenient and efficient to study agroecosystem performance and sustainability using models than to experiment with the system itself.

Introduction. In the next three to four decades, the world must double production with a new kind of agriculture to feed, cloth, and house a global population that will increase not only in numbers but in aspirations. It will be challenging enough just to double production, but we are now being asked not simply to attain that goal but to do so without compromising the stability and resiliency of agroecosystems. And to complicate matters even more, this increased production will have to be achieved within the context of uncertain global climate change. It is not surprising then, that there is now widespread agreement among researchers and administrators that business as usual will not do, and that a new kind of agriculture will need to be invented for the future. What option do we have as soil scientists, and how do we seek out the best of all options to meet the human needs that lie ahead? This I believe is the question the symposium organizers have asked us to address.

Sustainable Agriculture. The term sustainable agriculture is now used so frequently and in so many ways that it has become virtually meaningless (Ruttan, 1991). To give meaning to sustainability, I will disaggregate the term into its component parts and show how the parts combine and interact to form a whole (sustainability) which is larger than the sum of its parts. It was Gordon Conway (1982) who first used sustainability as a property of agroecosystem, along with three other properties including productivity, stability and equitability. In his numerous papers (1985a, 1985b, 1985c) Conway defined productivity as the yield, profit or benefit derived from land, labor and capital inputs; stability as the constancy of yield, income or benefit over time; sustainability as the capacity of an agroecosystem to withstand and recover from stresses
and perturbations imposed on it; and equitability as the equal sharing of benefits derived from the system.

Today sustainability is used to encompass all of the above properties and for this reason, I have chosen to substitute the term resiliency for Conway’s sustainability and to combine the four subproperties, namely productivity, stability, resiliency and equitability into a single emergent property which I will call sustainability. There are at least three advantages to defining sustainability in terms of systems properties. First, by doing so, sustainability can be seen as the result of trade-offs among systems properties. For example, productivity and stability can be increased by irrigation, but often at the risk of lowering resiliency through salinization and water logging.

The second advantage lies in making productivity an integral part of sustainability. This view can be employed to reassure farmers that sustainability does not need to be gained at the expense of productivity. In fact this approach makes high productivity a requisite for high sustainability.

The third advantage of separating sustainability into distinct properties is that the properties themselves can be quantified and measured. Figures 1a to 1d illustrate the four properties that comprise sustainability and suggest how they might be quantified and measured.

**Balancing Systems Properties.** Any future agriculture that focuses too heavily on a single systems property is bound to fail. Agriculture is in trouble today because it concentrated too heavily on productivity. Farming systems research (FSR) introduced over two decades ago to diffuse criticisms leveled against the production-oriented green revolution fell by the wayside because it too focused on one system property. When critics pointed to the uneven distribution of benefits derived from the green revolution, promoters of FSR rushed in to fill the equitability gap, but failed to see how equity was inextricably linked to productivity, stability and resiliency of agroecosystems. Today we are making the same generic mistake of overemphasizing a single property, namely, resiliency. We are mistakenly equating resiliency with sustainability. Sustainability is not resiliency or equitability, or stability or productivity but all of them. Sustainability is an emergent agroecosystem property, and is based on the principle that whole entities exhibit properties which are meaningful only when attributed to the whole, not to its parts (Checkland, 1981). The error of the past is that we have tried to circumvent and reduce the complexity of agroecosystems by focusing on the part that happened to attract the most public attention.

LISA (low input sustainable agriculture) is an example of how popular public opinion can reset priorities for agriculture. A new breed of organic farmers is claiming that low input agriculture can be profitable and beneficial to the environment.

Health stores that market natural, organically grown foods are opening at a faster pace than super markets that sell ordinary farm products. Even the packages into which items are placed prominently announce their recycled origin. Can such an organically-based, environmentally benign agriculture befall the same fate as the green revolution and FSR. The answer is most probably yes!
Figure 1a. Productivity is yield or net profit derived from an agroecosystem.

Figure 1b. Stability is the constancy of production over time.
RESILIENCY

Figure 1c. Resiliency is the capacity of an agroecosystem to withstand and recover from stresses and perturbations imposed on it.

EQUITABILITY

Figure 1d. Equitability is the equal sharing of benefits derived from an agroecosystem.
Who are the customers that patronize natural food stores? Do you see a proportionate number of low income people flocking to buy more expensive organically grown foods? LISA, it appears, seems to be catering to the rich who harbor a pathological fear of poisons in foods. A LISA that caters to the whims of the rich and neglects the basic food requirements of the poor is not likely to be around for very long. LISA can survive only if future agriculture succeeds in fusing the benefits gained from the green revolution, FSR and LISA into a higher order emergent property that is larger than the sum of its parts. This higher order property is what sustainable agriculture is about.

With this introduction, I shall attempt to outline how the goal of sustainable agriculture might be attained and offer glimpses into the future of what agricultural research in general, and soil science research in particular, might be like.

**Research on Sustainable Agriculture.** It should be pointed out at the outset that sustainable agriculture is attainable only in the context of overall sustainable development. Just as productivity is a part of sustainable agriculture, sustainable agriculture is a part of sustainable development. And what the world is striving to achieve is not sustainable agriculture, but sustainable development. What we don’t want to achieve is to win the battle for sustainable agriculture and lose the war for sustainable development. The critical assumption of this paper is that sustainable agriculture can be rendered consistent with sustainable development if the former is treated as the product of productivity, stability, resiliency and equitability of agroecosystems.

But to fuse the four systems properties into a higher order emergent property is easier said than done. The fusion process is difficult because agroecosystems can be studied at various hierarchical levels beginning, for example, with the soil and rising to the level of the field, farm, village, watershed, nation, region and the world. Researchers, even from the same discipline, who work at different levels, often talk past each other. Thus agriculture is constrained not simply by its failure to operate in an interdisciplinary mode but also by its inability to relate research results obtained at one hierarchical level to those below or above it. This means that research conducted at the watershed or regional level for policy analysis should relate to farmer practices at the field or farm level.

Much of the research we undertake today is directed at the soil or field level and is largely disciplinary in scope. In fact, our research is even more restricted. We do not even do soil science research, but in fact proudly specify that we do soil physics or soil chemistry research or research on any one of a long list of subdisciplinary topics. It is only necessary to examine our conference program to confirm the validity of what I have just said.

However, our discipline-oriented research is not the root of our problems. Our problems reside not in what we do, but in what we fail to do. We fail to synthesize and organize what we publish in our professional journals into forms our clients can use to make better agronomic, business and policy decision. The knowledge we have is locked away in libraries, personal files and our minds, and is, for all practical purposes, inaccessible to those who need it most. One of the great tragedies of modern science is that decision makers at all levels make critical decisions
without the benefit of knowledge we take for granted. Thus one logical approach, one that our clients and research administrators will support, is not simply to do more research, which is certainly needed, but to organize what we already know into products our clients want and will use. This implies that our research should be more client driven and product-oriented.

**A Client Driven, Product-Oriented Soil Science.** Soil science is of interest to the general public only insofar as it can answer questions of immediate interest to people. It turns out that the problems people face are not disciplinary problems, but systems problems. Can a soil scientist, for example, when asked by a farmer to recommend the optimum nitrogen fertilizer rate for a variety of crops being planted on several kinds of soil, seeded on any given day of the year, for a number of planting densities, labor and fertilizer costs, and for a variety of anticipated prices for the harvested product, provide the farmer with a satisfactory and reliable answer? I think not and yet that is precisely the type of answers farmers and policy makers need. Furthermore, what did the farmer mean by optimum fertilizer rate? Was it to optimize profit or environmental quality or both?

We now believe that to be effective, soil scientists will have to join forces with colleagues from other disciplines to produce decision aids that can simultaneously optimize profit (productivity), constancy of production (stability), environmental quality (resiliency), and equitability. Such multi-criteria decision making is essential for an agriculture that contributes to sustainable development. Given this state of affairs, the era of costly, inefficient, trial-and-error field experiments in which only fertilizer rate and final yield are measured must come to an end. This is not to imply that field experiments are unnecessary. It means that field experiments must become more process-oriented so that our understanding of processes and their interactions can be used to create models that can predict outcomes of human interactions with the environment. Since production outcomes depend largely on factors such as temperature, rainfall and day length over which humans have little or no control, we must, as a minimum, examine the full range of the soil-plant-atmosphere continuum. At the risk of sounding like a broken record, soil scientists can function at this level of integration only by joining forces with colleagues from other disciplines.

Figure 2 illustrates what can be achieved when members of an interdisciplinary team put their heads together to study nitrogen dynamics in the soil-plant-atmosphere continuum. The figure shows that a crop's response to applied nitrogen involves many factors, many of which such as weather are beyond the control of humans. These uncontrolled, random factors introduce risk and uncertainty into farming and policy making and compel decision makers to gamble with nature.

Gambling is a risky game of probabilities. Risk-averse farmers often design complex cropping patterns that produce low but dependable yields under situations of risk and uncertainty. They fight variance with variance. Their farms often consist of a blend of crops chosen not for high performance in the average year, but to produce adequate yields in the worst years. Thus a new technology, whether it be a new crop, product, or practice, needs to be evaluated over decades to expose hidden dangers which one or two years of on-farm trials cannot reveal. A solution to this problem was proposed by Anderson et al. (1974) who advocated investment in risk-oriented
Figure 2. Nitrogen dynamics in the soil-plant-atmosphere continuum. (Source: Godwin et al., 1984).
research. Since the risk of crop failure or income loss resides in the lower tail of a probability distributions, risk-oriented research depends on our capacity to generate whole probability distributions of production outcomes. If, for example, weather is the principal cause of yield variations, farmers (and policy makers) would want to know the long-term average impact and its variance. For risk-averse decision makers, a low variance may be as important or more important than a high mean. What farmers want are high yields (high productivity) and high stability (low yield variance).

Clearly, the type of agroeconomic experiments we now conduct are not designed to be risk-oriented. Some journals require data from at least two seasons of agronomic trials before articles will be accepted for publication, but two seasons of trials are insufficient for generating whole probability distributions. And long-term experiments are unpopular with research administrators and scientists alike because they are expensive and slow to generate publishable data. We are thus left with one last approach that will satisfy our clients, administrators and ourselves. We must generate the required information not by field experiments but by \textit{ex ante} means.

Dealing with Risk and Uncertainty. Agriculture, like all businesses, is a risky, decision-making enterprise. Farmers and policy makers are constantly faced with the task of matching and allocating time and resources to efforts that are likely to produce desired outcomes. Since deviations from expected outcomes are often caused by random environmental variables over which the decision maker has little or no control, chance and risk enters the decision making process. Thus, farmers and policy maker, however unwilling, are compelled to deal with risk and uncertainty by gambling with nature. Our role as scientists is to improve the odds in favor of the decision makers. In farming, risk is minimized by matching the requirements of crops, products, practices and policies to the physical characteristics of land and the resource and attitudinal characteristics of the farmer. Nix (1984) describes three ways by which this matching process can be achieved. The first is by trial-and-error, the second by taking successful practices to other locations with similar agroenvironments (a method he calls the analogue approach), and third, by understanding natural processes and applying this understanding to diagnose and prescribe alternative ways to rectify mismatches through systems analysis and simulation. Systems analysis and simulation is the means by which we can generate the information decision maker needs by \textit{ex ante} means. This approach requires that we capture, condense and organize what we know into dynamic, process-based models which can mimic behavior and performance of agroecosystems. The research we do should be to validate models and fill knowledge gaps exposed during model development and validation.

A key premise of systems analysis and simulation is that it is more convenient to use models to study a system than to conduct experiments on the system itself. The myriad of field experiments which we conduct each year and which Nix (1980) disparagingly calls "white peg agronomy" is based on learning about systems by conducting experiments on the system itself. The vast majority of genotypeXenvironmentXmanagement agronomic experiments we conduct fall in this category. Such experiments are too slow, expensive and unreliable even now, and will become even less useful if climate change occurs at the anticipated pace and magnitude. Field research is too slow because there are too many farmers with different goals and idiosyncracies, growing too many different crops on vastly different soils in different agroclimatic zones and operating
under different economic and infrastructural constraints. It is too expensive because there is not enough capital to hire all the technical help to reach the critical number of farmers who need help. And field experiments are unreliable indicators of what will happen in the future because even if every available technology and practice were tested on every farm this year, there is no assurance that the test results will be the same next year or any year thereafter because weather varies from year to year, and climate may, and probably will, change with time. Agriculture will become a more complex enterprise because policy makers will require farmers to increase productivity and equitability without compromising the stability and resiliency of the agroecosystem. If soil science is to survive as a viable profession, we must demonstrate to our clients and to those who support our research that we can apply systems analysis and simulation to support decision making in a timely and cost-effective manner.

**Modelling Agroecosystem Performance.** Enough is now known about the way crops interact with the environment and how they develop and grow under its influence so that we can now simulate the growth and development process as outlined in figure 2. We can do so provided we have the input information with which to drive the simulation model. The minimum amount of information needed to operate the model consists of daily weather information, including minimum and maximum air temperature, rainfall, and solar radiation; soil characterization data including particle size distribution, bulk density, organic carbon and nitrogen content, and pH; and the growth and development characteristics of the crop cultivar known as the crop genetic coefficient (Hunt and Pararajasingham, 1993).

Two additional sets of information are required to begin the simulation. These include soil initial conditions and management inputs. We know, for example, that the initial inorganic nitrogen level in the soil will affect responses to nitrogen applications. We must also input initial nutrient, pH and water content before we begin the simulation.

We must also specify the management options such as the planting date, row spacing, planting density, crop variety, and amount and frequency of fertilizer and pesticide application. We must also input the location since all other things being equal, agroecosystems performance varies greatly with location (e.g., latitude).

It is useful to note that the input data needed to run the simulation model are identical to data a human expert would need to diagnose agricultural problems and prescribe solutions for them. The model serves as a substitute for a human expert, but lacks the powerful reasoning capacity of the human mind. The model makes up for this deficiency with its memory and computational capacity.

While it takes human experts to organize what we know about processes in the soil-plant-atmosphere continuum, a single individual is not likely to remember all the key factors that govern genotypeXenvironmentXmanagement interactions. The knowledge captured and organized in the model compensates for the unreliability of the human memory. The human mind is even more deficient in its ability to quantitatively assess how all of the factors interact and contribute to the final outcome. Modern laptop computers are able to use historical weather to simulate 50 years of genotypeXenvironmentXmanagement interaction in a matter of a few minutes. No
human mind can accomplish such computations as quickly and reliably.

In a sense, the model enables the client to conduct environmentally sensitive agronomic experiments in the computer. An agronomic experiment that would require 50 years to complete can now be completed in less than an hour. This means that experiments that would never be installed in the field can now be conducted at no risk or cost to the decision maker. This ability to exploit the power of information technology is already changing the way we do research.

We can illustrate how much research can and will change in the future by giving an example of what models are now capable of doing. A typical example might involve a group of farmers which is barely making ends meet with the best technology, and have now been asked to adopt new environmentally benign practices. The farmers are at the mercy of an environmental group who has persuaded the elected officials to adopt a policy that would prevent further increase in levels of nitrate nitrogen in the local ground water supply. The farmers would like to comply with the new regulations but are fearful that the crops and management practices which they have adopted through years of trial-and-error will now have to undergo a risky and uncertain change. They do not have the time or resources to experiment with new farming methods that will enable them to meet the new environmental standards and still derive sufficient income from farming.

It turns out that farmers have many options to reduce nitrate leaching into ground waters without reducing yield or increasing the cost and drudgery of farming. The options might include applying less fertilizer, applying the same or more fertilizer but applying it in two, three or more applications, changing to a slow release nitrogen fertilizers, replacing inorganic nitrogen fertilizers with green manures of different carbon-nitrogen ratios applied at different rates and times, or to grow an entirely new crop. What farmers lack is the time and resources to find the right combination of crops, products and management practices that will solve their problems.

Today it is possible for an extension agent to sit down with a farmer, environmental group or elected official to explore alternative ways to find a satisfactory solution to the type of problem just described. But before extension agents can evaluate the economic and environmental outcomes of each option, they must have the soil and long-term weather data for the study area. The information technology must consist of the soil, weather, and crop database; validated simulation models and application program to enable the extension agent or any other user to conduct agronomic experiments in the computer.

The extension agent or client can specify the experimental treatments. For example, a farmer may wish to conduct an experiment that involves three plant populations, two nitrogen rates applied at planting time and 30 days after planting, using two varieties, one early and the other late maturing. The experiment would be repeated for 50 consecutive years to evaluate the year-to-year fluctuations in outcomes. The entire experiment can be repeated on a sandy, loamy or clayey soil or any specified soil. The experiment can be designed to answer and evaluate any number of "what if" questions and scenarios. What if the planting date had been delayed by two, three or ten weeks? What if the urea normally used by the farmer is replaced by sulfur-coated urea or ammonium sulfate? What if inorganic nitrogen fertilizer were replaced by green manures with C-N ratios of 20, 40, or 60, and applied at 2, 4, 6 or 12 tonnes/ha?
All of the above and many more scenarios can be evaluated and compared at no risk and cost to the client. Another feature of the technology is its ability to analyze and display the simulated results almost instantly for easy assessment.

In most cases, it is useful to enable clients to compare the current with the new and untried practices. There is considerable value in simulating current practices alongside the new and untried for several reasons. First, a model that can mimic current farm performance to the satisfaction of farmers is necessary to generate the trust and confidence they need to believe in the capability of models to simulate reality in the field. Any model that is unable to simulate outcomes of current practices is not ready, and should not be used to support decision making. The second reason for simulating outcomes of current practices is to enable farmers to see how economic and environmental outcomes of the new and untried practices compare with the one currently in use. Any new option that is selected must be substantially better than the current one. Simulation models therefore, can be viewed as a device for screening alternative strategies from which the client can choose. The key to sustainable agriculture and development is to enable individuals to make better choices for themselves and for society. Today the knowledge people need to make sound decisions is inaccessible to them. That is the great failure and tragedy of science and technology.

**Modelling Agroecosystem Performance.** What, for example, can subsistence farmers do to extricate themselves from poverty's grip? In many instances, and especially in Africa, subsistence farmers find themselves in a losing battle to meet the food demand of a population that has doubled in the past 20 years and is likely to double again in the next 25 years. The traditional farming system that served the subsistence farmer so well is now crumbling under the pressures of population expansion. What can science and technology do to reverse this trend?

In the industrialized countries, technology enables a few to produce food for many. In the development countries, the same technologies often contribute to unemployment and social unrest. Thus, the goals of most agricultural development efforts call for increased income and employment. The aim of science and technology, therefore, is not merely to increase production, which is relatively easy to do, but to increase productivity without sacrificing stability and resiliency of the agroecosystem, and to use improvement in the three biophysical properties to achieve equitable sharing of benefits derived from the system.

The ability to deal simultaneously with more than one system property is now a reality. Keating et al. (1991), for example, have used a modelling approach to study the probable effects of nitrogen fertilizer on yield, stability and resiliency of cultivated land in the semi-arid regions of Africa. They used models to investigate the factors influencing maize response to nitrogen in the drier regions of Kenya. They investigated soil and management factors including organic matter, mineral nitrogen at planting time, soil water and soil runoff characteristics, plant density, and timing of nitrogen application with the onset of the rains. They concluded that models have reached the stage where they can provide useful insights into complex cropping systems, especially in regions of high climate risk.

Thornton and Saka (1993) have also used a modelling approach to study ways to improve
agroecosystem performances in Malawi. They showed that new practices and maize varieties perform differently in different locations. The modelling approach enabled them to effectively deal with the site specificity of "best management practices."

In both studies, the results of the simulated experiments were presented graphically as depicted in figure 3. In the figure cumulative probability is plotted as a function of an agroecosystem property such as crop yield, net profit, or nitrogen leached below the root zone. Such a curve is generated by repeating the experiment over many consecutive years. The simulated outcome is arranged in order from the lowest to the highest value. If the outcome is normally distributed, the 50% cumulative probability corresponds to the average value; otherwise it corresponds to the median.

The other feature of the cumulative probability curve is its slope. A steep slope indicates low variance and high stability. What farmers look for are strategies that promises high mean productivity (high means) and high stability (low variance). Figure 4 illustrates a case in which two strategies result in identical means, but differ greatly in variance. The risk-averse farmer will almost always choose a strategy with a low variance.

If, on the other hand, the property being investigated is nitrogen leaching into the groundwater or soil loss from wind and water erosion, the farmer will choose management strategies that lead to low means and variances corresponding to high resiliency.

Not only do the cumulative probability curves allow farmers and policy makers to assess the productivity, stability or resiliency of a particular management practices, they also enable them to compare and choose the most desirable practice from a set of management alternatives. When more than one curve appears on the graph as is the case in figure 3, the curve furthest to the right is the preferred strategy. Anderson (1974) refers to the curve on the right as the stochastically dominant strategy. Of course, if the curve represents soil loss, nitrogen leaching or methane emission, the curve on the left would be preferred.

The ability of models to simulate means and variances of alternative strategies provides economists with tools to assess the benefits and cost of risk-related activities. Harrison et al. (1991) describe how model outputs can be related to technology adoption rate, extension costs, impact on consumers, changes in demand for rural labor and finance, and environmental impacts. What Harrison et al. seem to be saying is that the socio-economic (equity) issues can be more easily dealt with if the biophysical outcomes stemming from human interactions with the agroecosystem can first be predicted.

**Systems Simulation and Climate Change.** In periods of unchanging climate, the past can serve as a mirror of the future. By using historical weather data as model inputs to simulate "what if" scenarios, we assume that simulated outcomes hold for the past, present and future. But if future climate differs from past climates, we can no longer use historical climate and weather data to predict what is likely to occur in the future. We now have no alternative but to explore the future with estimated weather and climate generated by general circulation models (GCMs) based on projected increases in greenhouse gases. These models are still unable to predict present
Figure 3. Cumulative probability versus yield (or profit) curves for low and high productivity strategies. Each point represents the outcome for a particular year. A comparison of strategies simulated for 19 years demonstrates that the strategy on the right is more productive.

Figure 4. Cumulative probability versus yield (or profit) curves for low and high stability strategies. The curve with the steeper slope represents a more stable strategy.
climate on a site specific bases and therefore are unlikely to do so for future climates, and differ in their projected change in average global temperature and precipitation for a doubled CO<sub>2</sub> concentration. In short we are far from being able to predict future climate with any degree of certainty. This element of uncertainty does not need to prevent us from exploring the future with the GCMs. What the GCMs need to do is to provide us with a range of climate change scenarios within which future climate will fall.

The soil-plant-atmosphere continuum (SPAC) models we currently have can be used to assess the impact of the full range of probable climate change on agriculture. The SPAC models can also be used to study alternative means to counter the negative effects of climate change. These counter-measures may involve adoption or new crops, practices and products. Rosenzweig et al. (1993) have studied the potential effects of climate change on crop yields, world food supply and regional vulnerability to food deficits. The study included an analysis of both biophysical processes and economic responses to shifts in comparative advantage caused by climate change. This study was possible only because the outputs from the GCMs could be used by existing SPAC models to simulate the effects of "what if" climate scenarios on agroecosystems performance.

Summary and Conclusion. Agricultural research is today discipline-oriented and largely driven by priorities of the researchers. This approach has produced a modern farming system in the industrialized countries that enables a few farmers to feed large numbers of people who take inexpensive and bountiful variety of agricultural products for granted. They are now demanding that foods be not only cheap and plentiful, but not be contaminated with agri-chemicals and be produced in an environmentally benign way.

In the developing countries the situation is different. Although food shortages are still an exception rather than the rule, it is clear that production will have to be doubled within the next two decades to keep pace with population expansion and rising human aspirations. These nations need quick solutions to prevent spreading of poverty, hunger and social unrest. The disciplinary, researcher-driven approach is not likely to succeed in the developing countries which depend on risk-averse farmer to produce farm products with a minimum of purchased inputs.

One way to circumvent the new problems faced by agriculture is to use ex ante means to study farming systems instead of conducting slow, costly and risky experiments in farmers fields or the research station.

Ex ante screening of new crops, products and practices acceptable to farmers is possible through simulation models that have been field validated. To enable farmers, agribusinesses and policy makers to diagnose and prescribe alternative solution to problems, the research community must adopt a systems approach to help clients achieve objectives specified by them. The systems approach requires researchers to:

1. Form interdisciplinary teams to produce client-oriented results.
2. Emphasize process-oriented research that measures more than final yield and treatment variables.

3. Be product-oriented and make certain the products are wanted and will be used by clients.

4. Collect and store a minimum set of soil, crop and weather data for easy retrieval and input into models to diagnose and prescribe solutions to problems on a site-specific basis.

The systems approach is necessary because the constraints that stand in the way of sustainable agriculture and development are not disciplinary constraints but systems constraints. This approach provides soil scientists with an opportunity to join forces with colleagues from other disciplines to regain the public trust and support we once enjoyed.
Literature Cited


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Information Technology Requiring Soil Data


I. INTRODUCTION

Information technology (IT) develops rapidly in terms of capabilities and diversity. It is recognized that the acquisition of IT systems by user organizations is a complex process based on a long life cycle which requires prudent planning and management (B. Walters and D. Reeves, 1993). Higher performing information technology and increasing application of modelling procedures need also more and better soil data to be properly applied. The danger is that sophisticated technology will be used on poor data sets, thus diminishing the quality of data interpretation and land use decision-making.

Hereafter, IT hardware and software are analyzed with regard to their capabilities for processing soil data and their implications on data needs. Additional reference is made to models whose increasing complexity imposes frequently special data constraints.

II. HARDWARE TECHNOLOGY

Hardware technology continues to get better and faster at rapidly decreasing prices. By the time you purchase your new hardware and start using it, computer technology will have better functional capabilities, offer faster processing speeds and will have lower prices.

A. Computers

The computer technology is worth over 100 billion Dollars a year ranging from personal computers to supercomputers. Recent advances in chip technology offering faster processing times, at lower prices, are changing the way we look at computerized systems now. New chips available on the market are: Pendium from INTEL offering a 32-bit computing at 66 MHz for less than US$ 1,000; MIPS Technologies' R4000 offering a 64-bit computing at 100 MHz; the Alpha AXP from DEC offering a 64-bit computing at 150 MHz; and the Power PC 601 developed by Motorola, IBM and Apple offering a 32-bit computing at 66 MHz for half the price of the Pendium. The price of one chip containing about 100 bits of memory in 1970 could buy about 10,000,000 bits of memory in 1989 (Muller, 1993).

These advances and the evolving working environments including smaller forms such as laptops, notebooks and palmtop systems make very appealing the change into computerized systems for managing natural resources in a sustainable manner. The gap between personal computers and workstations is also diminishing rapidly. For example at the lower price end, the INDY from Silicon Graphics' Indigo workstation product line is available at just over US$ 5,000. The INDY includes a MIP R4000 CPU, benchmarks at 34 SPECint92 and 35 SPECfp92, and competes for a market share against products such as Hewlett Packard's 715/33, Sun Microsystems' SPARCclassic, Digital's 300i and IBM's M20.
B. Data capture devices

Spatial databases are usually fed from two different sources: (a) primary data collection from aerial photographs or satellite remote sensing imagery, and (b) secondary data collection from conventional cartographic sources.

Data capture from primary sources using image processing techniques has failed in producing automated soil delineations. Unduly optimistic attempts aiming at total automation of imagery classification led from a period of scientifically interesting, but ultimately unsuccessful, research into more sophisticated trials to use remotely-sensed data in an isolated image processing environment. Approaches to extract information evolved from unsupervised (clustering) classifications of multispectral imagery to supervised per-pixel classifications of multispectral images, and later to the use of textural and contextual techniques using multispectral, multitemporal and multisensor remote sensing imagery (Davis and Simonett, 1991).

Developments in the synergism of remote sensing and geographic information systems have increased the possibility of using more intensively remote sensing products. Several image processing techniques to enhance images for visual interpretation are available in integrated systems; resulting information can be used as a layer in a GIS. Model-based and knowledge-based classifications are being performed integrating image processing and GIS approaches with encouraging results.

The use of photogrammetric principles and devices allows the extraction of data directly from aerial photographs more accurately and rapidly in rugged terrain areas. The monoplot procedure is gaining more acceptance for data capture directly from aerial photographs or satellite imagery (ortho-photo, ortho-image).

The secondary data collection approach is still the most common way of converting analogue data into digital format. Table digitizers principally but also scanners and photogrammetric stereoplotters are used to capture cartographic data. Digitizing requires a human operator to position a map on a table and trace a cursor over cartographic features leading to the capture and digital representation of points, lines and polygons. In general, digitizers vary in size from approximately 30 X 30 cm to 120 X 120 cm. In contrast, ALTEK has a digitizer table of 150 X 300 cm, the DATABAK table digitizer. Prices vary according to size and resolution from US$ 500 to 10,000.

Scanners are devices used to convert analogue source documents into digital form usually in a raster format. The scanning process involves systematic sampling of the source document by either transmitted or reflected light. Scanners for a document size of approximately 90 cm are available at varying resolutions: 300 dots per inch ($10,000) to 1,000 dpi ($25,000). Analytical stereoplotters used for capturing photogrammetric data at high resolution can be found at prices ranging from $50,000 to 100,000 depending on the configuration.

C. Data output devices

Output devices are also getting better and available to more general users. Softcopy data are usually presented on color monitors, liquid crystal diode (LCD) panels and video projectors. Hardcopy data are generated by dot-matrix, ink-jet and laser printers, pen plotters, electrostatic raster plotters, flat bed plotters and film recorders. Pen plotters range in prices from $5,000 to 10,000, can handle up to E-size media, use up to eight pen turret to select liquid ink, and plot at speeds up to 42 inches per second. Electrostatic plotters cost around $30,000 for black and white output to $60,000 for color output, and work at resolutions of 400 dpi and media sizes of approximately 90 cm. Smaller format
outputs, up to A3 size, both black and white and in color are produced with the different printers available on the market. Depending on type and size, prices vary from $500 to 5,000.

Advances in display resolution, symmetric multiprocessors, possibilities of rendering 3-D models and multimedia, together with better and faster chips at ever decreasing prices, as well as improved fiber optics, cellular and wireless communications, handwriting and speech recognition, and the increased utilization of global positioning systems (GPS) and satellite multisensor products, will positively influence the use of GIS and promote more sophisticated approaches to model the real world into digital format.

III. SOFTWARE TECHNOLOGY AND TECHNIQUES

A. Geographic information systems

The demand for the storage, analysis and display of complex and voluminous environmental data has led, in the last decade, to the use of computers for data handling and the creation of sophisticated information systems (Tomlinson, 1976). The effective use of large spatial data volumes is very much dependant upon the implementation of efficient systems that can transform the data into usable information.

1. Growing importance of GIS

The geographic information system is a technology which is fast becoming an essential means for analyzing and graphically transferring knowledge about our world. A GIS has been defined as a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes (Burrough, 1986). GIS are changing spatial data collection procedures and analytical processes. They also support decision-making through scenario modelling and the formulation of alternatives for development and conservation planning. Therefore, GIS are rapidly becoming standard tools in resource planning or mapping agencies for the processing of basic data about the location, quantity and availability of natural and human resources.

At present quality software, supported by powerful hardware of increasing capability, is readily available for analyzing geographic information. Visualization technology provides high resolution color display capabilities and interactive editing. Versatile software systems can rapidly interconvert raster and vector (point, line, polygon) data. Some of them are actually comprehensive toolboxes containing separate software packages which can perform discrete functions or be combined to accomplish more complex applications. Such multipurpose and modular systems offer maximum flexibility in meeting the needs of a wide variety of users and, by allowing the addition of new functions, can keep up with rapidly changing demands in a dynamic field.

2. Basic geometric entities

Spatial data are usually described using four (4) primitive types of geometric encoding entities: points, lines, polygons and continuous surfaces (Dangermond, 1982; Burrough, 1986).

Points are 0-dimensional objects that have position in space but not length. Point data embrace all spatial entities that are positioned or described by a single X-Y coordinate pair. Points can be of two kinds: (a) observations relating to discreetly distributed phenomena such as oil and water wells or surface mining operations, and (b) observations relating to continuous distributions such as rainfall records from weather stations or soil temperature measurements from individual pedons. The choice of the entities which can be cartographically represented as points depends on the scale of the map.
For instance, a town may be represented as a single point at a small scale but as a two-dimensional object at a larger scale.

**Lines** are 1-dimensional objects having a length. Lines include all linear features built up of straight line segments with two or more coordinates. Line entities can be static (structural type) or dynamic (flow). Examples of the first category are the transportation infrastructure such as highways and railroads or the utility infrastructure for gas, electricity, telephone or water distribution. They do not carry inherent spatial information about connectivity. In contrast, a collective network of line segments defining existing traffic flows or capacities and stream flow data are examples of dynamic line data (Star and Estes, 1989).

**Polygons** (or area data) are 2-dimensional objects having a length and width. They constitute the most common data type used in GIS. They are bounded regions. The boundaries may be defined by natural phenomena such as landforms or by man such as forest stands or land use units. The most common polygon types are environmental and natural resource areas such as land cover, geologic or soil units; socio-economic areas such as census tracts; land record areas concerning land ownership or tax information. Polygons can be adjacent where the boundary of one polygon is shared by at least another polygon, or nested where areas of different attributes are wholly enclosed within another area (holes and islands).

**Continuous surfaces** are 3-dimensional objects having a length, width and height or depth. Examples of continuous surface data are elevation, rainfall, temperature, population density data. Most commercially available GIS cannot handle true 3-dimensional data, although they can process topographic data, usually as a digital elevation model (DEM), and display isometric views and contour maps. Most DEM use either gridded elevation matrices or triangular meshes (TIN) to represent terrain features. In these cases, the elevation or z-coordinate is treated as a dependent variable. Some systems allow the draping of another mapped feature such as the soil mantle, land cover or satellite images (Landsat MSS or TM, SPOT) onto an isometric view of a topographic elevation surface, thereby creating an illusion of a 3-dimensional scene.

Common GIS applications involve the mapping of essentially 2-dimensional land surface phenomena such as land use, forest or soil data. Some applications can be accomplished by reducing the 3-dimensional representation to a quasi 2-dimensional one through the use of surfaces. The surfaces representing bedding planes, for example, can be contoured or displayed as isometric views. However, in these cases, the elevation of the surface is not a truly independent variable, and such systems are best defined as quasi 3-dimensional or pseudo 3-dimensional.

There are several ways of organizing geographic data in a computer. The data model of the earth or the description of map features and their relationships are represented in terms of basic entities such as points, lines, areas and surfaces. The non-spatial data or sets of attributes describing the ranges of properties that apply to the entities are stored usually in relational database management systems. The spatial distribution of points, lines, areas and surfaces is represented in digital form via two basic types of spatial model: tessellation or raster and vector models.

### 3. Data analysis and spatial modelling capabilities

One of the most important characteristics of GIS is their capability for data analysis and spatial modelling. Conventional GIS analysis and manipulation capabilities include map overlaying, reclassification procedures, proximity analysis, optimum corridor and other cartographic modelling techniques (Burrough, 1986; Aronoff, 1989). Reclassifying map categories involves operations that reassign thematic values to the categories of an existing map as a function of the original value, the position, the size or the shape of the initial configuration associated with each category. For instance,
a soil map may be reclassified into a permeability map. Overlaying maps results in the creation of a new map where the values assigned to every location on that map are computed as a function of independent values associated with the location of two or more existing maps. Determining distance and conductivity includes operations for measuring cartographic distances and results in the creation of new maps in which the distances and routes between points can be expressed as simple Euclidian distances or as a function of absolute and/or relative barriers. These capabilities are used either separately or in conjunction with other simulation or statistical modelling techniques as illustrated in figure 1.

Figure 1. Analysis in a GIS (From Zinck and Valenzuela, 1990)

Spatial modelling requires good quality map information. Geostatistical techniques are increasingly used at different stages of the soil survey operation to improve the precision of the boundaries and the purity of the map units. Nested sampling is conducted at an early stage to establish proper observation densities. Grid sample areas are surveyed at a later stage for determining the composition of the map units or defining the degree of reliability of the soil information (Zinck, 1990). Increasingly, GIS can handle directly or via interfaces geostatistical packages for kriging and spatial analysis.

Efficient spatial modelling demands not only good data but also a large variety of georeferenced data which might be missing from the available databases. Sometimes such missing data, whose systematic capture is usually expensive and time-consuming (e.g. soil-water relationships data), can be inferred from more conventionally stored data like particle size distribution, bulk density and organic carbon content via the use of pedo-transfer functions (Tietje and Tapkenhinrichs, 1993).
B. Databases and database management systems

Databases and database management systems provide unique benefits for handling large amounts of data (Martin, 1976; Healey, 1991). A database management system (DBMS) is comprised of a set of programs that provide facilities to manipulate and maintain the data in the database. They allow to manage the sharing of data in an orderly manner and ensure that the integrity of the database is maintained.

1. System characteristics

Main characteristics of the combination of databases with database management systems are as listed and explained hereafter (Date, 1986; Aronoff, 1989).

**Data independence.** Application programs are independent of access strategy, physical structure and characteristics of the physical storage devices where the application data are stored.

**Maintenance of data integrity and quality.** Redundancy makes updating more difficult and may cause problems with the integrity of the database. A properly designed database contains procedures for controlling data redundancy and handling data updating. Established rules and standards help avoiding inconsistencies.

**Data dictionary.** A data dictionary is a system specifically used for storing and retrieving information about the structures of a database and the data contained in that database.

**Validation and recovery.** Sharing of data improves the consistency of data, but makes the enterprise potentially more vulnerable to errors. Erroneous data inserted into the database by one application will affect all other applications sharing the same data. Therefore, the database management system must validate data before permitting their storage in the database and provide comprehensive recovery procedures.

**User views.** A DBMS provides a convenient user interface to create and maintain multiple user views.

**Security restrictions.** Databases include security tools to control access to the data. This is important particularly for inserting and deleting data. Only authorized users, at different levels of accessibility, can handle the database.

2. Database design

**Conceptual model.** The real world to be modelled can be viewed in three different manners: (a) as it actually is; (b) as it is perceived by humans; and (c) as it is described by symbols. In other words, modelling deals with (a) the reality itself; (b) a descriptive representation of this reality; and (c) data that characterize that representation (Hubbard, 1981; Peuquet, 1984). It is this characterization that is stored in the database and manipulated by the application programs.

The conceptual model of the real world to be represented should be specified. Figure 2 shows the conceptual model of the geoform-soil complex (geopedologic) approach. The logical content and some constraints are listed hereafter:

(a) The data in in soil map are number, location, ...
(b) The soil map is formed by several soil map units (SMU).
(c) The data held in SMU (soil map units) are symbol, area, ...
(d) A SMU has one or several polypedons.
(e) One polypedon can be part of several SMU.
(f) The data present in polypedons are name, classification, ...
(n) The data held in horizons are horizon number, symbol, depth, ...
Entity - relationship modelling. Chen (1976) proposed a semantic and diagrammatic technique known as the entity-relationship (E-R) model. It utilizes the concepts of entity, attribute and relationships. The design of the E-R model involves the following steps: (a) definition and identification of the various entities; (b) definition of the entity relationships; (c) representation of the model in a diagram; (d) assignment of attributes to the entities and construction of a fully-normalized table for each entity. A thorough study of the conceptual model and the design of the E-R model allow the definition and identification of the relevant entities. The following are the soil database entities: Soil Map, Soil Map Unit (SMU), Polymorphon, SMU/Polypedon, Polypedon, Pedon, Horizon (Figure 3).

Figure 2. Conceptual model of the geopedologic approach (From Zinck and Valenzuela, 1990)

Figure 3. Logical design of the soil database (From Zinck and Valenzuela, 1990)
3. Database models

Geographic information systems have adopted and adapted the three main data models proposed for generalized databases: the hierarchical, network and relational models. The data model, on which a database system is based, represents the organization, description and manipulation of the database. It includes a set of primitive operations, commonly referred to as data language, data sub-language or data manipulation sub-language, that can be used to manipulate the data stored in the database. It is beyond the scope of this paper to discuss the merits of each model. However, because the relational model is still the most accepted data model, its characteristics are discussed hereafter.

A relational structure can be thought of as a set of normalized relations between entities or elements defined in a collection of domains (Figure 4). A normalized relation may be viewed by the user as a two-dimensional entity table, corresponding usually to a separate file in the database. Each row of the table, termed tuple or record, contains selected information belonging to one element of the relation (e.g. individual soil horizons). Each column of the table, termed attribute or field, contains a set of attribute values, each belonging to a specified row element. Attribute values can be either qualitative (e.g. soil structure type) or quantitative (e.g. soil horizon depth). The complete set of values reported in one column and describing the range of variation of a given attribute constitutes the domain of that attribute. Figure 5 illustrates a relational table.

![Figure 4. Relational model](image-url)
An important feature of a relational data structure is that associations between tuples are represented by data values in columns drawn from a common domain. Of all attributes in a particular entity table, there is usually one that uniquely identifies the tuple entries in that entity table. This attribute is said to be the primary key. A primary key may not be restricted to a single attribute and can also be a combination of several attributes which together have the unique identification property. An entity table may sometimes contain more than one attribute combination providing the unique identification property. Common primary key attributes must be present in all related entity tables. They are used as identifiers to access and query a set of tables via a join operation for extracting selected information which can be visualized through virtual tables.

The real world, however, is more complex than can be shown in a simple relational data model, and has functions and relationships that are not supported by commercial products. Although relational models have relations implicit in their structure, they cannot handle properly the connections between two large natural resource entities such as soil and water for instance. A relation does not have direction or degree of association. A relational model, although efficient and robust from the systems' point of view, is too simple to represent the complexity of the real world (Worboys, Hearnshaw and Maguire, 1990).

Figure 5. Relational table
Object orientation

Currently, a major research topic is the use of object-oriented techniques in the design and implementation of geographic information systems. Object orientation has often been used without a clear definition of what it actually entails. A definition of object orientation is that an entity of whatever complexity and structure can be represented exactly by one object. The most important elements in the object-oriented model are objects and classes. These elements and their relationships involve several basic concepts such as abstraction, inheritance, encapsulation, polymorphism, message passing, persistence. The object-oriented model is built on the four basic modalities of abstraction: classification, generalization, association and aggregation (Brodie, 1984).

Object is defined as a "tangible or visible thing, or something that may be apprehended intellectually or towards which a thought or an action is directed", or as a "software element which has state, behaviour and identity" (Booch, 1991). An object is an entity with a complex state described by instance variables (attributes) and a set of procedures or methods (instance methods) that operate on the object. The state of an object encompasses all its properties (usually static) plus the current values (usually dynamic) of each of the properties. The behaviour is the way an object acts and reacts in terms of its state changes and message passing (Booch, 1991). The existence of an object is independent of its value. In contrast to the philosophy of the relational model, it is possible for two objects to have equal values and still be identified unambiguously. The identity of an object is an unique property of the object that distinguishes it from all other objects. The concept of message passing is an important one in object orientation. It represents the way objects interact in a system defining transitively the system's behaviour. Objects exhibit behaviour when they receive or send a message requesting information from another object. Creating, accessing or deleting the state of an object are performed by sending messages to the object.

All three characteristics of an object, i.e. state, behaviour and identity, coexist in a single object thanks to encapsulation or information hiding. This concept refers to the practice of including within an object everything it needs (data, methods, rules), in such a way that no other object needs ever to be aware of its internal structure. Information about the object can only be obtained by sending it a message, which has to be one belonging to the set of valid messages defined by the object's methods.

Class is a set of objects that share a common structure and behaviour. The objects of a class have the same attributes and can call the same procedures or methods. Each class belongs to a superclass from which it can inherit attributes and methods. Inheritance is the transitive transmission of properties from one superclass to all related subclasses and subsequent levels of subclasses, thus reducing information redundancy and maintaining integrity (Woelk, 1987). Operations of the superclass are valid to all objects of the subclasses, because subclass objects are also objects of a superclass. Operations which are specifically defined for a subclass, however, are not applicable to superclass objects. Properties which are common to a superclass and its subclasses are defined only once, at the superclass level, and inherited by all objects of the subclass. Subclasses may have additional specific properties and operations which are not shared by the superclass. Figure 6 illustrates an example of inheritance.

Object orientation provides powerful tools that scientists are beginning to use for natural resources information systems. The object-oriented approach allows to model complex relationships in a more robust manner than the relational model. Its application, however, is limited by the difficulty in recognizing unique spatial objects and properly describing their relationships (Burrough, 1992). There is still a long way to go to understand and comprehend the physical relationships between and the processes acting upon rock, soil, vegetation, water and atmosphere.
Figure 6. Inheritance concept in object orientation (From Egenhofer and Frank, 1989)

C. Relief representation and correction

1. Digital elevation and terrain models

A digital elevation model (DEM) is a digital representation of the continuous altitudinal variations of a portion of the earth’s surface. If terrain features of morphological significance are added to such an elevation representation, the resulting model is termed digital terrain model (DTM) (Burrough, 1986).

The generation of digital terrain models usually comprises the following tasks (Weibel and Heller, 1991):

- DTM generation: sampling of the earth’s surface of interest, model construction
- DTM manipulation: modification and refinement of the DTM, derivation of intermediate models
- DTM interpretation: DTM analysis, information extraction
- DTM visualization: graphic rendering of DTM and information derived from it
- DTM applications: development of appropriate application models for specific disciplines

The data necessary for the generation of DTM are (Radwan, 1990):

- Terrain elevations sampled at regular grid points and/or irregular points such as spot heights, peaks, pits and lines (i.e. contours, cross sections and boundaries of rivers, terraces, etc.).
- Positional and elevation data of distinct morphometric features such as terrain peaks, points of slope discontinuities, ridge lines, etc.

Currently, most DTM are generated using three data sources: ground surveys, photogrammetric compilation and/or digitized cartographic documents. Other sources include matching of overlapping digital images (aerial photographs or satellite imagery such as stereo SPOT), radar, sonar, bore holes or seismic data. These data are subject to various processing and conditioning phases before being used to generate the model. Conditioning processes include transformation of coordinates, interpolation, filtering, rating of points significance for terrain form representation, compression, etc.
DTM are represented in various structures, the most common ones being the rectangular grid and the irregular triangulated network (TIN). The handling of regular grids is simple and related algorithms are relatively easy to implement. Grid density, however, has to be very high to represent adequately the terrain. TIN structures reflect more efficiently the terrain with fewer points. Topological relations have to be computed or recorded explicitly. They are more complex and difficult to handle.

DTM can be analyzed and information extraction can be performed visually or by quantitative techniques. Slope values, gradient and aspect can be easily derived from the model. Several other geomorphometric parameters including local relief, drainage density, hypsometric integral, slope and aspect statistics can be estimated (Evans, 1980; Pike, 1988). They can be later used as input in modeling procedures for erosion and landslide hazard assessment, trafficability evaluation, road selection, hydrologic and erosion models, etc.

DTM can be visualized as simple contour lines, hillshading views and various other forms of depicting the relief in combination with thematic data (e.g. soil or vegetation) or other digital products such as aerial photographs or satellite imagery. Figure 7 illustrates an isometric view of an area in the coffee belt of the Colombian Andes.

Figure 7. Isometric view, Colombian Andes

2. Monoplotting

The most common problems faced when working with aerial photographs in terrains with complex relief are image displacements, bending lines, and variations in scale of the photographs. Most commercial GIS try to solve these problems using the technique of "rubber-sheeting", i.e. stretching in some places and contracting in others, so that image points will match given control points and further triangulation can adjust the entire image. This process is reliable only in flat terrains. Most simple transformations fail to match exactly photographs to reality in areas with variable topography. Obvious discrepancies in terms of area and shape occur where there are elevation changes. This is because most digitizing programs or rubber-stretching procedures neglect the basic geometry relating the image of the photograph to the ground truth.
The proper transformation that correctly matches an aerial photograph to map coordinates is controlled by the geometry of the photograph accounting for relief, tilt, and tip, and by the camera characteristics. Relief displacement or the relative distortion of the image on the photograph due to the shape or topography of the ground has to be accounted for when working with aerial photographs in rugged terrain. The use of a digital elevation model (DEM) can help handle the relief variable and, if combined with a proper understanding of the camera characteristics and geometry of the photographs and the appropriate software, data can be directly digitized from a single photograph accurately and rapidly.

The geometry of aerial photographs is well documented in photogrammetry. A photogrammetric resection basically consists in the determination of the six parameters of the camera at the time of the exposure, i.e. three rotational or angular elements for the attitude and three linear elements for the position of the central projection. Calculations are based on the position of three or more objects on the ground and their corresponding position on the photographic image. Thus, three dimensional collinearity equations relate the central projection of the photograph, image or photo coordinates \((x, y)\), and ground coordinates \((X, Y, Z)\). Figure 8 shows the basic concept and the bundle equations for photographs.

\[
X_i = \frac{X_0 + \Delta \cdot R \cdot X_i}{X_0 + \Delta \cdot R \cdot Y_i} = \frac{1}{\Delta_1} \cdot A \cdot \frac{X_i - X_0}{Y_i - Y_0} \cdot \frac{Z_i - Z_0}{Z_0}
\]

\[
R = \begin{bmatrix}
\cos \theta & \sin \theta & 0 \\
\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[
A = \begin{bmatrix}
\cos \phi & 0 & \sin \phi \\
-sin \phi & cos \phi & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

Direct equations:
\[
x_i = -c (X_i - X_0) / h
\]
\[
y_i = -c (Y_i - Y_0) / h
\]

Inverse equations:
\[
X_i = (X_0 + \Delta \cdot R \cdot X_i) / (X_0 + \Delta \cdot R \cdot Y_i)
\]
\[
y_i = (Y_0 + \Delta \cdot R \cdot Y_i) / (Y_0 + \Delta \cdot R \cdot Y_i)
\]

Figure 8. Bundle equations for aerial photographs (From Bargagli, 1991).
Position of the central projection
Rotation of the photo coordinate system with respect to the ground system
Principal distance of the camera
Photo coordinates of a specific point
Corresponding ground coordinates
Three-dimensional rotational matrix function of $\kappa$, $\varphi$ and $\omega$
Scale factor

The three-dimensional rotational matrix $(A)$ is formed by multiplying rotations around the three axes of the coordinates $(X, Y, Z)$. Each rotation is a function of the corresponding angle $(\kappa, \varphi$ and $\omega)$. To use these equations, the position of the central projection and the rotational matrix (attitude) have to be known. They are calculated by performing a single photograph photogrammetric orientation solving the rotational parameters and position of the central projection with the use of ground control points. Although three well distributed points are enough to satisfy the equations, it is recommended to use four to eight additional points to enable statistical accuracy tests.

The solution is based in computing initial approximations for the six parameters, which are iteratively adjusted by minimizing the discrepancies between the observed or given photo coordinates $(x, y)$ and the ones computed from the direct equations of figure 8, until the corrections become negligible. The linear square adjustment solution permits the use of any number of control points (minimum three), and statistical tests of the solution can be performed.

To find the ground position $(X, Y, Z)$ of any photo coordinate, combinations of input and output driven procedures are performed. With the photo coordinates and an approximate height (e.g. the mean height $Z_m$), and using the inverse bundle equations, approximate ground coordinates are found for a given position such as:

$$X_a = f(x, y, Z_m) \quad Y_a = f(x, y, Z_m)$$

The actual height of such a position can be read from the DEM: $Z_a = f(X_a, Y_a)$.

Now, using this approximate position and the direct formula it is possible to find the corresponding new photo coordinates such as:

$$(x_n, y_n) = f(X_a, Y_a, Z_a)$$

The outcoming coordinates are compared with the original photo coordinates $(x$ and $y)$. If the differences are big, the procedure is repeated but by computing now ground coordinates from the original photo coordinates and the new height $(x, y, Z_a)$ until the differences become negligible.

IV. MODELS

The two fundamental compartments of a GIS are the data base and the model (or rule) base on which the data base management system operates. Raw spatial and thematic data must be transformed by formalized interpretation and evaluation procedures into usable information for specific purposes. Models, from simple regression equations to more sophisticated process and simulation models, allow to perform such transformation of primary data into derived information. Hydrologic, erosion, land evaluation and environmental models, among others, make large consumption of soil data.
A. Hydrologic models

A hydrologic model can be defined as a mathematical representation of the flow of water and its constituents on some part of the land surface or through subsurface environments (Maidment, 1991). The spatial components in hydrologic modelling are surface watersheds, pipes or stream channels, subsurface aquifers, and lakes or estuaries. All of these four components are three-dimensional objects that can be satisfactorily approximated in a computerized manner. Depending on the way hydrologic models account for randomness, space and time characteristics of hydrologic phenomena, they can be classified as illustrated in Figure 9.

![Figure 9. A classification system of hydrologic models (From Chow, Maidment and Mays, 1988)](image)

A hydrologic system is a set of physical, chemical and/or biological processes acting upon input variables to convert them into output variables (Clarke, 1973). If the variables are free from random variations, the model is called deterministic. In contrast, stochastic models include random variables with probabilistic distribution. Mathematical simulation of natural hydrologic systems may be achieved by means of either a lumped-system model or a distributed-system model. Lumped-systems do not consider the spatial distribution of the input variables, property values being spatially averaged. In such models, space coordinates (position) are not important and all parts of the system being simulated are regarded as located at a single point in space. The use of a lumped-system model does not explain the mechanisms of the basic hydrologic processes. Distributed-system models simulate the hydrologic processes at various distributed points or areas within the space of the system. It involves more than one independent variable, i.e. the space coordinates in addition to the usual time variable. Table 1 lists the most commonly used hydrologic models (Maidment, 1991).
Table 1. Summary of hydrologic models (From Maidment, 1991)

<table>
<thead>
<tr>
<th>SURFACE WATER MODELS</th>
<th>SUBSURFACE WATER MODELS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SINGLE EVENT RAINFALL-RUNOFF</strong></td>
<td><strong>GROUNDWATER FLOW</strong></td>
</tr>
<tr>
<td>HEC-1</td>
<td>PLASM</td>
</tr>
<tr>
<td>Tr-20</td>
<td>MODFLOW</td>
</tr>
<tr>
<td>R.LUDAS</td>
<td>AGUCIFEM-1</td>
</tr>
<tr>
<td>DR3M</td>
<td></td>
</tr>
<tr>
<td><strong>CONTINUOUS STREAMFLOW SIMULATION</strong></td>
<td><strong>GROUNDWATER CONTAMINANT TRANSPORT</strong></td>
</tr>
<tr>
<td>SWRRB</td>
<td>AT123D</td>
</tr>
<tr>
<td>PRMS</td>
<td>BIOID</td>
</tr>
<tr>
<td>SHE</td>
<td>RNDWALK</td>
</tr>
<tr>
<td></td>
<td>USGS MOC</td>
</tr>
<tr>
<td></td>
<td>MT3D</td>
</tr>
<tr>
<td></td>
<td>MODPATH</td>
</tr>
<tr>
<td><strong>FLOOD HYDRAULICS</strong></td>
<td><strong>VARIABLY SATURATED FLOW AND TRANSPORT</strong></td>
</tr>
<tr>
<td>(Steady flow)</td>
<td>VS2D</td>
</tr>
<tr>
<td>HEC-2</td>
<td>SUTRA</td>
</tr>
<tr>
<td>WSPRO</td>
<td></td>
</tr>
<tr>
<td>(Unsteady flow)</td>
<td></td>
</tr>
<tr>
<td>DMBRK</td>
<td></td>
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<tr>
<td>DWOPER</td>
<td></td>
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<tr>
<td><strong>WATER QUALITY</strong></td>
<td></td>
</tr>
<tr>
<td>SWMM</td>
<td></td>
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<tr>
<td>HSPF</td>
<td></td>
</tr>
<tr>
<td>QUAL2</td>
<td></td>
</tr>
<tr>
<td>WASP</td>
<td></td>
</tr>
</tbody>
</table>

B. Soil loss and conservation models

Soil loss prediction models can be classified in two categories, i.e. empirical and analytical models (T. Loran et al., 1988). Empirical models make use of statistical analysis operating on large soil data sets and long-term rainfall records. They generate results which are mainly site specific and do not explain the processes involved. Statistically derived soil loss equations need, therefore, ample adjustments when applied outside their birth area (e.g. the USLE model). In contrast, analytical models intend to predict soil losses through process orientation. Due to their complexity they require accurate calibration and validation (e.g. the ANSWERS model). Large data sets are needed to satisfy process simulation. Some erosion models include mechanisms to select soil conservation practices and evaluate their cost effectiveness (e.g. the COSTS and SOILEC models). Table 2 lists some of the most commonly used mathematical deterministic soil erosion models (Roo, 1993).
Table 2. Summary of erosion models (From Roo, 1993)

<table>
<thead>
<tr>
<th>ACRONYM</th>
<th>NAME</th>
<th>YEAR</th>
<th>PROCESSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>USLE</td>
<td>UNIVERSAL SOIL LOSS EQUATION</td>
<td>1970</td>
<td>E</td>
</tr>
<tr>
<td>MUSLE</td>
<td>MODIFIED USLE</td>
<td>1975</td>
<td>E</td>
</tr>
<tr>
<td>RUSLE</td>
<td>REVISED USLE</td>
<td>1981</td>
<td>E</td>
</tr>
<tr>
<td>MUSLE87</td>
<td>MODIFIED USLE 1987</td>
<td>1987</td>
<td>E</td>
</tr>
<tr>
<td>SUSLE</td>
<td>DIFFERENTIATED USLE</td>
<td>1990</td>
<td>E</td>
</tr>
<tr>
<td>ALEMSA</td>
<td>SOIL LOSS ESTIMATOR FOR SOUTH AFRICA</td>
<td>1981</td>
<td>E</td>
</tr>
<tr>
<td>CLEAMS</td>
<td>CHEMICAL RUNOFF AND EROSION FROM AGRICULTURAL</td>
<td>1982</td>
<td>EHNPE</td>
</tr>
<tr>
<td>GLEAMS</td>
<td>GROUNDWATER LOADING EFFECTS OF AGRICULTURAL</td>
<td>1983</td>
<td>EHNPE</td>
</tr>
<tr>
<td>ARM</td>
<td>AGRICULTURAL RUNOFF MODEL</td>
<td>1978</td>
<td>EFNPE</td>
</tr>
<tr>
<td>MMF</td>
<td>MORGAN-MORGAN-FINNEY</td>
<td>1984</td>
<td>E</td>
</tr>
<tr>
<td>EPIC</td>
<td>EROSION PRODUCTIVITY IMPACT CALCULATOR</td>
<td>1984</td>
<td>EFNPE</td>
</tr>
<tr>
<td>KYEHM</td>
<td>KENTUCKY EROSION MODEL</td>
<td>1990</td>
<td>E</td>
</tr>
<tr>
<td>WEPP</td>
<td>WATER EROSION PREDICTION MODEL</td>
<td>1989</td>
<td>E</td>
</tr>
<tr>
<td>EROSION2D</td>
<td>2-D RAINFALL EROSION MODEL</td>
<td>1990</td>
<td>E</td>
</tr>
<tr>
<td>MEDALUS</td>
<td>MEDITERRANEAN DESERTIFICATION AND LAND USE</td>
<td>1992</td>
<td>EFNCE</td>
</tr>
<tr>
<td>GSU</td>
<td>COLORADO STATE UNIVERSITY MODEL</td>
<td>1977</td>
<td>E</td>
</tr>
<tr>
<td>ANSWERS</td>
<td>AREAL NONPOINT SOURCE WATERSHED ENVIRONMENT</td>
<td>1977</td>
<td>E</td>
</tr>
<tr>
<td>KINEROS</td>
<td>KINEMATIC EROSION SIMULATION</td>
<td>1990</td>
<td>E</td>
</tr>
<tr>
<td>EUROSEM</td>
<td>EUROPEAN SOIL EROSION MODEL</td>
<td>1990</td>
<td>E</td>
</tr>
</tbody>
</table>

E = erosion; R = runoff; N = nutrients; P = pesticides; C = crop growth

C. Sustainable land management models

For being one of the principal components of the life support system, together with water, air and biota, the soil resource imposes a strong control on sustainable agriculture and sustainable land management. A large variety of empirical approaches and formalized models has been proposed to tackle this issue as illustrated in table 3. Qualitative land evaluation frames as well as quantified yield prediction models are largely soil data driven. Less conventional approaches make intensive use of pedo-archaeological and micromorphological soil data to search for long-lasting land management practices in the past. Similarly, models based on the concept of co-evolution between socio- and ecosystems implement the classic soil state factor equation to evaluate the dynamic equilibrium of cultural landscapes (Farshad and Zinck, 1993).
Table 3. Summary of sustainable land management approaches (From Farshad and Zinck, 1993)

<table>
<thead>
<tr>
<th>Land evaluation approaches</th>
<th>Retrospective approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Attribute rating and matching techniques</td>
<td>• Archaeological data analysis</td>
</tr>
<tr>
<td>• Productive potential estimation</td>
<td>• Historical data analysis</td>
</tr>
<tr>
<td>• Agroecosystem analysis</td>
<td>• Analysis of landscape evolution</td>
</tr>
<tr>
<td>• Carrying capacity modelling</td>
<td>• Soil micromorphology studies</td>
</tr>
<tr>
<td>• Environmental impact analysis</td>
<td></td>
</tr>
<tr>
<td>Co-evolutionary approaches</td>
<td>Knowledge-based approaches</td>
</tr>
<tr>
<td>• Agricultural system analysis</td>
<td>• Conventional expert knowledge</td>
</tr>
<tr>
<td>• Cultural landscape and landuse analysis</td>
<td>• Indigenous knowledge</td>
</tr>
</tbody>
</table>

D. Environmental models

Environmental models vary from regional critical (pollution) load models to global climate change models. Critical load refers to the maximum amount of acidifying deposition, mainly from sulphur and nitrogen, an ecosystem can receive without suffering long-term damage in its structure and functions. In industrialized countries, the acidification of soils, and consequently lakes and streams, is caused by the input of acidity to the catchments mainly from long-range transboundary air pollution. The only long-term source of alkalinity to neutralize this acidity is the weathering of minerals in the soils of the catchment areas.

Critical loads can be calculated using empirical and process-oriented models including dynamic simulation models and steady-state models. For instance, the Steady-State Water Chemistry (SSWC) method determines exceedances of incoming total acidity over allowed critical loads. In contrast, the First-order Acidity Balance (FAB) method accounts for the processes controlling the acidity balance of a catchment area (Henriksen et al., 1993). Similarly, the steady-state PROFILE model and its dynamic version SAFE calculate critical loads from bearable chemical limits for selected biological indicators using as input data major soil properties such as horizon thickness, depth to bedrock, particle size distribution of each horizon, weatherable minerals in the B-horizon, soil temperature and moisture regimes, together with other environmental parameters (Sverdrup et al., 1992).

Similarly, global climate change models need soil information since the production, consumption and emission of greenhouse gases are affected by physical, chemical and biological processes occurring in the soil mantle. Information on soil geography handled via GIS is indispensable to extrapolate point data on gas emissions and fluxes to global scale ecosystems. The estimated doubling of the atmospheric CO₂ from pre-industrial epoch to the beginning of the 21st century has been used as a main criterion to construct general climate circulation models (GCM). Such models predict a global rise in temperature of 2 to 5°C by the middle of the next century. Main causes of global warming are increasing atmospheric concentrations of carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). Soil as a component of the ecosystem contributes to the balance of greenhouse gases both as a source and as a sink, in particular in critical gas emission zones such as areas subject to deforestation or desertification, paddy rice cultivation areas, permafrost areas and landfills (Bouwman, 1990).
V. CONCLUSION

There is a deepening gap between the extensive capabilities of information technology and the shrinking availability of soil data relevant in terms of quantity and quality. Information systems can handle increasing amounts and diversity of data. Complex models demand more and better data. So far, soil survey has been the main traditional source for dissemination of such data. Although they provide a large variety of data able to satisfy many application purposes, conventional soil survey operations have been questioned because of insufficient visibility, inappropriate presentation and poor accuracy of soil information, together with high survey costs. For efficiency reasons the minimum data set approach has been promoted to fulfill specific application needs, but with unconvincing success because successive applications may require repeated, thus expensive data collection from the same area. To fully benefit from the advances in information technology, soil data capture and implementation face a two-fold challenge. On one hand, innovative and diversified applications must be developed, with special emphasis on monitoring dynamic properties of soil in its many resource facets as a natural body, medium for plant growth, water-transmitting mantle, structural material and ecosystem component (Dumanski, 1993). On the other hand, modern techniques of data transformation, analysis and classification, via environmental and geostatistical modelling, must be used to deal with the multivariate time/space continuum of the soil mantle (Burrough, 1993).

REFERENCES

Development of Soil Databases for Global Environmental Modelling


Abstract. Earth and atmospheric scientists require up-to-date and geo-referenced data on the world's natural resources, including climate, geology, landforms and soils for their modelling studies. ISRIC is meeting this demand by developing quantified databases on the geographic distribution and characteristics of soil resources that can be used at different scales of operation. The database development activities started in the mid-eighties when ISRIC computerized the information held in its Soil Reference Collection. This pedon database, with acronym ISIS, now holds over 450 fully described profiles representative of the soil units of the FAO-Unesco Soil Map of the World. A second thrust has been to develop a methodology for updating both the "area" and "attribute" data on world soils. This is SOTER, the 1:1 M World Soils and Terrain Digital Database project, the development of which was endorsed by ISSS during its 13th International Congress at Hamburg. After testing of a methodology and software in parts of South and North America, the revised procedures for soil data description and handling were published jointly by ISRIC, ISSS, FAO and UNEP. The SOTER system handles input for a range of applications, including land evaluation, studies of crop production potentials and population supporting capacity. SOTER databases, linked to models and GIS, permit a geographic quantification and characterization of areas of concern (e.g., desertification, land degradation, soil pollution), permitting identification of areas for follow-up studies at larger scales and policy formulation.

A practical limitation to a 1:1 M SOTER is that world coverage will require from 10-20 years. In the meantime, modellers still require a geo-referenced soil data set representative for the main soil units of the world. This demand is being met at ISRIC through WISE, a project entitled "World Inventory of Soil Emission Potentials". A suite of soil profiles, considered to be representative for a particular FAO-Unesco soil unit in a given area, is being linked to the "area" data held by a ½ by ½ degree grid-version of the FAO's "cleaned" 1:5 M Soil Map of the World. The WISE database, and auxiliary databases, will be used first to provide a refined estimate of potential methane production, and possibly emission, from soils under wetland rice. The database also holds the basic data for an assessment of the vulnerability of soils to pollution and other global environmental studies, pending full world coverage by SOTER at a scale of 1:1 million.

Introduction. From the Stone Age to the current industrialized era the activities of Man have interfered increasingly with the functions of the biosphere, both in positive and negative ways (2,20, 27, 41, 43, 57, 61). The environmental links between soils, food crops and water
supplies mean that if soils are degraded or polluted, there is every likelihood that food-chains and drinking waters will be affected also. Soils are also natural sources and sinks of radiatively-active trace gases such as methane and nitrous oxide, which enhance global warming and affect the chemistry of the atmosphere (9, 14, 15).

Researchers need to have access to uniform and compatible environmental databases, linked to GIS, for their modelling. Simulation models aid in understanding and predicting mid-term and long-term effects of environmental change, and GIS software allows a multivariate approach in the spatial and temporal domains. An important application of models is to convert qualitative observations and quantitative measurements into knowledge which may be used to simulate scenarios for making decisions. Models are a simplification of reality, describing only those aspects of a complex system so that most of the observed variability can be explained. They are necessary tools, for instance, for calculating crop production potentials and for studying the possible consequences of processes of global change.

Development of a model for a particular application, e.g. methane emission potentials from wetland rice soils, requires a sound understanding of the main controlling processes and their quantification. In the preliminary models, insight into the controlling processes is still vague. Comprehensive models can be developed for systems in which the essential elements are well understood. They are often large, intricate and not user-friendly. Consequently, they are used mainly for scientific research by the scientists who developed them often employing very specific data. To arrive at a workable and widely applicable model, it is often necessary to give a simplified representation of the perceived controlling processes, resulting in a summary-type model.

Initially, the scientific basis for developing a model can be obtained through laboratory experiments, supplemented with field studies. Field experiments are important in assessing the influence of spatial and temporal variability in the perceived controlling factors of physical, chemical and biological processes. As the scientific understanding of processes at the micro-scale increases, in principle the concept can be scaled-up to the meso- and macro-scale by linking the models with databases in a GIS. Nonetheless, the intricacies and uncertainties associated with the scaling-up of site data to the macro-scale remain inadequately understood (18, 19, 52, 73).

Geographic databases of parameters such as vegetation cover, climate and soil properties will determine extrapolation and modelling capabilities at the global level (13, 44, 47). These databases will be needed at scales that reflect their effect on regional and global processes which are relevant to modelling goals (73). A number of less than satisfactory General Circulation Model results have been attributed to inadequate parameterization of values used for e.g. soil water-holding capacity estimated from the "topsoil texture" only (71). It is incumbent upon soil scientists to apply recent digital technologies to produce soil databases and applications which are readily understandable by user-groups in the resource planning, management and policy areas.

In this paper, we review the development and implementation at ISRIC of three soil databases, which operate at different scales of resolution, namely: a) ISIS, the ISRIC Soil Information System; b) SOTER, a 1:1 M World Soils and Terrain Digital Database; and c)
WISE, a 1:5 M soil database developed for a World Inventory of Soil Emission Potentials. Applications of the databases are discussed, and potential problems identified.

ISIS, the ISRIC Soil Information System.

The system. When the predecessor of ISRIC was founded in 1966 its main task was to assemble, analyze and describe soil monoliths representative of the legend units of the Soil Map of the World (31). The reference collection now holds over 450 monoliths from over 60 countries, mainly from subtropical and tropical regions. A large number of these are permanently exhibited in ISRIC's museum section, together with pictorial information on the site and physico-chemical properties.

Since 1988, management and handling of the data collected for ISRIC's reference collection is possible with ISIS (68). This relational database management system formed the basis for the SDB Soil Database of FAO-ISRIC (30). Version 4.0 of ISIS is written in dBase IV and permits handling and analysis of:

a) Site data, which include about 60 mainly descriptive (coded) attributes on location, geology, landform, soil surface properties, hydrology, land use and vegetation;

b) Quantitative synoptic climatic data as obtainable for meteorological stations that are considered representative for the conditions prevailing at the profile site.

c) Profile data, including: i) soil classification according to the Legend of FAO-Unesco (31), the Revised Legend (32), USDA Soil Taxonomy and the local system; ii) soil profile descriptions according to the FAO-ISRIC Guidelines (30); and iii) physical, chemical and mineralogical attributes per soil horizon.

Data collection. Analytical data held in ISIS are determined in ISRIC's laboratory using standardized laboratory procedures (67). At the end of 1993, over 450 fully checked profiles were stored in ISIS, while another 400 profiles are still held in archives. In the coming two years, this manuscript information will be added to ISIS. This involves screening of the available data for errors and data gaps. Where necessary, soil samples held in ISRIC's store-rooms will be re-analyzed to meet the quality criteria of the database. New profiles for ISIS are being collected mainly through the NASREC programme which aims to establish National Soil Reference Collections (36).

Applications. At first, monoliths held in the collection were used to publish extensive Soil Monolith Papers, mainly of relevance to soil-specialists (1). The emphasis now has changed to the production of Soil Briefs which present a simplified description of a reference soil profile in its ecological setting, and its potential uses (39). A set of soil data and climate data graphs can be generated from ISIS using the Soil Data Graph facility (17). An important application of ISIS data by NASREC participants is land evaluation for which the FAO Framework (26) is used as the common basis. A module to transfer data from ISIS into the ALES system (51) is being developed. For those soils (or map units) identified as being potentially suitable for a proposed land use, it is possible to obtain an indication of crop production potentials. A module (50) is available which permits selection of the appropriate ISIS soil data sets and to update the climate data files necessary for running the WOFOST model (65, 66). Data held in ISIS can be displayed as listings per country, which are being compiled on a country basis into so-called Country Reports for wider distribution. ISIS data are used further in testing proposed criteria for soil classification, for instance in the context.
of the World Soil Reference Base activities. ISIS provides also a validated set of data, analyzed according to uniform and standardized procedures, for the other databases under development at ISRIC. Data held in ISIS can be "off-loaded" to these databases using an automated transfer-facility.

**SOTER, a World Soils and Terrain Database**

*Origins.* The Soil Map of the World, published by FAO-Unesco (31), is based on data available in the sixties and early seventies. Since then new and updated maps have become available for many parts of the world, information which needs to be included into a revised edition. The new surveys lead to the development of a Revised Legend (32, 33), the application of which requires some map unit boundaries to be redrawn. At its 13th Congress in Hamburg, ISSS asked ISRIC to coordinate the development of a methodology for a World Soils and Terrain Database (11, 12, 56). SOTER would utilize information technology to develop a 1:1 M database, containing digitized map units in a GIS and their attribute data in a relational database management system. The integrated system was to hold the data necessary for improved mapping and characterization of world soil and terrain resources, and for monitoring changes therein (63).

*Mapping approach.* The general approach adopted with SOTER is to screen all existing soil and terrain data in a geo-referenced area and to complement the terrain information with remote sensing where necessary (63). Basic to this approach is the mapping of land areas showing a distinctive pattern of land form, surface form, slope, parent material, and soils. These areas are delineated on the base map as SOTER units. In the database, each SOTER unit is identified by a unique label and characterized by: a) its location and topology, and b) its attribute data, i.e. characteristics (Fig. 1).

The land of a SOTER unit displays similar patterns of surface form, slope, micro-relief, and parent materials. The main criterion for separating SOTER units at the highest level of differentiation is physiography. Areas falling within a similar landform are further segregated according to their lithology or parent material; this then forms the terrain unit. Next, terrain components are delineated within each terrain unit, mainly with reference to surface form, slope, micro-relief and texture of the unconsolidated parent material. Terrain components are divided further with respect to their main soils, corresponding with the soil components.

Each soil component is characterized using one representative soil profile which has been selected from a number of similar, typical profiles by regional correlators. When available, an indication of the range of the variations for each attribute can be indicated (63). Ideally, the set of profiles for which these ranges were calculated should be stored in a national profile database based on SDB procedures (29). This approach should be seen as providing a good compromise between the spatial "limitations" imposed by a 1:1 M map scale, and the amount of information that can be physically and meaningfully incorporated in the key attribute database of SOTER.
Subdivisions at a level below that of the terrain unit cannot be represented on a 1:1 M map. The attribute data for each constituent "terrain unit", "terrain component" and "soil component", however, can be handled in the database (Fig. 2). The complement of non-spatial attributes is listed in the Annex, showing that a digital 1:1 M SOTER database would be able to handle more information on soil conditions than has been the case so far. The attribute-files are defined into "structures" compatible with widely-used commercial software database management systems, including dBase, INFO and ORACLE. Different GISs, such as IDRISI (34), ILWIS (37) and ARC/INFO (24), have been linked with the databases for pilot areas situated in North and South America, initially to produce a range of thematic maps. Data from the Latin American pilot area were used also during a training course for participants from Argentina, Brazil and Uruguay (62).

Applications. ISRIC personnel reviewed the potential of the SOTER database for land evaluation (3), and developed an application program for Soil Water Erosion Assessment (SWEAP; 64). It contains two modules, modified after the Universal Soil Loss Equation (USLE) and the Soil Loss Estimation Model for Southern Africa (SLEMSA), respectively. Results of runs for hypothetical situations of vegetation/land use/management are written to files or listed in tables per SOTER unit component. The files can be manipulated with GIS to generate erosion hazard maps and other thematic maps.
SWEAP has been tested with the data sets from the North American (64) and Latin American (21) pilot areas. In a separate activity, algorithms developed by Shields and Coote (54) were used to generate maps of the rate and risk of soil degradation due to wind erosion, water erosion and salinization (53). Results obtained for the North American area with the algorithm for water erosion risk (53) and those obtained with SWEAP (64) were found to be generally consistent. Once converted to a standard digital format and loaded to a credible commercial GIS, numerous other tabular and map products may be quickly and cost-effectively generated (53).

Figure 2. Schematic representation of a SOTER unit, and structure of the attribute database with its area data and point data (1:M stands for one to many relations, and M:1 for many to one relation; see Annex for listing of SOTER attributes) (63).

Proposals for identifying mapping units on small scale maps and their classification into vulnerability classes for pollutants, using a SOTER-based GIS-approach, have been elaborated during an international workshop (8). In this project, a "soil pollution application" oriented SOTER database for Europe is proposed (10). The capacity of soils to absorb specified chemical compounds and to release them when triggered by changes in environmental or socio-economic conditions, will be assessed to reveal the most vulnerable soils. Overlaying of the vulnerable areas with a map of loadings with the considered chemicals, will permit identification of areas where "delayed and sudden" effects of pollution - termed Chemical Time Bombs (57) - may occur. These initial activities would serve to
identify areas at risk, and form the basis for implementing regional programmes at a larger scale (10).

**National and Regional databases.** Soil science has long recognised the strong links between soil and terrain. Nonetheless, although used in the compilation of the Soil Map of the World, the physiographic information has not been mapped explicitly (31). A global physiographic map would add much useful terrain information to the map units of an updated Soil Map of the World. Such base maps have been compiled for Central and South America, and Africa using the SOTER methodology for describing landforms (23, 72). Proposals for the compilation of a similar physiographic map for South-east Asia are in an advanced stage.

New priority areas for application of national and regional SOTER databases have been allocated in Africa, Central Europe and Central America. A 1:1 M SOTER database for Kenya is now being developed, and international funding for a similar database for Hungary has been secured. In Latin America, the first pilot area is being extended to cover an additional 46,000 km² in Argentina and Uruguay. At a later date, these national and regional databases can be "merged" into one central SOTER system for the world.

The first phase of an operational approach to a globe-covering SOTER database will be the development of continental SOTER-shells (10, 48), which would include a basic-set of readily available soil and terrain data collected using the standardized and uniform SOTER procedures. As a first step in this direction, a 1:5 M SOTER-shell database for South America is being developed in cooperation with FAO and national organizations.

**WISE, a 1:5 M soil database.**

**Rationale.** As worldwide coverage by SOTER at 1:1 M scale will require from 10 to 20 years to be completed, there remains an immediate need for accurate and reliable information on a multitude of soil-related environmental threats such as an assessment of the status of human-induced soil degradation, and the role of soils in enhancing the "greenhouse effect". This consideration has prompted ISRIC to start with a project called "World Inventory of Soil Emission Potentials" (WISE). Following a survey of the literature and an international workshop, the attributes that would be needed to develop a 1:5 M global soil database were identified (4, 9). WISE uses a grid-cell size of ½ by ½ degrees (4), a commonly used format in global change research. It is to form an improvement on the 1 x 1 degree database which Zobler (74) derived from the original printed Soil Map of the World.

**Methodology.** The geographic data, i.e. extent and type of FAO soil units in the grid-cells, is being derived from the "cleaned" digital version of the 1:5 M Soil Map of the World according to set rules (28). The gridding is being done by the Land and Water Division of FAO (46). The "area" data on the distribution of FAO soil units within each grid cell will be linked to a database of soil profile "attribute" data, using GIS. The ultimate WISE database, as schematically depicted in Figure 3, will comprise:

a) A GIS-file with information on the type and extent of the component FAO soil units of each ½ x ½ degree grid-cell, corresponding with the "area-data";

b) A suite of 'actual' soil profile data for the respective FAO soil units, to which is attached a subfile listing the analytical methods and source of the primary data;
c) A set of files containing derived characteristics for the topsoil and subsoil of the respective FAO soil units. These will provide a uniform basis for production of thematic maps and subsequent modelling activities.

Figure 3. Schematic representation of the WISE database (4).

Guidelines for soil profile selection and a protocol for completing Soil Data Entry Sheets (5) formed the basis for an international data collection programme. The data handling system of WISE uses elements of the ISIS and SOTER methodology, with simplifications necessary to accommodate the 'broader' scope of the WISE database (6). Table 1 gives an overview of the number and type of soil profiles stored in WISE as of November 1993, including the 450 ISIS profiles. The total will continue to increase as new profiles are received from countries world-wide, particularly those of the high-quality digital data set of the Soil Conservation Service (SCS) at Nebraska. Data sets similar to those held by WISE are being used for the compilation of a European profile database linked to the 1:1 M soil map of Europe (42), and requests for a similar database have been expressed by the Digital Information System working group of the International Geosphere-Biosphere Programme (IGBP-DIS; 35).

Applications. Once the WISE database is complete, a range of thematic maps and statistics can be produced, for instance for soil organic-C pools and water holding capacities. A procedure to refine estimates of potential methane production, and possibly emission, in wetland rice soils is being developed in close cooperation with specialist staff from the
International Rice Research Institute (IRRI) in the Philippines and Nagoya University in Japan, within the framework of the current WISE project (9).

Table 1. Overview of soil profiles held in WISE per FAO-Unesco soil unit (Total of 1,502 per November 1993).

<table>
<thead>
<tr>
<th>Soil Unit</th>
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<tr>
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<tr>
<td>C: Chernozems (26)</td>
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<tr>
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<td>Ch = 13</td>
</tr>
<tr>
<td>D: Podzoluvisols (5)</td>
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</tr>
<tr>
<td>Dd = 3</td>
<td>De = 2</td>
</tr>
<tr>
<td>E: Rendzinas (16)</td>
<td></td>
</tr>
<tr>
<td>F: Ferralsols (180)</td>
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<tr>
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<td>Fh = 27</td>
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<tr>
<td>G: Gleysols (96)</td>
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<tr>
<td>Gc = 2</td>
<td>Gd = 27</td>
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<tr>
<td>H: Phaeozems (83)</td>
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<tr>
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<td>Hg = 6</td>
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<tr>
<td>I: Lithosols (5)</td>
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<tr>
<td>J: Fluvisols (82)</td>
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<th>Y: Yermosols (16)</th>
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For abbreviations of FAO-Unesco soil units see (31)

Discussion and Conclusions. Global environmental databases, such as SOTER and WISE, are necessary to study questions arising at the supra-national level, for instance in the context of transport of water, gases and pollutants. National needs for soil information are geared more to resolving well-defined problems. The factors that determine global change integrate political, socio-economic, legal and environmental/ecological considerations which vary with scale. And at each scale, the requirements for data will be very specific (19, 40, 52). As a rule, global databases will require coarser data than are needed for national or local investigations. The SOTER procedures for mapping landforms can be used at different scales of operation from 1:100,000 to 1:5 M, with minor adaptations in the definitions for the spatial attributes (23, 49, 72). Methods and procedures must be developed to ascertain the uncertainty, or error, associated with specific types of data and their derived products. Important considerations in developing the global databases have been: a) the kind of data users need, b) how to obtain this information, and c) how to present it to the user community. The first question remains difficult to answer, because all possible applications of 1:1 M and 1:5 M soil databases for global environmental research are difficult to anticipate. Likely applications of the WISE database include: a) simple extrapolation of process studies for similar soils to estimate regional or zonal fluxes of a trace gas; b) process model studies for regional and global flux estimates; and c) interpretation of inverse-modelling estimates of terrestrial source and sink terms.

Only information on those soil characteristics that are widely available from 'routine' soil surveys can be included in a global soil database, necessitating a pragmatic approach. Research must show which factors, for instance climate, geology, hydrology, soils or land use, control processes significant with respect to a particular 'problem' at a particular scale. To understand the response to change we must acquire a quantitative understanding of: a) the heterogeneity of the system under observation (frequencies of natural variation), and b) the linkage between spatial and temporal patterns and their driving processes (73).

In the process of collecting soil data from a multitude of sources for a global soil database, the quality and validity of the original data must be evaluated carefully. Neither SOTER nor WISE encompass new soil surveys. However, for some applications, new data collection and measurement techniques are needed (22). In a data compilation activity based on "existing data" we have no choice but to accept the data at face value as it is the only data available.
Therefore it is crucial to present information on the nature and (presumed) accuracy of the data and its sources. In WISE, for instance, this is done through inclusion of the "soil description" status which indicates whether a profile and its attributes have been collected according to uniform and standardized procedures in one laboratory (e.g. ISIS and SCS) or according to a varying set of national procedures. Comparison of different analytical procedures, for instance for CEC assessment and available-P, often remains difficult (70). The question that arises is what "variance" in soil data is acceptable for applications at a particular scale. At the macro-scale, this may well not be the largest source of errors, an aspect that deserves further research.

In ISIS, SOTER and WISE, chemical and physical data from 'actual' profiles are stored as 'measured values', indicating the methods according to which they were determined. Such quantitative data are needed to calculate ranges (e.g. extremes, medians and standard deviations) for selected soil characteristics. Like for ISIS, there is no maximum for the number of profiles per soil unit in the WISE database; with larger numbers the effectiveness of the database will be improved, allowing for a better estimation of medians and confidence intervals for selected (quantified) attributes.

Sets of measured soil data are needed to develop pedo-transfer functions (PTFs) and to provide input for quantitative models. Should the need arise, these measured data can always be recombined into class-values according to the specific needs of the user. This is a useful feature as boundaries for defining classes differ widely between countries (69). These common differences in class definitions and boundaries often make it difficult to 'correlate' classes between different systems, making it difficult to off-load this type of information "directly" from one digital system to another (59). For instance, criteria for defining slope-classes as used in ISIS (68), SDB (29) and the 'Guidelines for Soil Description' (30) are difficult to equate. Similarly, in view of differences in terminology at the international level, it can be difficult to equate different horizon designations in a database (16).

Some physical soil attributes are seldom collected on a routine basis, particularly water retention versus tension relationships, and the unsaturated hydraulic conductivity, because they are cumbersome to measure and expensive. The solution then is to estimate these relationships from available soil data such as particle-size distribution, organic-C content and bulk density through pedo-transfer functions. Accuracy of the prediction of these PTFs, can vary strongly with the functions used (60).

Extensive screening of survey monographs from all the regions of the world by the WISE project has shown that soil data are often poorly presented. It is imperative that soil profiles be described according to uniform and internationally accepted standards, such as the 'Guidelines for Soil Description' (30), and classified also according to an internationally recognized system, such as the FAO Legend or Soil Taxonomy, to provide a sound basis for international correlation. It is deplorable that even apparently simple data, such as the geographic location of a profile pit as geographic coordinates (state-grid reference or degrees-minutes-seconds), is seldom provided. What are we to do in a GIS, if we only know that a profile is located at e.g. 20 km from the road leading from alpha to beta in country theta?
Another aspect of importance is the regional accuracy and reliability of the geographic base map from which the spatial data are derived. Spatial data for global maps typically are collected from a variety of sources, creating a source of heterogeneity. Because of cartographic generalization, a map only reflects a representation of reality at the considered scale. Assessing map accuracy and the accuracy of results, derived from the overlay of various maps and other spatial data types of either known or unknown accuracy, remains an important topic of research (25, 55). In the WISE project it is recognized that parts of the Soil Map of the World are out of date (28). Had global coverage by a 1:1 M SOTER database been available, the WISE database development activities would have benefitted from it greatly!

Many current 1:1 M soil databases essentially specify the FAO mapping units and their composition/extent, information on topsoil texture and phases (35, 58). Soil science, however, has long recognised the strong links between soil and terrain; this aspect is being considered in the first step for the upgrading of the 1:5 M Soil Map of the World for which physiographic maps of Central and South America and Africa have been compiled (23, 72). In using physiographically defined terrain and soil components, as opposed to essentially taxonomically defined soil mapping units, the SOTER approach provides a better geographical basis for studies of environmental degradation than has been possible so far.

The development of WISE precedes, and complements, the activities of IGBP-DIS in developing a world soil database along similar principles (35), in which ISRIC is cooperating. Upon the scheduled publication of the first release of WISE, towards the end of 1994, the database will be made available to interested scientists.

Information collection and dissemination at ISRIC does not only concern soil and terrain attribute data. Also needed is information in cartographic form and in bibliographic sources available for a geo-referenced area for which a computerized system has been developed (STRING; 45). Through the development of ISIS, SOTER, WISE and STRING, the International Soil Reference and Information Centre is strengthening its user-servicing capability as ICSU World Data Centre in the field of soil geography and classification. The various database development activities provide the "building stones" for developing a comprehensive system on world soil resources, linked to GIS.

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References.


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Wen Ting-tiang, 1993. A draft physiographic map for Central and South America (at a scale of 1:5 million) based on the SOTER physiographic mapping system for application at global level. Food and Agriculture Organization, Rome.


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<td>58 classification FAO</td>
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</tr>
<tr>
<td>59 classification version</td>
<td>44 degree of erosion</td>
</tr>
<tr>
<td>60 national classification</td>
<td>45 sensitivity to capping</td>
</tr>
<tr>
<td>61 Soil Taxonomy</td>
<td>46 rootable depth</td>
</tr>
<tr>
<td>62 phase</td>
<td>47 relation with other soil components</td>
</tr>
</tbody>
</table>
Soil Data for Models and Resource Management on Different Scales

R. Schmidt*, W. Schröder, and M. Tapkenhinrichs. College of Forest Science and Land Use Planning Eberswalde; Department of Geography, Univ. of Kiel; Center of Agric. Landscape and Land Use Research, Eberswalde; Germany

Introduction. Soil data are necessary, for several scientific and practical purposes, both in land use and environmental protection. In form of uniform basic data, however, they are hardly available. Hence, there is a need to develop generalization methods that offer a possibility to make reliable statements about soils and soil associations (mapping units) from limited basic data. The retrieval of data by using available information is very important because:
(a) gaining basic data of the soil cover is very labor consuming and requires a high level of analysis,
(b) soil process modelling has significantly improved but is depending on the data base,
(c) the meaning of evaluation of soils for preservation and use of recourses has increased compared to years or centuries ago.

Today, the use of soil maps is to a high extent depending on the possibility to extract data or ranges of data for quantification. Numerous research was done in this area (1)(2)(5). More detailed methods are needed to close these gaps and to make reliable, regionalized, and reproducible statements about soil processes, soil conditions, and soil changes. There are presently two approved approaches,
(a) the detection of process relevant data that were not measured, by description of the correlation of the relevant process parameters. This results in parameter models or pedotransfer functions, that contribute expected values for soil properties, areas, and regions.
(b) the detection of the area structure of value distribution by geostatistics. This regionalization gives assumptions for the spatial generalization of specific statements for an area.

Both approaches offer a new theoretical and methodical base for regional soil science or soil geography. This base includes an important assumption to structure and built soil information systems or to implement the factor "soil" in GIS. Statements about soil properties and soil processes are scale dependent. Hence, problems of gaining, generalization, and use of soil data on different scales are discussed in this study. The objective is to give appropriate principles and methods to make soil data available depending on different scales (1 : 2,000 to 1 : 1,000,000).

Material and Methods. The investigation area is the North German lowlands, marked by deposits of the late Pleistocene glaciation (Weichsel). This region is characterized by a narrow change of glacial till, end moraine, sandy outwash, and alluvial sediments (Figure 1). Hence, the soil cover is very heterogeneous. Figure 2 shows a soil catena of the glacial landscape with a complete sequence of 3-5 soil types covering a distance of 100 m. The following soil types (FAO-UNESCO) are typical for the catena of the glacial till landscape: Calcaric Regosol (eroded soils) on top and upper slope, Calcic - Gleyic Luvisol on middle slope, Haplic Luvisol and Gleyic Luvisol on lower slope, Cumulic Anthrosol on footslopes, Terric Histosol in depressions.
The variability of the soil parameters is high. The investigation was done on three different scales (Figure 1):

(a) Test site, 1 : 2,000 - 1 : 10,000
(b) State of Brandenburg, 1 : 100,000 - 1 : 200,000
(c) Germany - New States, 1 : 750,000 - 1 : 1,000,000

Different parameters on different scales were derived or taken from soil maps and corresponding documentation (Table 1).
Table 1. Investigation levels and soil parameters.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Grid size; number of samples</th>
<th>Data bank</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test site Eberswalde - Groß Ziethen (2 ha)</td>
<td>12.5 x 12.5 m, n = 170</td>
<td>Basic data</td>
<td>Soil: texture; organic matter content; pH; P, K</td>
</tr>
<tr>
<td>State of Brandenburg (agricultural used land)</td>
<td>500 x 500 m, n = 60,196</td>
<td>Agricultural soil map (MMK) (7)</td>
<td>Soil form associations: substrate, hydromorphic features, slope by heterogeneity classes</td>
</tr>
<tr>
<td>Germany - New States</td>
<td>7 x 7 km, n = 12,310</td>
<td>Soil map; Atlas DDR 1 : 750,000 (12)</td>
<td>Soil associations (dominating and second dominating soil form); relief by heterogeneity classes</td>
</tr>
</tbody>
</table>

**Figure 2. The soil cover of the till plain in North-Eastern Germany**

The test site was monitored over several years to describe the temporal and spatial variability of selected soil parameters by geostatistics. Data sets of mapping units (soil form [substrate type and soil type] associations, 1: 100,000, or soil associations, 1 : 750,000) were completed by related soil physical and soil chemical data. The latter were taken from the profile and laboratory data base PRODAT (7).
Results

1. Test site

The means of the analysed soil parameters of the test site correspond with the expected conditions (surface condition of a Gleyic Luvisol under cultivation). However, they show a high variability which is expressed by the high standard deviation (Table 2).

Table 2. Maximum, minimum, mean, and standard deviation for selected soil parameter (test site "Eberswalde - Groß Ziethen").

<table>
<thead>
<tr>
<th>Soil parameter</th>
<th>Statistical values (n=176)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Clay and fine silt (%)</td>
<td>9.0</td>
</tr>
<tr>
<td>C_t (mg/100g)</td>
<td>0.6</td>
</tr>
<tr>
<td>pH (KCl)</td>
<td>4.4</td>
</tr>
<tr>
<td>N_t (mg/100g)</td>
<td>20.0</td>
</tr>
<tr>
<td>P^* (mg/100g)</td>
<td>2.2</td>
</tr>
<tr>
<td>K^* (mg/100g)</td>
<td>3.3</td>
</tr>
<tr>
<td>* plant available</td>
<td></td>
</tr>
</tbody>
</table>

The plant available nutrients P and K show the highest variability. C_t and pH which are harder to control show a lower variability. The parameter soil texture, clay plus fine silt content show medium variability. Altogether, the soil parameters indicate an increasing variability as follows:

pH < C_t, N_t < clay and fine silt < K, P

This ranking was confirmed by repeated testing. Other research has also confirmed these results (4). Spatial heterogeneity and neighborhood relations of the associated soils on the test site were quantifiable. The results of the autocorrelation analysis (2) on the base of a 12.5 x 12.5 m grid give different sampling distances resulting in an independent sample (Table 3). Over this distance an interpolation would give trustful results, without taking additional samples. This distance is often modified by the plow direction in cultivated fields.

Table 3. Distances between spatial independent sampling points for selected soil parameter (test site "Eberswalde - Groß Ziethen").

<table>
<thead>
<tr>
<th>Soil parameter</th>
<th>E-W direction</th>
<th>N-S direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay and fine silt (%)</td>
<td>84</td>
<td>24</td>
</tr>
<tr>
<td>C_t (mg/100g)</td>
<td>36</td>
<td>48</td>
</tr>
<tr>
<td>pH (KCl)</td>
<td>36</td>
<td>84</td>
</tr>
<tr>
<td>N_t (mg/100g)</td>
<td>24</td>
<td>36</td>
</tr>
<tr>
<td>P^* (mg/100g)</td>
<td>108</td>
<td>48</td>
</tr>
<tr>
<td>K^* (mg/100g)</td>
<td>12</td>
<td>60</td>
</tr>
<tr>
<td>* plant available</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is possible to quantify the periodical spatial distribution of the soils (Figure 2) by a neighborhood analysis of the associated soils. The basis for this is the analysis of the frequency of the contact of specific soil types or soil forms (6). The result can be expressed as a matrix of the spatial order (8). The typical neighborhood relation for the soils of the glacial till landscape of
Northern Germany shows Luvisols of different properties. A close relation of different soils to anthropogeneous soils and the bogs of the interior depressions also exists in this landscape. Based on the investigation of the spatial distribution of the soil parameters and soils at a test site, the following statements can be supported:

(a) The variability of the measured values and their spatial deviation is very high. Consequently, a transformation of soil data from point measurements to non-investigated points is problematical.

(b) The variability can only partly be explained by correlation and analysis of the neighborhood relations.

(c) Mean values and the typical location and neighborhood properties match the typical values for specific soils and soil associations. This implies that the data of the test site cannot be used as single values but as the sum of reference data for further integration and evaluation.

2. State of Brandenburg

The state of Brandenburg occupies an area of 29,052 km² with a high percentage of agricultural land. The second scale level (1 : 100,000 - 1 : 200,000) is already relevant for practical application in land use planning and for environmental protection. The heterogeneous data base for the state of Brandenburg requires methods for data adaptation and data homogenisation for validation purposes on this level. These methods need to produce soil data that can be controlled and used in a GIS. Two levels are developed:

(a) an extraction of representative soils for the state of Brandenburg and

(b) the relation of typical soil data.

The extraction of representative soils is done by evaluation of soil maps (digitized and hard copy 1:100,000). The area size and the neighborhood relationships are analysed and classified on the base of typical soil associations (9). Typical soil type combination were used for the state of Brandenburg, such as Podsol-Braunerde (Dystric Cambisol) in combination with Fahlerde (Eutric Podzoluvisol) or Podzol-Braunderde (Dystric Cambisol) in combination with Gley (Dystric or Eutric Gleysol) instead of using the soil type Podsol-Braunerde (Dystric Cambisol).

Based on the soil association soil parameters like organic matter content and pH vary. It is possible to determine data sets that are valid for soil associations. Examples for some representative soils are shown in table 4. These samples were extracted among 100 representative soils from the 60,196 data sets of the digitized soil map for the state of Brandenburg.

Typical soil data were related to the 100 representative soils by valuation of the profile and analysis data of 3,000 soil profiles (2 - 5 horizons) from Brandenburg (7). This profile data can offer data disposition in the following ways:

(a) Soil data for representative soils by statistical interpretation on base of soil types or soil forms (combination of soil type and substrate type)

(b) Soil data for typical soil horizons by statistical interpretation on the base of soil horizons, differentiated by soil texture.

The determination of soil data for representative soils is based on all available profile and analysis data of one representative class (Table 4). However, the investigation grounded on different total numbers of typical soil types and soil associations for the state of Brandenburg, which did not guarantee a uniform population.
Table 4. Examples of representative soil classes of the state of Brandenburg

<table>
<thead>
<tr>
<th>Soil classes (by frequency and neighborhood)</th>
<th>Number of data sets</th>
<th>Typical soil profiles with analytical data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Absolute (n = 60,196)</td>
<td>Percent</td>
</tr>
<tr>
<td>1. Eutric Cambisols</td>
<td>3,496</td>
<td>5.8</td>
</tr>
<tr>
<td>2. Eutric/Dystric Cambisols with Eutric Podzoluvisols</td>
<td>10,397</td>
<td>17.3</td>
</tr>
<tr>
<td>3. Eutric Podzoluvisols with Eutric Podzoluvisols</td>
<td>2,376</td>
<td>4.0</td>
</tr>
<tr>
<td>4. Eutric/Dystric Podzoluvisols with other soils</td>
<td>6,927</td>
<td>11.5</td>
</tr>
<tr>
<td>5. Dystric Cambisols with Gleysols</td>
<td>2,848</td>
<td>4.7</td>
</tr>
<tr>
<td>6. Gleysols</td>
<td>6,142</td>
<td>10.2</td>
</tr>
<tr>
<td>7. Histosols with Gleysols</td>
<td>4,648</td>
<td>7.7</td>
</tr>
<tr>
<td>8. Histosols</td>
<td>2,145</td>
<td>3.6</td>
</tr>
</tbody>
</table>

The aggregation of soil data for typical soil horizons is based on data from soil horizons, differentiated by soil texture (substrate-horizon groups by Vetterlein (11)). The substrate-horizon-groups were developed for the following soil physical parameters: Bulk density (g cm\(^{-3}\)), pore volume (Vol.-%), porosity (Vol.-%), field capacity (Vol.%), permanent wilting point (Vol.%), clay content (%), organic matter content (%) and others (11).

This aggregation represents a new data base that can be used for the regionalization of soil hydrological parameters. The substrate-horizon groups represent aggregated, but regional different parameters, for water transport models. They can also be used for the derivation of pedotransfer functions (10) to make a more detailed evaluation of the landscape water budget.

Another simplified use of the substrate-horizon-groups is to aggregate them for horizon sequences or soil types as well as for soil sequences in landscapes (Figure 3). With this "building block" principle it is possible to get a first approximation of the heterogeneity of the soil cover.

The use of soil data of the middle scale level can be summarized as follows:

(a) Soil data of the middle scale level have to be gained by selection, statistics, and aggregation methods. If the data base is large enough it is possible to make data for modelling of soil processes and for the evaluation of available soil recourses.

(b) Aspects of area structure, like the association of soils, have to account for data use. The selection of "representative soils" is a simplified method to quantify typical soil differences by regarding the soil association.

(c) The data disposition on the middle scale level is highly important since there is a need for reliable data for practical applications in landscape, regional, and administrative planning. Data availability can be increased by a soil information system. A soil information system was installed for the state of Brandenburg (7), with the following data and interpretation levels:

- area data bank from soil mapping
- point data bank of soil profiles and - analysis
- method bank for models and interpretation

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3. Germany/New States

There is no relation to concrete data any more in this third scale level (1 : 750,000 - 1 : 1,000,000). A strong generalization is necessary for the description of soils and soil associations on this level. This results in a delineation of typical soils or soil association of larger regions. Statistical methods are reduced since the data base, in general, is too small to characterize all soils in their spatial relation. This requires specific regionalization methods on this specific scale. This was performed with grid maps for Germany as a whole and for the new states in Eastern Germany (12). Modelling of large spatial correlation and processes, such as the recharge, distribution, and pollution risk of ground water requires data sets with uniform area resolution. The grid format is suitable for data management, even though there are often specific data missing for single grid elements. The data have to be related by data transformation in different steps:

(a) Determination of certain soil parameters (texture, root depth, field capacity etc.) for dominating soil types of the soil maps (12) (Table 5).

(b) Classification of the soil parameter and relation of mapping units (soil type and soil associations) to soil classes.

(c) Transfer of parameter to grid format 3 x 3 km.

Different levels of data transformation show that the data disposal must have expert character. To insure the transfer the generalization must be based on data that already include reference data for dominating soils. Reference data were taken from the described data bank (paragraph 2.) and information from the literature were added.
Table 5. Mapping units of the soil map of Germany-New States with characteristic soil parameters (examples).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Associated soils</th>
<th>Parent materials</th>
<th>Texture class</th>
<th>Org. matter content</th>
<th>Field capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>%</td>
<td>mm/dm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Soil associations of the mountain regions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B 11</td>
<td>Eutric Cambisols</td>
<td>Basalt</td>
<td>L</td>
<td>3.0</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Eutric Leptisols</td>
<td>SL</td>
<td>3.0</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>B 9</td>
<td>Dystric Cambisols</td>
<td>Metamorphic rocks,</td>
<td>SL</td>
<td>2.8</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Cambic Podzols</td>
<td>granites</td>
<td>2.8</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>B 13</td>
<td>Eutric Cambisols</td>
<td>Basalts</td>
<td>L</td>
<td>3.5</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Soil associations of the loess regions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G 8</td>
<td>Haplic Chernozems</td>
<td>Loess</td>
<td>SiL</td>
<td>4.0</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Eutric Cambisols</td>
<td>Rocks</td>
<td>SL</td>
<td>3.0</td>
<td>37</td>
</tr>
<tr>
<td>G 9</td>
<td>Haplic Chernozems</td>
<td>Loess</td>
<td>SiL</td>
<td>4.0</td>
<td>37</td>
</tr>
<tr>
<td>H 13</td>
<td>Haplic Luvisols</td>
<td>Loess</td>
<td>SiL</td>
<td>3.0</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Gleyic Luvisols</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Soil associations of the Pleistocene lowland</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M 1</td>
<td>Cambic Arenosols</td>
<td>Sandy outwash</td>
<td>S</td>
<td>1.0</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Dystric Cambisols</td>
<td>LS</td>
<td>1.5</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>P 6</td>
<td>Calcic Luvisols</td>
<td>Glacial till</td>
<td>L</td>
<td>2.0</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Eutric Podzoluvisols</td>
<td>LS</td>
<td>1.7</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>U 2</td>
<td>Gleysols</td>
<td>Sandy outwash</td>
<td>S</td>
<td>2.5</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Gleyic Arenosols</td>
<td>S</td>
<td>1.2</td>
<td>21</td>
<td></td>
</tr>
</tbody>
</table>

The data disposition on the third scale level is problematical. For overviews on a European scale, data of representative soils are used and defined for bigger soil areas (9). This is summarized as follows:

(a) Disposal of data on a large scale has to be done by estimation methods that have to include reference data from typical soils to insure the transfer for larger areas.

(b) Generally, it is not possible to give single values or means. The characterization is done by classification based on the data base and the model requests.

(c) Soil heterogeneity and soil association can only be characterized in a primitive way. In general, it is possible to derive greater interrelations and neighborhoods.

**Conclusions.** This research shows that soil data have to be gained and aggregated for models and resource management on different scales by appropriate methods:

(a) On the test site scale (1 : 2,000 - 10,000) level (topological dimension) (8) data have to be gained by measurements at defined points. The spatial variability of the parameter is high due to soil genesis and anthropogenic impact. Consequently statistical values, such as the mean, do not represent the true conditions. However, the measurement at a grid point or from a typical position has to demonstrate patterns in the spatial variability. It is only possible to characterize this heterogeneity by investigations in the topological dimension.
The latter is the basis for the transformation of measuring results to the medium scale level.

(b) On the medium scale level (chorological dimension) (8), soil data are disposed first by statistical values (mean, standard deviation), and second by characteristic features which show the spatial pattern of the soils. One assumption is that data are gained by investigations on a large scale from transects (representing test sites) or sections of the soil cover. Interpretation for the state of Brandenburg show acceptable results for this scale level by using these methods. These rational methods are highly important for planning, land use, and environmental protection.

(c) The transformation from point data to spatial data is problematical on the third scale level. The heterogeneity of the soil units can not be considered because the units are large. Characteristic or representative soil types or soil parameter are given for larger areas. Statistical methods are of limited use for this selection. Important is the knowledge of the pedologist, who selects the characteristic soils from numerous single data and profiles.

Literature Cited.


Amount of Organic Carbon in Canadian Soils

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Abstract. A soil carbon database was set up using twenty-eight 1:1 million scale soil landscape maps covering the entire area of Canada. These soil landscape maps and the associated databases (containing the major land and soil components for 14,000 polygons) are in the ARC/Info GIS system. The soil carbon database includes those soil attributes (horizon designation, thickness, texture, bulk density and percent organic carbon) used to determine the amount of carbon in the soils occurring within a polygon. This information is entered for up to three layers of each soil occurring in a polygon, with the specific soil horizons assigned to each layer depending on whether the soil is mineral or organic. Polygon information from the soil landscape databases and soil carbon information from the soil carbon database (approximately 105,000 soil carbon data sets) were used to calculate the amount of organic carbon in each soil layer of each polygon. Various soil carbon values were calculated for a 1482 x 10^3 km^2 study area, representing approximately 20% of the soil area of Canada. The average organic carbon content for the various soil orders ranged from 3.3 to 17.3 kg m^-2 (surface) and from 5.1 to 60.6 kg m^-2 (total). The highest total soil carbon contents were associated with soils of the Organic and Cryosolic orders. The mass of organic carbon in all soils in the study area was 12.5 Gt (surface) and 36.4 Gt (total). Based on these figures, the preliminary estimate of the soil organic carbon mass for the entire soil area of Canada is approximately 63 Gt (surface) and 183 Gt (total).

Introduction. Approximately three times more carbon occurs in soils than in terrestrial vegetation (11). It is estimated (10) that 27% of this soil carbon occurs in tundra and boreal forest ecosystems. Since a large part of Canada lies within these regions, a significant portion of the world's soil carbon occurs in Canadian territory. Therefore, the Canadian Soil Carbon Project (13), which used a geographical information system (GIS) environment, was initiated in late 1991 to determine the amount of organic carbon in all Canadian soils, as well as the quantities in different soil orders (1) (for approximate conversion to U.S. taxonomy, see Tables 3 and 4) and different soil layers. The database was designed so that carbon values for the upper 30 cm of both mineral and organic soils could be determined separately. This soil layer (surface layer), which is the one most likely to interact with the atmosphere, is the layer that is most sensitive to environmental change. The Canadian soil carbon database also provides a means of determining the relationships between amounts of soil carbon and the attributes included in the database, including soil drainage, mode of deposition of the soil parent material, broad vegetation cover and land use.

There is little published data concerning the amounts of organic carbon in various Canadian soils, but some values are provided for cultivated and noncultivated pedons of Chernozemic and Luvisolic soils (2, 7), for highly cryoturbated pedons (Turbic Cryosols) (8), and for Cryosols (14). Some information concerning amounts of soil carbon in the various ecoclimatic provinces is available from other researchers, including values for various global life zones (10), and for the ecological provinces in Canada (9), which also includes an estimate of 76.4 Gt (gigatonne; 1 Gt=10^9 tonnes=10^{12} kilograms =10^{15} grams) for the mass of organic carbon in Canadian forest...
soils. Most of these estimates use a relatively small number of pedons to represent large areas. For example, estimates for the Arctic and Boreal areas of the entire world (10) use a total of 308 pedons, with only 48 pedons being from Arctic areas and 260 from Boreal areas.

In this paper, a series of five maps running from the U.S.-Canada border to the High Arctic islands is used to demonstrate the Canadian Soil Carbon Project (13) and to provide preliminary information about the total and surface amounts of organic soil carbon in Canadian soils, aggregated by various major soil types and ecoclimatic provinces.

**Description of Study Area.** To provide a preliminary determination of the amount of organic carbon in various Canadian soils and ecoclimatic provinces, a series of five maps running from the Alberta-Montana border to the High Arctic islands (Figure 1) was selected for this study. This study area includes most of the major soil orders and ecoclimatic provinces occurring in Canada. The soils in the study area comprise 1,482,277 km², which is 19.9% of the soil area of Canada.

**Materials and Methods.**

**Soil Landscapes of Canada Database.** The Soil Landscapes of Canada (SLC) database is part of Agriculture Canada's National Soil Database (NSDB). The NSDB, which is in the ARC/Info GIS format, is maintained by the Centre for Land and Biological Resources Research in Ottawa, Canada and forms the basis for digital soil mapping for the country. The SLC database is only one of numerous soil databases contained in the NSDB. The SLC database contains spatial data in the form of generalized soil landscape polygons at 1:1 million scale. It provides the core database and spatial framework to which additional land- and soil-related information is appended (3).

The primary component of the SLC set is data relating to the unique soil landscape polygons, the smallest spatial elements that can be identified using this GIS system. These elements can be simple soil landscape polygons, containing one soil or nonsoil landscape component, or complex soil landscape polygons containing a number of soil and/or nonsoil landscape components (3).

The SLC data is found in two related data tables, the Polygon Attribute Table (PAT) and the Soil Landscape Component Attribute Table (SLAT) (Figure 2). The PAT (Table 1) provides information defining the spatial elements of the polygon; the SLAT (Table 1) provides information concerning the soil landscape of the polygon. These tables and other associated tables are linked by three attributes: the province code, the map sheet number and the unique polygon number (Tables 1 and 2). For each polygon in a soil landscape map there may be one or more components with associated SLAT records that are linked to the PAT through the unique soil polygon number (3). Within each component record, the percent of the polygon area occupied by the component is recorded.

These two tables, the PAT and the SLAT, form the basis of the Soil Landscapes of Canada database. This database contains soil landscape data for the entire Canadian land mass and is composed of 28, 1:1 million scale, map sheets (Figure 1) consisting of approximately 14,000 polygons.

**Soil Carbon Layer Attribute Table.** The Soil Carbon Layer Attribute Table (SCAT) contains information necessary for calculating amounts of soil carbon (3). The organic carbon (%) attributes in this table (Table 2) were obtained using the induction furnace laboratory method (12). The SCAT is linked to the PAT and SLAT tables (Figure 2) by the province code, map sheet number...
and unique polygon number. The SCAT includes those soil attributes (layer designation, thickness, texture, bulk density and percent organic carbon) needed to determine the amount of carbon in soils occurring within a polygon. This information is recorded for up to three distinct soil layers within each soil component, with the specific soil horizon groups assigned to each layer depending on whether the soil is mineral or organic. For mineral soils, the surface organic layer (L, F, H horizons) is included, except for cultivated soils. The attributes in the carbon layer records have also been flagged to indicate if the attribute values were measured or estimated. Approximately 105,000 soil carbon layer records are included in the SCAT.

The PAT and SLAT information from the SLC database and the SCAT information were used to calculate both the amount of soil carbon in each layer of each soil component within a polygon and the average soil carbon content for each polygon.

**Analysis of Soil Carbon Data.**

**TOTAL CARBON MASS,** expressed as kilograms or gigatonnes of carbon (kg or Gt), refers to the total mass of organic carbon for the entire area of each soil component. This mass is calculated by combining the attributes (percent organic carbon, bulk density and layer thickness) stored in soil carbon layer records in the SCAT with the area covered by the soil component. The carbon values thus calculated for each of these soil layers are then combined and adjusted by the amounts of coarse fragments to obtain the total carbon mass of each soil component.

For mineral soils, in most cases, carbon mass is calculated for a depth of one metre, but for mineral soils with lithic contact (shallow soils over bedrock) it is calculated for the depth to the contact (if less than one metre). For organic soils the carbon mass is calculated for the total depth of the peat deposit.

**TOTAL CARBON CONTENT,** expressed as kilograms per square metre (kg m$^{-2}$), is a measure of the average amount of organic carbon in each soil within a soil landscape. To obtain this value, the total carbon mass in each soil component, measured in kilograms, is divided by the area covered by this component, measured in square metres (m$^2$). The total carbon content is thus an expression of the soil carbon mass in a one metre square column of soil. If the soil column is one metre deep, the total carbon content is analogous with carbon density.

**SURFACE CARBON MASS,** expressed as kilograms or gigatonnes of carbon (kg or Gt), refers to the mass of organic carbon within the top 30 cm (0 to 30 cm depth) of a soil component. It is calculated in a manner similar to that used to determine the total carbon mass, except that this value refers only to the 0 to 30 cm depth of the soil.

**SURFACE CARBON CONTENT,** expressed as kilograms per square metre (kg m$^{-2}$), is a measure of the average amount of organic carbon within the top 30 cm layer of soil. It is calculated in a manner similar to that used to determine the total carbon content, except that this value refers only to the 0 to 30 cm depth of the soil.

Even though the soil carbon masses and contents are initially determined on the basis of the individual soil components, it is possible to combine these values in various ways in order to obtain soil carbon values for many different purposes, limited only by the information contained in the database. Examples of such database products are soil carbon maps or tables in which the amount of organic carbon is expressed on the basis of map polygons, soil orders or great groups, parent materials, ecological divisions, etc. In this paper, the total and surface carbon contents and masses are given for each soil order and ecoclimatic province in the study area.
Results.
Although soil carbon data is available for all 28 map areas, covering the entire area of Canada, soil carbon values have been calculated for only the five map areas comprising the study area of this paper. Soil carbon values are now being calculated for all 28 map areas, but these values are not yet available. As a result, all values presented in this paper are preliminary and subject to refinement when analysis of all the map areas is completed.

*Soil Carbon in Major Soils.* Nine soil orders occur in the study area. For each of these soil orders, the average carbon content and the carbon mass were calculated for both the surface layer and the total soil (Table 3 and Figure 3). Similar data were calculated in more detail for the Cryosolic and Organic orders (Table 4).

The greatest average surface carbon content occurs in soils of the Organic Order (17.3 kg m$^{-2}$), followed by Gleysols and Cryosols (10.1 and 10.0 kg m$^{-2}$, respectively) (Figure 3A and Table 3). Within the Cryosols, Organic Cryosols have the greatest average surface soil carbon content (21.2 kg m$^{-2}$). In the Organic Order, both Fibrosols and Mesisols have relatively high surface carbon contents (14.2 and 26.0 kg m$^{-2}$, respectively) (Table 4). The greatest average total carbon content is found in soils of the Organic Order (60.6 kg m$^{-2}$), followed by Cryosols (34.0 kg m$^{-2}$). The average total carbon content of the remaining soils are much lower. Within the Cryosols, Organic Cryosols have the greatest average total carbon content (85.7 kg m$^{-2}$) (Table 4).

Cryosols contribute by far the largest surface soil carbon mass (6.9 Gt), approximately 55% of the surface carbon mass of the study area (Figure 3B and Table 3). Within the Cryosols, Turbic Cryosols have the largest surface mass (3.9 Gt), approximately 31% of the total surface carbon mass found in the study area. Soils of the Organic Order contain the second largest amount of total surface carbon (1.8 Gt) (Figure 3B and Table 3). Cryosols also contain the largest total carbon mass (23.5 Gt), approximately 65% of the total carbon mass of the study area. Within the Cryosols, Turbic Cryosols contain about 34% of the total carbon mass of the study area.

*Soil Carbon in Major Ecoclimatic Provinces.* The study area includes portions of twelve ecoclimatic subprovinces in five major ecoclimatic provinces (Table 5) (5). The surface and total carbon contents and masses found in the soils of these ecoclimatic provinces are presented in Figure 3, C and D, and Table 5. The greatest surface and total carbon contents (10.5 kg m$^{-2}$ and 30.8 kg m$^{-2}$, respectively) are found in the Boreal Ecoclimatic Province, with the highest values occurring in the Mid Boreal Ecoclimatic Subprovince. For this subprovince, the surface carbon content is 12.6 kg m$^{-2}$ and the total carbon content is 38.0 kg m$^{-2}$. The second highest total carbon content, 33.6 kg m$^{-2}$, occurs in the Mid Arctic Ecoclimatic Subprovince.

The largest surface carbon masses occur in the Arctic and Boreal ecoclimatic provinces (4.7 Gt), with approximately 38% of the surface carbon mass of the study area being found in each of these ecoclimatic provinces. They are followed by the Grassland and Subarctic ecoclimatic provinces (1.3 Gt and 1.2 Gt, respectively), with approximately 10% of the surface carbon mass in each. Soils in the Arctic and Boreal ecoclimatic provinces also contain the highest amounts of total soil carbon, with 15.0 Gt in the Arctic and 13.8 Gt in the Boreal. Together, these two ecoclimatic provinces contain 28.8 Gt of organic carbon, approximately 79% of the total carbon mass of the study area, with 41% in the Arctic Ecoclimatic Province and 38% in the Boreal Ecoclimatic Province.

*Estimated Total Carbon Mass in Canadian Soils.* Surface and total carbon masses found in the study area (Table 3), which represents about 20% of the soil area of Canada, were also used to
estimate the amount of organic carbon in soils of the entire country. This approach, which assumes that the study area is uniformly representative of the remainder of the country and then extrapolates the values obtained for 20% of the area to yield values for 100% of the area, gives an estimate of 62.6 Gt surface carbon mass and 182.8 Gt total carbon mass for Canadian soils.

Using information concerning the distribution of soils in Canada (4) and carbon content values obtained during this current study, however, it is possible to calculate the total amount of carbon in all Canadian soils (Table 6). Using this approach, the surface carbon mass of all Canadian soils is estimated to be 77.1 Gt and the total carbon mass, 184.9 Gt.

Both of these estimates have weaknesses, however, and accurate values may not be obtained until carbon data have been calculated for all 28 map areas and the total carbon content of Canadian soils is determined.

Discussion. A large portion of the organic carbon found in Canadian soils occurs in mid and high latitudes (northward from the southern limit of the Boreal forest). Two soil orders, Cryosols and Organic soils, contain high amounts of total carbon and are also the dominant soils in these regions, covering large areas. If these two soil orders the surface carbon contents are also high, suggesting that large amounts of carbon could be directly affected if environmental change occurs. The low pH and nutrient status and the anaerobic conditions in soils of the Organic Order contribute to carbon fixing. For Cryosolic soils, Organic and Turbic Cryosols are the major contributors of soil carbon because of both their properties and the large areas they cover. In addition to low pH, low nutrient status and anaerobic conditions, cold soil temperatures make Organic Cryosols an even more effective carbon sink (per unit area) than other Cryosols (Table 4). The mechanism responsible for the large amount of carbon in Turbic Cryosols (mineral soils) is cryoturbation, which continuously translocates organic material from the surface to the lower soil horizons. Since the depth of the active layer in Turbic Cryosols fluctuates with changes in the permafrost conditions, the near-surface permafrost can contain significant amounts of carbon.

Gleysolic and Chernozemic soils also have relatively high carbon contents. Gleysols (wet soils) usually have a peaty or high-organic-content surface horizon. Because of their wetness, the rate of decomposition of organic matter is slow and these soils also act as a carbon sink, although not as effectively as soils of the Organic and Cryosolic orders. The deep, organic-rich, Ah horizon in Chernozemic soils contributes most of the carbon in these soils. In some cases deeper horizons also contain significant amounts of carbon because of downward movement of organic materials.

Podzolic soils occur in only limited portions of the study area (412 km²). Thus, their carbon contents are suspect and will be updated when the main Podzolic areas of Canada are evaluated.

The carbon layer data in the SCAT were compiled from field samples collected over the last two decades. The information does not represent the carbon content of Canadian soils at any single point in time. As a result, this carbon data cannot be used directly to measure changes in organic carbon content during these two decades. Process-based models can, however, incorporate data from this database to predict changes in carbon content resulting from climate change, management practices, or other factors.

The total soil carbon content for Black Chernozemic pedons has been estimated to be 4.6 to 16.4 kg m⁻² and for Luvisolic pedons, 5.3 to 7.8 kg m⁻² (2, 7). Results obtained during this study, however, indicate that the average total soil carbon content for Chernozemic soils is 13.3 kg m⁻² and for Luvisolic soils, 9.6 kg m⁻². The total soil carbon content of Turbic Cryosols has variously
been found to be 3.2 to 100.9 kg m$^{-2}$ (8) and 17.7 to 82.2 kg m$^{-2}$ (14). Values of 3.9 to 5.4 kg m$^{-2}$ for Static Cryosols and 86.3 to 176.6 kg m$^{-2}$ for Organic Cryosols have also been found (14). Although Cryosol studies report a wide variation in soil carbon content values for these soils, the average soil carbon content values obtained in other studies (8, 14) are within the ranges found in this study, except for the Static Cryosols.

Data about average soil carbon contents in the various ecoclimatic provinces (9, 10) and data calculated during this project are presented in Table 7. The values presented in this paper are higher than those presented in the other two studies, except for the Subarctic Ecoclimatic Province, where one study (9) gives a higher value, and the Grassland Ecoclimatic Province, where the other study (10) has a slightly higher value. It should be noted that the highest Grassland Ecoclimatic Province value of 13.3 kg m$^{-2}$ (10) is very close to the value of 12.2 kg m$^{-2}$ obtained in this study, but the corresponding value of 4.9 kg m$^{-2}$ in the third paper (9) is much lower. The average carbon contents presented in this paper for the Arctic, Subarctic and Boreal ecoclimatic provinces include the soil carbon contributed by organic soils (peatlands), which are very common in all three of these ecoclimatic provinces. One of the other studies (9), however, considered only mineral soils, and it is not clear whether the other (10) incorporated organic soil (peatlands) data.

Little previous data is available for comparing the total amount of carbon of all Canadian soils. Forest soils in Canada have been found to contain approximately 76.4 Gt of carbon (9), but this estimate does not include the carbon contained in peatlands. It has been estimated that Canadian peatlands (including both soils of the Organic Order and Organic Cryosols) contain 135 Gt of carbon (6).

**Summary and Conclusions.**

1. A soil carbon database was established for Canada in association with twenty-eight, 1:1 million scale, soil landscape maps. These soil landscape maps and associated databases (containing major land and soil components for each of the 14,000 polygons) are in the ARC/Info GIS system.

2. The soil carbon database includes those soil attributes (soil horizon designation, thickness, texture, bulk density and percent organic carbon) used to calculate the mass of soil carbon in the soils occurring within a polygon.

3. Soil carbon masses were calculated for three layers for each soil component and then combined and adjusted by the amounts of coarse fragments to obtain the total carbon mass of each soil component.

4. Average soil carbon content for the nine soil orders ranged from 3.3 to 17.3 kg m$^{-2}$ (surface) and from 5.1 to 60.6 kg m$^{-2}$ (total).

5. Soils of the Organic and Cryosolic orders (Histosols and Pergelic subgroups) had the highest total carbon contents.

6. A preliminary estimate of the mass of organic carbon in Canadian soils obtained values of 62.6 Gt (surface) and 182.8 Gt (total).

7. The Boreal, Arctic and Subarctic ecoclimatic provinces had the largest total average soil carbon contents (30.8, 26.2 and 21.7 kg m$^{-2}$, respectively).

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Acknowledgments. Many soil scientists from Canadian Soil Survey Units across Canada participated in compiling the soil landscape and soil carbon databases. Special thanks are due to Barbara Lacelle for designing the quality control algorithms and for the GIS correlation and to Mike Ballard for setting up and running the system used to calculate the carbon values.

Literature Cited.


Figure 1. Map showing the study area and the coverages of the 28 SLC maps.
Figure 2. Structure of the National Soil Database.

NATIONAL SOIL DATABASE (NSDB)

SOIL LANDSCAPES OF CANADA (SLC)

Polygons
Attribute Table (PAT)

Soil Landscape Component
Attribute Table (SLAT)

Soil Carbon
Layer Attribute Table (SCAT)

ASSOCIATED DATABASES
Figure 3. Soil carbon contents and soil carbon masses in various soil orders (A and B) and ecoclimatic provinces (C and D). The codes used for soil orders are: CI - Chernozem, SL - Solonet, PD - Podzol, LV - Lithosol, BR - Brunisol, GL - Gleysol, OR - Organic and CR - Cryosol. The codes used for ecoclimatic provinces are: GA - Arid Grassland, GS - Subhumid Grassland, GT - Transitional Grassland, LB - Low Boreal, MB - Mid Boreal, HB - High Boreal, LS - Low Subarctic, HS - High Subarctic, LA - Low Arctic, MA - Mid Arctic and HA - High Arctic.
Table 1. The Soil Landscapes of Canada Polygon Attributes and Soil Landscape Component Attributes.

<table>
<thead>
<tr>
<th>Polygon Attributes</th>
<th>Soil Landscape Component Attributes</th>
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<td>Province code</td>
<td>Province code</td>
</tr>
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<td>Map sheet number</td>
<td>Map sheet number</td>
</tr>
<tr>
<td>Unique polygon number</td>
<td>Unique polygon number</td>
</tr>
<tr>
<td>Area of the polygon</td>
<td>Component type</td>
</tr>
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<td>Perimeter of the polygon</td>
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<td>Kind of material</td>
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<td></td>
<td>Vegetation cover or land use</td>
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<tr>
<td></td>
<td>Soil parent material mode of deposition</td>
</tr>
<tr>
<td></td>
<td>Coarse fragment content (%)</td>
</tr>
<tr>
<td></td>
<td>Rooting depth (cm)</td>
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<tr>
<td></td>
<td>Drainage class</td>
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<tr>
<td></td>
<td>Soil development</td>
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<tr>
<td></td>
<td>Calcareous class</td>
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<td>Local surface form</td>
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<td></td>
<td>Slope gradient class</td>
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<td>Soil name code and modifier</td>
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Table 2. Soil Landscapes of Canada Soil Carbon Layer Attributes

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<td>Component number</td>
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<td>Layer number</td>
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<tr>
<td>Layer designation</td>
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<td>Layer thickness (cm)</td>
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<tr>
<td>Texture of the mineral layer</td>
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<tr>
<td>Bulk density</td>
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<td>Organic carbon (%)</td>
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Table 3. Amount of organic carbon in various soil orders in the study area and correlation of Canadian and U.S. soil classification terminology.

<table>
<thead>
<tr>
<th>Soil Classification</th>
<th>Soil Carbon Content (kg m⁻²)</th>
<th>Soil Carbon Mass (Gt)</th>
<th>Area (10³ km²)</th>
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</thead>
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<td>Mollisol and Alfisol</td>
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<td>Spodosol</td>
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<td>Luvisol</td>
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<td>Boralf and Udalf</td>
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<td>Inceptisol</td>
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Table 4. Amount of organic carbon in the great groups of the Organic and Cryosolic Orders in the study area.

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<tr>
<th>Soil Classification</th>
<th>Soil Carbon Content (kg m⁻²)</th>
<th>Soil Carbon Mass (Gt)</th>
<th>Area (10³ km²)</th>
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Table 5. Amount of soil organic carbon in the various ecoclimatic provinces and subprovinces in the study area.

<table>
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<tr>
<th>Ecolimatic Provinces and Subprovinces</th>
<th>Soil Carbon Content (kg m(^{-2}))</th>
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Table 6. Amount of organic carbon in all Canadian soils.

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<th>Soil</th>
<th>Soil Carbon Content (kg m(^{-2}))</th>
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<th>Soil Carbon Mass (Gt)</th>
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</tr>
</tbody>
</table>

* Areas given in Bentley (1978).

Table 7. Comparison of total carbon contents for the four ecoclimatic provinces.

<table>
<thead>
<tr>
<th>Ecoclimatic Province</th>
<th>Total Carbon Content (kg m(^{-2}))</th>
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<tbody>
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<tr>
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<tr>
<td>Boreal</td>
<td>30.8</td>
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<tr>
<td>Grassland</td>
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</table>
A Spatially Distributed Soil, Soil Hydrological and Agroclimatic Model for the Prediction of Climate Change in the European Community

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Summary
Most attempts to predict the effects of potential climate change on the agricultural productivity of soils have been made either on small, intensively-managed experimental sites, or at scales and resolutions of several tens or hundreds of km. There are few predictive tools useful to the land use planner, or the policy maker, at the local or regional level, with the implications this has for spatial resolution on the ground. Within the European Community there is a large amount of detailed soil, land use and climatic data, much of it at very high resolution (tens or hundreds of metres). A very large part of these data is in digital form, and can be manipulated readily by computers, often within geographic information systems. The current project has produced a model which uses such detailed information to predict the effects of climate change on land use within the European Community. The model has been designed deliberately to make use of simple (but reliable) soil data from soil surveys, in relation to crop suitability, as well as data from experimental sites. The new model (ACCESS - Agroclimatic Change and European Soil Suitability) thus runs at two levels, which complement each other. The essential difference is one of data availability, because this affects profoundly the time steps at which the model can operate, and the level of detail with which processes can be simulated. ACCESS-I is a general approach to allow extrapolation to large areas of land, and has less intensive data requirements. It uses the results of the site specific, detailed data and modelling within the second part of the model - known as ACCESS-II - for validation and calibration. If sufficient data are available, ACCESS-II can be run for large areas, but this situation is likely to be unusual, and would be more demanding in computing time.

1.1 Introduction
The agricultural area of the European Community is about 1.3 million km², most of which lies between the latitudes 37°N and 58°N, and longitudes 10°W and 27°E. The Community is one of the largest agricultural producers in the world, and its Common Agricultural Policy is an important part of its budget. Thus, any change in food productive capacity, or in the boundaries of the regions in which major crops can be grown, is of considerable significance, as is the potential for the introduction of new crops. Further, a major practical aspect of research into the possible effects of potential climate change on soils is to define the potential effects on food supply. There is also a secondary interaction in that land use commonly has a profound effect on water supply, water quality, regional infrastructure and the planning process.

Global warming is predicted to give, for Europe as a whole, a mean rise in temperature of about 3°C over the next 50 to 100 years (Viner and Hulme, 1993), whilst precipitation is expected to increase by about 10 per cent. Expected changes in the seasonal and spatial distribution of the latter are currently little known, and difficult to predict (IGCC, 1992). However, winters will probably
become wetter, and summers drier, although the frequency and severity of so-called 'extreme events' e.g. severe storms, flooding etc. might increase (IPCC, 1990). The most important result of this overall change will, for land use considerations, be an increase in summer soil moisture deficits, which could be large in some regions. Some basic climate change scenarios are presented in section 2.7.

Recent attempts to predict the effects of climate change on land use within the European Community have important limitations e.g.:

i) they regard the soil as essentially uniform, and are driven almost entirely by climate;

ii) they operate at very coarse scales (Parry, 1990; DoE, 1991);

iii) they are essentially statistical in their approach and do not give enough attention to processes and mechanisms, particularly with respect to soil/climate interactions.

Such approaches can be useful in giving a very broad picture, but do not provide tools which give enough detail for realistic land use planning at the local or regional scale, nor consider the water resource implications of the potential changes in soil-climate-agriculture systems, nor allow accurate predictions in changes of harvests and matters related to the agricultural economic sector. Because of the very coarse scales, little use can be made of the very large amounts of high resolution soil, land use and climate information available within the Community (Hough, 1990; Commission of the European Communities, 1991; Narcisco et al., 1992).

The project described in this paper is concerned with modelling the potential impacts of predicted climate change; not with predicting climate change itself. The basic strategy was to build a model that uses climatic variables as part of the evaluation of land for crop suitability. Because the climate variables are not fixed, the approach can deal with any proposed climate change scenario. Validation of the model is, however, carried out against current climatic situations.

The main objective was to have the ability to predict the effects of any climate change scenario on the cropping potential of an area of land. The knowledge base is the known soil pattern, the properties of the soils, and the growth requirements of the intended crop(s). Historical meteorological data can be used to test the functioning of the model. Direct temperature effects on crop performance can be predicted from existing physiological models. However, the possible combinations of crop-soil-climate interactions are large and complex. Therefore, we chose to use data from national experimental soil-crop programmes as the basis for modelling and simulation. A novel aspect of the project is to support regional modelling, which we call Level I modelling (ACCESS-I, above), through detailed site modelling (Level II modelling - ACCESS-II). Thus, the more empirical-statistical, spatial approach of ACCESS-I is validated by the more process-based, but site-specific, approach of ACCESS-II.

We have taken the framework of an existing crop-agroclimate model, which relates crop requirements to soil-climate factors, and developed this into a tool usable over a wider spectrum. Initial development concentrated on improvements to the water balance-crop growth module, the erosion module, the land use/sustainability module and the fertility module. The second stage concentrated on extension of site-specific modelling to larger areas (a process called by us 'spatialisation'). Throughout the development of the model, considerable attention was given to assembly of databases with common data input formats, and standardisation of output formats compatible with common GIS formats.

The project began in late-1992 within England, France and Spain, and the initial development work was carried out between those countries, represented by the authors of this paper. Mid-way through the project, the work was extended to Hungary (Research Institute for Soil Science and Agrochemistry, Budapest) and Poland (Institute of Agrophysics, Lublin), increasing the potential area of application to agricultural land by about 250 000 km², and introducing a wider range of climate types and soil problems. The project is scheduled for completion in late-1994, so this paper describes the project at approximately the half-way stage. Thus, there are some questions to which the final answers are not yet certain. One of these is the methodology for calculating potential evapotranspiration, and it is clear from this text that more than one approach is under investigation.
at this stage. Likewise, the model has not, at the time of writing (November 1993), been subject to sensitivity analysis.

1.2 The Basic Model
The overall structure of the original land-evaluation model is derived from earlier work by Thomasson and Jones (1989). The compartments of this framework are sub-models; some complex, others very simple. These sub-models form a logical sequence, which lead to a suitability rating for a chosen crop-soil combination, run against given climate data. The model takes into account the limitations imposed by:

a) site factors: slope, aspect;
b) soil factors: depth, stoniness;
c) tillage properties: machinery work days, compaction risk;
d) agro-climatic factors: altitude, accumulated temperature;
e) crop available water: precipitation minus evapotranspiration.

The original model uses climate patterns derived from long-term meteorological datasets to give an average response of the soil i.e. to predict soil status and crop suitability in 6 years out of 10. However, it is possible to simulate a single growing season at a very simple level, using data for that year. The output of the model is the classification of a soil in relation to a particular crop, so that a soil map can then be classified in terms of crop suitability. The model can be run at a range of scales depending on the detail of the input data. Such suitability maps can be drawn automatically from a digitised soil map (see, for example, Rounsevell and Jones, 1993).

1.3 Data sources
The European Community is large and diverse so it was clear that the model had to be tested under a range of conditions. For this reason we selected three regions as test areas, each having good soil, crop and climate data, much of it in digital form, and a network of experimental sites/farms where extensive site-specific data are available:

a) central England: cool, humid climate;
b) Languedoc-Rousillon, France: Mediterranean climate;
c) Andalucia, Spain: very hot, dry summers, limited winter rainfall.

In Eastern and Central Europe the test areas are:

i) Lublin Upland, eastern Poland: warm continental, with snow cover in winter;
ii) Middle Tisza Region (Nagykunság), eastern Hungary: dry continental, cold winters, little snow.

The compilation of the databases concentrated on:

a) site factors - topographic maps and/or landform analysis;
b) soil factors - soil mapping (survey) and associated databases;
c) tillage properties - calculated from the number of days at which the soil is likely to be too wet for mechanical cultivation;
d) agro-climatic factors - from meteorological data;
e) crop-available water - calculated from precipitation data (long-term or short-term) and a simple model of soil hydrological properties.

The database for soils in central England was constructed in relation to the digital National Soil Map (Mackney et al., 1983), and its associated database (LandIS - see Ragg et al., 1988). Daily rainfall and temperature data for the test area were obtained for 30 years for 130 stations. In France (Languedoc-Rousillon) the climate data comprise daily values of rainfall and temperature over 20
years for 75 locations spread across Languedoc. Because soil data collected during soil surveys do not include the soil hydraulic properties, we carried out an extensive sampling program to determine these soil properties for the main soil units. The other soil data come from the soil database for the region (Bornand et al., 1993). For Spain, soil and crop data were obtained from the Catalogo de Suelos de Andalucia (de la Rosa, 1984). Climate data were collected specifically for this project from 62 climate stations within Andalucia, and entered into a database. The Polish data come from the Institute of Agrophysics (Lublin) and the Institute for Soil Science and Plant Protection (Pulawy). In Hungary, the soil database is a compilation from the Hungarian Soil Information System (TIR) (Csillag, 1988) by the Research Institute for Soil Science and Agrochemistry (Budapest), whilst a database of climate data is being assembled by the Hungarian Meteorological Office. In addition, a comprehensive database of crop growth requirements, crop phenology, and crop yield was established for major crops for all the test regions by all the partners in the project.

2.1 Revision of the Basic Model Structure
This basic framework was developed for use in England, and assumes:

- a) winter rainfall exceeds transpiration, and vice versa in summer; in relation to crop growth modelling;
- b) an average level of management, and mechanised farming is usual;
- c) there are no nutritional limitations (major or minor elements), and that soil pH is adequate;
- d) no erosion risk;
- e) crops are restricted to grass, winter cereals, potatoes and sugar beet;
- f) no irrigation requirement.

Most soil-crop models are developed and validated from experiments made at specific sites. Large datasets with many variables can be obtained, and temporal and spatial distribution established with precision. Such models commonly require very large numbers of input variables, which cannot be obtained for several crop types on large areas of land, where soil and climatic variation can be considerable. This gives very real problems in applying crop/land use modelling to such areas, where this kind of modelling has an important role to play in supporting planning and policy decisions. The restriction of models solely to experimental sites, which will always be a small part of any environment, is to question the ultimate purpose of their development. Spatialisation of data is dealt with below. We developed the revised model (ACCESS) to work at two scales:

- a) regional (Level I): large areas form several hundred to several thousand hectares in extent; this part of the model is known as ACCESS-I.
- b) test sites (Level II): experimental sites, usually at the farm or field scale, where intensive collection of data has occurred, often over many years. Such sites provide the rigorous framework within which the model can be validated. This is ACCESS-II.

Although the two parts of the model are different in the amount of input data required, the scale at which they are intended to operate, and their targets, they are intended to work as one package. The user chooses the scale at which it is desired to work, and the software within the model then selects the appropriate route through the sub-models. The most important difference between the two parts of ACCESS is the approach to the soil water-balance modelling. This is discussed below. Further, there is no reason why the model (at both levels) cannot deal with a wider range of crops than the original Thomasson and Jones model (loc. cit.), provided that the necessary parameters for modelling the crop are known e.g. phenology, water requirements etc. However, for the purposes of this project and the development of a working model, we concentrated on the following strategic crops:

ACCESS-I: maize, winter wheat, sunflower, potatoes, grass;
ACCESS-II: winter wheat, maize, sunflower.

It is important to realise, however, that the present form of the model makes no attempt to model crop quality except through yield, and this affects the choice of crop(s) to be modelled e.g. vines are not included because the judgement of the product is largely on the basis of what is in a bottle, and not what is on the plant. Nor, at the moment, does the model include routines to consider the socio-economic aspects of crop suitability e.g. through cost-benefit analysis, although such research is in progress.

It was clear from the beginning, that the basic model was inadequate in some respects, either because no routines existed for certain aspects e.g. soil fertility, salinization risk, or that the existing routines could not deal sufficiently well with a known problem throughout the Community e.g. erosion risk. The most important change, however, was to improve the soil water-balance model, so as to deal with different rainfall distribution patterns in relation to cropping seasons, more intense rainfall events, soils with well-developed vertic characteristics and so on. Changes in these components, and the ways in which they could interact, also required revision of the system of land-evaluation. The revised model is shown in Figure 1. In order to make the improved model widely available, it has been developed so that it will:

1. run on an IBM-compatible PC platform;
2. use standard data input formats;
3. provide output as standard file formats acceptable to a range of geographic information systems. All programming is compatible with Microsoft™ FORTRAN 5.1.

2.2 The Improved Water-balance and Crop-growth Model
Because ACCESS-I is the simpler component and is intended to be applied spatially over large geographical areas, a reduction in the number of input parameters was necessary. Simple soil survey information and a monthly meteorological time-step data are used, rather than the very detailed information, e.g. hourly or daily weather data, from experimental sites, which are not available for large geographic areas. The simplified inputs can cause certain difficulties in the development of such a model especially if a process-based approach is to be maintained. In particular, problems are encountered with the distribution of rainfall over the month where daily properties must be considered e.g. surface runoff and workability.

The central component of ACCESS-I is the soil water balance. This is a simple capacity model which considers transpiration, evaporation, root-front development and density, and the phenological development of the crop (from accumulated temperature). Water-limited crop yields are estimated from biomass accumulation using the principle of water-use efficiency (Feddes et al., 1978). Algorithms for the calculation of pedotransfer functions have been developed to enable prediction of soil physical properties from simple soil survey data. Potential evapotranspiration is calculated according to Thornthwaite's formula, with adjustment for latitude based on day-length. The potential evapotranspiration (PET) is separated into potential evaporation and potential transpiration following the Beer-Lambert law, and is based on leaf-area index (LAI). Root development is calculated from soil water pressure and soil resistance to penetration using the theory of root growth mechanics (Dexter, 1987). Actual transpiration is related to soil water pressure and a root sink term. The calculated monthly soil water balance is used to calculate the field capacity period by an interpolation technique. Likewise, the start and end of the growing season is calculated following the FAO approach, by which the growing period is defined as the time in the year during which rainfall exceeds 0.5PET, extended by the time that a maximum available water content of 100 mm in the soil has been depleted. In addition, the growing period is considered to be interrupted during the time that the mean air temperature is below 6.5°C. Accumulated temperature sums are estimated using TRIM (Temperature Remainder Index Model (Robertson, 1983)), whereas day-length and effective photoperiod are derived from Julian day number and latitude. Biomass accumulation is based on water use efficiency and accumulated transpiration deficit (van Keulen, 1982). The partitioning of the newly synthesised biomass of plant roots is based on phenologically dependent co-efficients. Final crop yield is obtained from final total
biomass using a crop dependent harvesting index. ACCESS-I is validated by ACCESS-II i.e. the output from the site specific model is used to assess the validity of the output from the simple model.

The soil water-balance model within ACCESS-II is derived from the French model MOBIDIC (Leenhardt, 1991), which is summarised in Figure 2 (our development stems from route 3), and the overall structure of the model is shown in Figure 3. The main simulation features of ACCESS-II are: i) simulation of evapotranspiration processes by separate simulations of soil evaporation and plant transpiration, ii) transpiration simulation based on an electrical analogy, iii) soil profile discretization into five centimetre layers (although the upper 5cm of the soil is treated as two 2.5cm layers so as to improve the simulation of evaporation), iv) simulation periods that extend over years so as to represent different climate change scenarios. Calibration of the model parameters was performed for different experimental data sets for soya, wheat and maize crops, provided by two agricultural experimental stations within Languedoc-Rousillon. Although calibration was satisfactory in most cases, further improvement of the model is necessary for the specific situation where moving water tables exist.

The main objectives of the crop growth part of ACCESS-II are simulation of leaf area growth, root growth, and yield, in relation to the availability of soil water during the growing season (Rambal and Cornet, 1982). The crop growth model used for calculating potential yields is derived from the EPIC model (Williams et al. 1983), but is revised for use in European conditions, using the same experimental data used in the validation of the soil-water balance approach (Figure 4) (Quinones and Cabelguenne, 1990). The root development model assumes a curvilinear development of roots against maximum depth attained in relation to the number of days between emergence and maturity (Borg and Grimes, 1986). The root density function is similar to that in the CORNGRO model (Childs et al., 1977). The model runs on daily meteorological data. For model run periods of 15 days or more, the differences between the evapotranspiration components of ACCESS-II tend to become small, seemingly due to mutual error cancelling.

The partitioning of daily rainfall into flow classes (macropore or 'by-pass' flow), run-off and infiltration) is made by a simple Soil Water Partitioning model (SWAP), which requires hourly rainfall intensity data. Because such data tend to be available only at a few stations, the latter are used to derive regression equations between hourly totals, hourly intensities and daily totals. These regression equations are then used to derive the required hourly data from the daily data from other meteorological stations in the test area. In SWAP, the soil moisture balance is calculated without attempting to identify the redistribution of water within the profile, this being estimated by a separate sub-model derived from an h-based scheme of the Richards' equation. The hourly hyetograph can be compared with matrix infiltration and macropore infiltration capacity to partition rainfall into: recharge to the soil moisture store, macropore flow, and surface run-off. Rainfall up to and including maximum infiltration capacity is matrix infiltration, any excess up to maximum macropore infiltration rate is macropore flow, and any excess above that is surface run-off. The thresholds - maximum matrix infiltration rate and maximum macropore acceptance rate - are functions of the soil state; in particular, the degree of soil structural development and moisture content. The model calculates a soil water balance for a single soil store, with matrix infiltration and evapotranspiration being added to and removed from the store as required. Macropore flow, however, is assumed to move directly to the drainage system, and is therefore unavailable to the soil storage.

The model has been used with both current climate data and data perturbed to represent a climate change scenario, the latter assuming a temperature increase of 3 °C, a 10 % increase in winter rainfall and a similar decrease in summer. Evapotranspiration was recalculated for each day from a series of monthly coefficients derived from climatic data, to give a relationship between temperature and evapotranspiration.

Initial work has run the model against 11 years of data for a site within central England. The mean contributions to each of the flow components were calculated for both current and changed climates. The results show that the amount of actual evapotranspiration will increase with change in climate, but there is no major increase in the macropore or surface flow.
2.3 The Land use-Sustainability Model

The central purpose of ACCESS is the estimation of water-limited crop yields, because we see water-stress as the major limitation to agricultural production. This has very practical consequences in the assessment land use potential for farmers, planners etc., and ACCESS is meant to be a practical tool. The basic concept is that of 'attainable productivity' for selected strategic crops, expressed as a yield value or yield class. This is the maximum possible productivity of a land unit within the constraints of the land unit e.g. drought stress, workability, length of growing season. These factors are clearly linked to the parameters considered by the crop-growth/water-balance model, and the latter can be used to guide the estimation of this parameter. However, in reality, the 'attainable productivity' is an ideal, and 'actual productivity' is the norm. The latter depends on management, which often affects the constraints imposed through the properties of the land unit. For example, irrigation could be seen as a management input, although a crop might not succeed without it. However, the economic return on the crop would still be too poor to pay for the irrigation infrastructure and the water. Thus, the actual productivity can be regarded as an 'efficiency indicator' of the potential of a land unit. In order to put these predictions of productivity into context, the modelled yields are categorised into one of four yield classes; high, medium, low and unproductive, which are derived from thresholds of attainable yield (Figure 5). The boundaries between each yield class are different for individual regions of the Community because they refer to the current state of agricultural output in each region. This means that, for example, winter wheat productivity of 6 t ha\(^{-1}\) in England and 4 t ha\(^{-1}\) in Spain can both be classified as medium yields because of the difference in the socio-economics of the two farming systems. These regional differences are defined by the Regional Economic Minimum Productivity (REMP) which represents the minimum yield that can sustain economic crop production.

If the actual productivity is less than the attainable productivity estimated by ACCESS, then clearly the farming system has reserves of productivity, which could compensate for climate change. A novel development is to extend the productivity concept to the definition of Land Use Types (LUT). Traditionally (e.g. FAO, 1976) the assessment of land use types i.e. agricultural systems that have developed in response to local circumstances, is made in subjective terms before a suitability assessment is made. We are using 'allowable' productivity i.e. the acceptable quantity of crop produced which allows a farmer to cultivate a particular land unit in a specified region, to define the LUT. Thus, there can be several LUTs for the same crop distributed through the European Community in terms of allowable yield. Figure 6 gives an example of the data input for a Land Use Type.

2.4 The Soil Erosion Risk Module

Predicted climate change, in southern Europe, will reduce vegetation cover. Under certain conditions, rainfall intensity could also increase. Thus, climate change should not be studied only from the standpoint of agricultural production. It is also necessary to examine the increase in the possibility of erosion i.e. the risk of damage to the soil. This refers back to the revision of the basic model (section 2.1.d). In the context of this project, erosion is the risk of water erosion on agricultural land, and uses the concept of an 'attainable erosion risk' class. This is the maximum possible erosion risk based on relief, soil erodibility and rainfall erosivity; these factors are known as 'land qualities' - LQ. Relief is self-explanatory, erodibility is a measure of the detachability of soil particles without regard to the influence of topography, and rainfall erosivity is a measure of the power of raindrop impact. Much of the initial approach is given in CORINE (1989). Relief is one of four slope classes which reflect low, moderate, strong and very strong risk of severity of erosion. Erodibility is a complex concept in that there is interaction between effective rooting depth, particle size distribution class, surface stoniness, surface horizon bulk density, and surface horizon permeability, giving four classes of severity (very low, low, moderate and severe). Erosivity is defined in terms of the 'derived Fournier/aridity index' (Morgan, 1979), and again gives four classes:
low, moderate, high, very high. The application of this system, via a matrix, to give the 'attainable erosion risk class', can be seen in Table 1.

2.5 The Natural Fertility Module
This project has assumed (2.1.c) that fertility is not normally a land use limitation in Europe, as it is a management option, but this is not necessarily always true. Further, climate change could delineate areas of land which are suitable for agriculture apart from a lack of natural fertility, which is defined chemically for the upper 20 cm of the soil (topsoil) and the layer between 20 cm and 50 cm. Our system uses ten criteria, of which up to three can be identified as limiting. The criteria are: pH, weatherable minerals, CEC, base saturation, exchangeable sodium percentage, electrical conductivity/salinization, C/N ratio, gley properties, K-supplying power, P-fixation power. Each category has two classes (high and low), the 'low' categorisation being non-limiting. The system does not give a quantitative measure of the degree of remediation required. It indicates where there are problems. These will require further investigation to give a reliable estimate of the degree of infertility and the practicability of remedial action. The combination of categories gives 18 fertility classes.

2.6 Spatialisation
The extension of site-supported modelling (ACCESS-II) to larger areas, requires spatial extension of soil properties measured previously at single points. In all the test areas, use is made of pedotransfer functions i.e. equations relating soil hydraulic properties to basic pedological variables available in soil databases. The pedotransfer functions were developed from the set of samples where both the pedological variables and the hydraulic properties were measured. They take the form of sets of algorithms or regression equations valid for the range of soils occurring in each region. Routines have been developed to estimate the soil water-release curve from particle size distribution, bulk density and organic carbon, over the range 0.05 to 15 bar suctions, unsaturated hydraulic conductivity, and soil resistance to root penetration (Simota and Loveland, In preparation). Methods have also been developed to estimate crop yield from similar data in conjunction with monthly weather data.

A more difficult problem was the interpolation of site-specific weather data to soil polygons. These polygons are 'better defined' spaces than climate zones, so the boundaries were kept, except where clear climate boundaries could be identified crossing the polygons. For practical purposes we worked with a lower polygon size of about 100 ha., although smaller areas could be modelled. In temporal terms, it was difficult to extend daily meteorological data to large numbers of polygons, because of the demands on computing time. Most of the development has thus run at decadal time-steps. The problems arising from the spatially irregular distribution of meteorological stations in relation to the distribution of soil polygons is dealt with by a technique involving 'spatial deformation' (Monastiez et al., In press).

Finally, the problem of irregular runs of climate data, or runs of data of various lengths for different sites, was approached through the use of a stochastic weather generator.

2.7 Climate Change Scenarios
The predictions of potential climate change are uncertain. General Circulation Models used for such prediction operate at very coarse scales e.g. predictions are often given on the basis of cells approximately 250 km by 250 km. Consequently, only regional approximations of climate change can be made at present, and Table 2 summarises the scenarios from which a choice will be made to test the model described in this paper (Kenny et al., 1993).

3.1 Conclusions
We have developed a model to estimate the suitability of soils within the European Community for a range of strategic crops under different climate change predictions. The model uses site-specific data to validate a simpler, regional model. The project has been developed within test regions from central England, southern France and southern Spain, and is being applied in Central and Eastern Europe. The model contains a robust crop-growth/soil water-balance component, and routines have
been developed to assess soil erosion, soil fertility and new approaches to land use. The model accepts standard data entry and output in formats compatible with a range of geographic information systems. Equations have been developed to calculate pedo-transfer functions from simple soil data, and new methods of spatialisation of data have been developed. This model is a powerful tool to evaluate crop suitability and land use within the European Community and related areas in relation to climate change.

Acknowledgements

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References


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**Table 1.** Part of the decision-tree approach to assessing the 'attainable erosion risk' class.

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<td>Small</td>
<td>Small</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>I</td>
<td>Erosivity</td>
<td>Small</td>
<td>Small</td>
<td>Small</td>
<td>Moderate</td>
</tr>
<tr>
<td>J</td>
<td>Erosivity</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>K</td>
<td>Erosivity</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>L</td>
<td>Erosivity</td>
<td>Small</td>
<td>Moderate</td>
<td>Moderate</td>
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</table>

Note: Under each severity level, the symbol > followed by a letter (B to L) is used to direct the user to the next step in the decision tree.
Table 2. Current predictions for climate change scenarios (after Kenny et al., 1993).

<table>
<thead>
<tr>
<th>Region</th>
<th>Year</th>
<th>(\Delta T) (°C)</th>
<th>(\Delta P) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td>Britain</td>
<td>2010</td>
<td>0.5 - 1.0</td>
<td>0.0 - 0.5</td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>1.0 - 1.5</td>
<td>1.0 - 1.5</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>2.0 - 3.0</td>
<td>1.0 - 2.0</td>
</tr>
<tr>
<td>Scandinavia</td>
<td>2010</td>
<td>0.5 - 1.0</td>
<td>0.0 - 1.0</td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>1.5 - 2.5</td>
<td>1.0 - 1.5</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>2.0 - 4.0</td>
<td>1.0 - 2.0</td>
</tr>
<tr>
<td>Mediterranean</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>- south</td>
<td>2010</td>
<td>0.0 - 1.0</td>
<td>0.0 - 0.5</td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>1.0 - 1.5</td>
<td>1.0 - 1.5</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>1.0 - 2.0</td>
<td>1.0 - 3.0</td>
</tr>
<tr>
<td>- north</td>
<td>2010</td>
<td></td>
<td></td>
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<td></td>
<td>2030</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europe -</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- continental</td>
<td>2010</td>
<td>0.5 - 1.0</td>
<td>0.5 - 1.0</td>
</tr>
<tr>
<td></td>
<td>2030</td>
<td>1.5 - 2.0</td>
<td>1.0 - 1.5</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>2.0 - 3.0</td>
<td>1.0 - 2.0</td>
</tr>
<tr>
<td>- west (marine)</td>
<td>2010</td>
<td>0.5 - 1.0</td>
<td>0.5 - 1.0</td>
</tr>
<tr>
<td></td>
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<td>1.0 - 2.0</td>
<td>1.0 - 1.5</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>1.0 - 3.0</td>
<td>1.0 - 2.0</td>
</tr>
<tr>
<td>- russian</td>
<td>2010</td>
<td></td>
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<td></td>
<td>2030</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(\Delta T\) and \(\Delta P\) are the changes in temperature and precipitation, respectively.
Figure 1. Information flows within the ACCESS model.
Figure 2. The structure of MOBIDIC (after Leenhardt, 1991). The development of ACCESS-II follows route 3.

- **Phenological development**
- **Root development**
  - **Maximum evapotranspiration**
    - ETP
    - ETM
  - **Potential evaporation and transpiration**
    - ETP
    - EP + TP
  - **Actual evaporation**
    - (van Keulen, 1975)
  - **Actual transpiration**
    - Feddes et al. (1978)
    - Rambal & Cornet (1982)
  - **Infiltration**
    - Law of 'all or nothing'
    - Function of hydraulic conductivity

Route 1
Route 2
Route 3
Figure 3. Basic structure of ACCESS-II

DATA STRUCTURES

FILE: names of data files
   COMAND: simulation commands
   CLIMAT: climate years
   PLANT: crop parameters

PROFILE LOOP(S)
   SOIL: profile characteristics
   POT: soil-water retention characteristics
   DISCRET: profile discretization
   INITIAL: initialization

YEARMY LOOP
DAILY LOOP

CROP DATABLOCK
   GROWTH: crop simulation

WATER BALANCE DATABLOCK
   IRRI: irrigation to a given threshold
   SEPAR: separation of transpiration and evaporation
   EVAPO: calculation of evaporation
   ROOTD: calculation of root density
   TRANSPI: calculation of transpiration
   RDSTR: redistribution, infiltration and drainage

RESULTS DATABLOCK
   CURVE: daily output
   NBDAYS: number of days

END OF DAILY LOOP
ARRAY: cumulative annual output

END OF YEARLY LOOP
PEDO: cumulative drainage from each soil layer

END OF PROFILE LOOP
Figure 4. Information flows within the modified EPIC model.
Figure 5. A hypothetical example of a regional analysis of crop yields used to define boundaries between yield classes.
Figure 6. An example of a land utilisation type (LUT) from southern Spain.

Current Conditions for the LUT: Sunflower/Rainfed
*BENCHMARK AREA: CAMPINA (SE-03), ANDALUCIA, SPAIN

*CROP (Helianthus annuus)
Main varieties: Florasol; Ariflor; Hysum-33
Growing season length: 159 days (mean); range 126-184
Maximum rooting depth (cm): 80-100
Phenological calendar: Emergence: end Feb/mid Apr; Ripening: mid July-end Aug

*MANAGEMENT PRACTICES
Primary tillage: 1 - mouldboard plough, September; 3 - disking, December-January
Secondary tillage: 1, interrow rotavator - end March - early May
Sowing: 4-8 kg seed/ha, 70cm row spacing, mid February - end March
Fertiliser: Urea 46% N, 100-150 kg/ha; December-January
Herbicides: 1.5 L/ha, trifluralin, mid February - end March
Pesticides: 50 kg/ha, Lindane 2%, mid February - end March
Harvesting: combined, end July - early September
Residues: straw ploughed in, October
Irrigation: nil
Artificial drainage: nil

*PERFORMANCE IN THE BENCHMARK AREA
Indicative yield/quality: 1.9 - 2.2 t/ha seed; 46 - 50% oil
Environmental impact: high erosion risk; low pollution potential
Implications of Agenda 21 on Soil Survey and Characterization Programs

R. N. Concepcion. Soil Research and Development Center, Bureau of Soils and Water Management, Philippines.

Introduction

The United Nations Conference on Environment and Development held at Rio de Janeiro in June 1 to 12, 1992 formulated the Agenda 21 which provided scientists all over the world a global framework for the implementation of country programs and projects on sustainable development.

The earth summit at Rio, according to Maurice Strong, the Secretary General of the UNCED, created universal efforts to establish new era of international cooperation and new dimensions in the partnership for sustainable global development. He further asserted that the Rio Declaration and its Agenda 21 action program are now on every country's development agenda. Agenda 21 took cognizance of the global concern for the widening disparities between and within nations and the inability of many countries to reduce the impacts of continuing deterioration of the ecosystems. The call for Sustainable Development puts into focus significant cross-sectoral issues involved in the use of land resources and consequently, the single requirement for a multi-disciplinary, integrated physical planning and management as a way to resolve the increasing land use conflicts and competitions.

The well-defined changes in the perspectives and directions imposed by the global agreement at Rio de Janeiro have direct impact on many existing technical tools on resource use assessment and management planning, especially in terms of the range and types of data needs as well as the required degree of multi-disciplinary integration for effective landuse interpretations.

One of the most widely utilized resource base technology is the United States Soil Taxonomy Survey and Classification scheme. As a major requirement of the Rio Declaration and the implementation of Agenda 21, the entire soil classification and characterization system must be flexible and be able to relate well with the global agenda for development by being dynamic and creative in terms of defining soil properties that can be used to guide efforts in the sustainable agricultural production and forestry development. As Cline (1949) emphasized, "the purpose of soil classification is to organize our knowledge into groups so that the properties of the objects classified may be easily remembered and the relationships between members of groups and between members within a group are readily understood. Any classification must have specific objectives." However, in addition to Cline's suggestion, the need is to encourage soil scientists to act beyond the sphere of pedology and develop operational partnership with other resource base disciplines to capture the broader meaning of decision variables for ecological protection and watershed productivity (i.e. relational data base for defining the correlative productivity of agriculture and forest cover).

The famous Rio declaration has adopted 27 principles which covered the concerns for man, his environment, and his efforts for development as well as the focus on specific special sectors such as concerns for women, youth, governments and policies, peace and order, and others. It is quite clear from the selected foregoing principles that above all considerations, the following broad parameters for Sustainable Development are quite evident: (a) man and the quality of his environs as effected by his own efforts to survive decently and to establish conditions for Sustainable Development; (b) good governance marked by rational political system; and (c) continuity or non-disruption in implementing rational policies on economic resource uses. Some of the basic principles that can serve as benchmark for the retooling and review of the present state of soil classification and characterization are as follows:

Principle 1 - "Human beings are at the center of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature."

Under this principle a major requirement is the consideration for man's (e.g., farming communities) social and economic welfare and the equal consideration for the quality of the surrounding environment during the entire efforts to maintain productivity in the use of the land and water resources. Soil survey and characterization must be able to include with sufficient focus on the status of and study of the proper environment for soil biological properties that will promote the use of environment-friendly production technologies that can be used to estimate sustainable yield levels.

Principle 4 - "In order to achieve sustainable development, environmental protection shall constitute an integral part of the development process and cannot be considered in isolation from it."

This principle is the bottomline for sustainable development where the resource base retains its ecological integrity for the future generation. In other words, the present generation merely borrow the present resources for their own economic and social welfare and therefore it is reasonable enough that such borrowed resources must be passed on, with equal if not better productivity, to the real owner, the future generations. This dictates the need to identify and include ecological parameters in the soil classification and characterization. These parameters must include soil fertility factors (e.g., present contents and ratio of macro and micro nutrients) which will allow precise application of balance fertilizers and other environment-friendly inputs (organic fertilizers, biological pest control, organic-based insecticides and pesticides).

Principle 6 - "The special situation and needs of developing countries, particularly the least developed and the most environmentally vulnerable, shall be given special priority. International actions in the field of environment and development should also address the interests and needs of all countries."
This will require soil classification and characterization schemes that will lead to the identification of islands and provinces that are ecologically fragile and the corresponding soil properties that will adequately identify their specific locations as well as the precise mitigative measures for their sustainable use for food security and other economic uses. Soil survey programs must give priority to the soil characteristics that will provide better definition of water availability and the sets of crops that are high nutritive and economic value and which will require less moisture.

Principle 9 - "States should cooperate to strengthen endogenous capacity-building for sustainable development by improving scientific understanding through exchanges of scientific and technological knowledge, and by enhancing the development, adaptation, diffusion and transfer of technologies, including new and innovative technologies.

This will require a community-based soils and land use mapping where farmers are trained to identify and locate their prime and marginal soils using some biological and plant indicators. For instance, cashew plants would indicate relatively acid soils and dry climate and therefore would need to identify specific soil properties related to the measurements of soil acidity and moisture availability, as well as the length of growing periods.

Soil scientists must be able to draw up lists of biological indicators for some specific soil properties. For instances, some crops in the Philippines are highly correlated to specific soil and climatic conditions as follows:

a. the presence of cashew, mango, and tamarind in an area would indicate a Ustic soil moisture regime and that the major requirement in the area would be irrigation. Cashew plants also indicate that the soils in the area are most likely acidic and clayey with relatively difficult tillage properties.

b. the presence of Nipa palms would indicate that the soils in the area may be suffering from salinity intrusions and that the ground water may have been of low quality for irrigation.

c. the dominance of a Chromolaena Odorata would indicate that the soils suffer from sever phosphorous deficiency and that pasture development in the area would be relatively difficult.

d. the presence of naturally growing bamboos can be indication that the area is located in the boundary between the wet and dry areas and that the site can have good sources of shallow ground water.

e. the presence of termite mounds can be an indication of seasonal/imperfect soil drainage.
Some crops in the Philippines are also indicators of possible migration patterns and the predominance of a certain ethnic groups, to wit:

a. the dominance of root crops planted in the paddy fields would indicate that the farmers must have come from the Bicol region, a typhoon-prone area;

b. the dominance of corn planting in the hillsides would indicate that the farmers must have come from the Visayas (mainly Cebu);

c. the dominance of tobacco crops can indicate that the farmers must have come from northern Luzon, mainly from the Ilocos region;

d. the presence of coconut being tapped for its sap for local wine would indicate that the farmers must have come from the Central and Eastern Visayas;

e. the presence of community that grows perennial and seasonal vegetables in their backyards may indicate that the community must have come from the northern Luzon, Ilocos region.

Scopes and Limitations of Soil Survey and Characterization Programs

In general, the present soil survey and characterization scheme is primarily based on the natural systems and therefore would not be able to document human-induced soil limitations.

Soil survey (Recel, 1988) is primarily a scientific tool that record in map format the values of all natural soil properties of the survey area. The resultant map becomes a means for various decisions makers and planners in understanding soil conditions of an area without the necessity of being physically present in the site. As defined in the 1990 edition of the Keys to Soil Taxonomy, soils refer to "collection of natural bodies on the earth's surface, in places modified or even made by man of earthy materials, containing living matters and supporting or capable of supporting plants out- of-doors." The upper limit of the soil is air or shallow water while the lower limit of soil is normally the lower limit of biologic activity, which generally coincides with the common rooting depth of native perennial plants. Under this definition, only natural process of soil development is recorded to define a Taxonomic unit. If one has to adopt for basic parameters of Rio and Agenda 21, it is crucial to identify and evaluate human induced land degradation and define the corresponding mitigative measures.

In general, soil survey provides good account and records of soil chemical and physical properties that are designed to measure soil productivity but land properties such as slope, topography are not inherent part of the taxa. Such that Entisols may be located both in the lowland and in the uplands and anywhere else in the watershed whose productivity and
technology inputs are uniquely different from one another. On the other hand, Agenda 21 prescribed for a wider range of concerns and land resources where soil properties together with relevant economic, market infrastructures, and socio-institutional parameters are factors of sustainable land development.

As prescribed in the Soil Taxonomy manual, soils include the horizons near the surface that differ from the underlying rock as a result of interactions, through time, of climate, living organisms, parent material, and relief. However, soil taxonomy classification and characterization records primarily natural soil processes but it failed to focus soil properties that will characterize (and form as part of the taxa), the human-induced soil degradation. For instance, basic soil fertility factors such as the contents and the balance/imbalance of major soil elements like N, P, K, Ca and Mg and other important minor elements like zinc and boron are not parts of the data sets that will characterize soil taxonomic units. However, in the actual use of the land in the Tropical countries like the Philippines, most soil chemical degradation are human induced degradation brought about by imbalanced fertilization practices. This is particularly true in Nitrogen-driven fertilizer production systems where nitrogen in the soil serve as shovel to remove major soil nutrient reserves particularly native N, P, and K. Several researches indicated that nutrient uptake with increasing levels of fertilizer application is not exclusively from fertilizer sources (Tandon, 1992). A significant proportion of it comes from the soil itself either through "priming effects" or as a result of better root growth and proliferation made possible by fertilizer application. Tandon (1992) further reported that the crop removal of soil P is 12-33 percent more in plots which were regularly fertilized with N as compared with unfertilized control plots. In long term experiments, this P-mining ability of N-plots varied with soil types as follows:

(a) 100-129 percent depletion in alluvial soils;

(b) 56-67 percent depletion in laterite, red loam, and mollisols (under rice based-systems);

(c) 33 percent in black clay soils; and

(d) 0 depletion in red loams under upland cropping systems (highly P deficient soils where crop growth in N-treated plots was poorer than in control plots).

Challenges and Issues of Agenda 21 on Soil Classification and Characterization

1. The need to review the minimum data sets to define sustainable agriculture.

Beinroth, (1988) emphasized the need to understand the quantitative relations derived from the genotype-environment-management interactions as well as the need to collect balanced sets of soil-crop-weather-management data that monitor the whole system and facilitate the identification of the "minimum data sets." The current soil classification and characterization system in the Philippines is closely tied-up with the USDA Soil Taxonomy system. The soil taxonomy scheme largely
depend on prescribed sets of laboratory analysis which represent the minimum data
sets required of soil surveyor to make reasonable land use suitability studies.
Eswaran (1977) identified three classes of soil analysis for various soil survey efforts
in the country.

Class 1 - a. Analysis required in Soil Taxonomy

1. General Data Needs for Horizon Characterization
2. Particle size distribution by pipet method.
4. Cation Ion Exchange Capacity (NH4OAc, pH 7)
5. Exchangeable bases (Ca, Mg, N, K)
6. pH in H2O and 1N KCL (1:1)
7. 1N KCL - Extractable Aluminum
8. Extractable acidity, BaCl2 - 1,4lithanolamine (pH 8.2)
9. CBD - extractable Fe2O3

b. Analysis required on a few selected profiles to test specific requirements
of soil taxonomy.

1. Bulk density - for Andepts and the "Hum" suborder and great
groups
2. pH in NaF - Andepts and Spodosols
3. 15 bar water - Inceptisols, Alfisols, Ultisols, and Oxisols
4. CEC by 1N NH4Cl - Oxisols
5. COLE value - Vertisols and Vertic Subgroups
6. Conductivity - Aridisols, some families
7. CaCO3, CaSO3 - Aridisol, Mollisols

c. Analysis required on a few selected horizons to test specific
requirements of soil taxonomy

1. P2O3 - anthropic epipedon
2. Pyrophosphate - spodic horizon
3. Fine/coarse clay ratio - argillic horizon
4. Clay mineralogy - argillic horizon
5. Fine sand mineralogy - soil families

Class 11. Analysis performed for specific purposes of problems

a. Physical and engineering
1. infiltration
2. permeability
3. available water
4. bearing capacity
5. other engineering properties
b. chemical properties of soil and water
   1. salinity, alkalinity
   2. pH fresh, dry or with oxidizers
   3. toxic substances (arsenic, boron, nickel, chromium, sulphides, iron)
   4. suspended solids
   5. dissolve salts (SAR)
   6. toxic substances (B, Mg, Li, Cl, So4, CO3, HCO3)
   7. pH

Class 111. Analysis for pedo-genetic studies
   1. mineralogiy
   2. micromorphology
   3. equilibrium studies

Other researchers prescribed minimum data sets for specific uses. Cagauan (1988), suggested that there are likewise minimum data sets prescribed for the Crop Environment Resource Synthesis (CERES) crop yield can be simulated (predicted) as affected by weather, soil, water, genotype, and soil nitrogen. For instance, the CERES crop model as follows:

<table>
<thead>
<tr>
<th>Type of Data</th>
<th>Data</th>
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<tbody>
<tr>
<td>Management</td>
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</tr>
<tr>
<td></td>
<td>planting date</td>
</tr>
<tr>
<td></td>
<td>plant population</td>
</tr>
<tr>
<td></td>
<td>irrigation dates and amounts</td>
</tr>
<tr>
<td>Weather</td>
<td>longitude and latitude</td>
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<td></td>
<td>solar radiation</td>
</tr>
<tr>
<td></td>
<td>maximum and minimum air temperature (daily)</td>
</tr>
<tr>
<td>Soil (by layer)</td>
<td>initial soil moisture content of</td>
</tr>
<tr>
<td></td>
<td>drained upper limit of soil water and</td>
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<td></td>
<td>lower limit of plant extractable soil water; or 0.33 and 15 bar water</td>
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<tr>
<td></td>
<td>contents from soil moisture release curves, soil texture, and cation</td>
</tr>
<tr>
<td></td>
<td>exchange capacity</td>
</tr>
</tbody>
</table>

2. The need to establish the role of soil survey and characterization on Global Food Security Efforts

As it is today, characterization efforts on soil survey are based on the natural systems and because of its isolation from other resource base technologists, there are
technical difficulties in relating them on specific needs to improve food security efforts in developing countries. At its best, the output from soil surveys (eg Soil Taxonomy Classification), can provide the state of soil fertility and its potential for estimating crop yields. However, it is clearly demonstrated that the sustainability of a certain crop performance in any given farming communities are greatly influenced by externalities such as management technologies, market, pricing policies on farm inputs and farm products, socio-cultural factors and the changing climate patterns which also have their own independent factors. It is about time that any efforts on soil survey, classification, and characterization must conform with the overall requirements and changes in the physical and economic environments affecting farm production.

In the Philippines, the Bureau of Soils and Water Management has been, for one decade and eight years, doing operational researches for the formulation of soil classification schemes which integrate the bio-physical, economic, socio-cultural and institutional parameters to define ecological-friendly subsistence farming systems and the economic/policy matters that actually exist at the time of the study.

The Department of Agriculture has already defined the land areas that are considered as the Key Production Areas (KPA) for Agriculture which are primarily based on the integrated land resources studies with soil survey playing the central role in defining the fertility environment of a given land management unit. In the Medium Term Development Agricultural Development Plan (MTDAP), the KPA approach identifies and focuses government support on certain priority areas whose agro-climatic features and market conditions are favorable for producing, processing, and marketing specific products. The plan likewise advocates on a simple concept of "Putting Land to Best Use" where the country expect to sustain the growing food requirements and even produce "export winners", competitively by defining the best use of country's land and water resources.

3. The Need for Soil Survey to Take a firm stand on issues of Land Use Conversion and argue for the Economic and Multiple Uses of Agricultural Lands

As a consequence of development and the expanding urban areas, land use conversion of prime agricultural lands become a serious threat to the capability of agriculture to sustain the growing food needs in the country. The Department of Agriculture through the studies conducted by the Bureau of Soils and Water Management (BSWM) identified nationwide, the Network of Protected Areas for Agriculture which then serves as the framework for the production land use in the country. Several advocacy efforts were done by the soil survey organization in the Philippines in order to reduce the impact of the rapid decline of agricultural lands caused by land degradation and land use conversion.

In an effort to formulate the concept of Agri-tourism as a marketing tool for agriculture by identifying ecology-friendly and models of sustainable farming areas that can be used as tourist destinations, the BSWM conducted a special study on the multi-
storey systems in areas near the Metro-Manila. The recent case studies conducted by the BSWM showed that one of the farming systems, Coconut and Coffee-based multi-storey systems, were found to be the market-driven farming system that are both ecologically and economically sustainable. The soil survey and characterization studies conducted by the BSWM in the proposed Industrial Sites in Metro-Manila, known as the CALABARZON which represent the provinces of Cavite, Laguna, Batangas, Rizal, and Quezon, showed as very interesting findings on the unique farming systems in the province of Cavite. When the findings of the soil survey were integrated with the analysis of the farming systems and other agri-support infrastructures, the BSWM was able to establish strong argument for retaining the lands in Cavite for agriculture and prevent them from further conversion to housing and industrial sites. The summary of the findings of the soil survey and characterization studies are as follows:

a. The soils in the area are composed of multi-layers of buried soils that resulted from various volcanic eruptions of the Taal volcano. The buried soils become the storage of rich reserve soil nutrients. Because of this superimposed layers of volcanic materials, the impacts of erosion are divided into on-site and off-site effects. In the case of Cavite soils, the soil erosion provides positive impact on the farm since it caused the exposure of the buried volcanic soils which is rich in soil nutrients; off-site effect of soil erosion is on the river systems which drain either toward the Manila bay or to the Laguna de Bay.

b. The multi-storey cropping in Cavite is one of the few examples of a Sustainable farming Systems which is never duplicated anywhere in the country. The Coconut and Coffee based cropping systems have the following unique characters:

b.1. The coconut-based multi-storey croppings has at least 3 -4 canopy layers underneath the coconut plantations.

b.2. Because of the multi-canopy layers and of the highly intermeshed root systems of all these crops, the retention of soil moisture and the protection of the shallow groundwater sources.

b.3. As ecological and economic system, the Coco-based multistorey systems perform at par with the forest vegetation.

b.4. The coco-based system are critical Key production area for various key commercial crops and are understood to perform the ecological function, equal if not greater) of the forest ecosystem.

b.5. the Multi-storey farming systems in Cavite represent a unique and an indigenous technology that must be preserved for use in the justification for arable lands from irrational land use conversion.

b.6. The historical value of the Cavite Coco-base Multi-storey system is parallel to that of the Banaue rice terraces.

4. The need to define and locate on map on suitable scales of planning the human-induced land degradation.
Asian Network of Problem Soils and Land Degradation has already established the institutional mechanisms to map human-induced soil degradation through SOTER and GLASOD methodology. The next expert consultation shall be held on 1995 in the Philippines.

5. The need to adopt a computer-aided Remote Sensing cum Geographic Information System for a more Efficient Data Management Scheme.

Given the voluminous data and information, the new concept of data management and utilization employ the computer-aided geographic information systems. The BSWM in the Philippines have already established and geo-coded Soil Information System, all technical parameters prescribed in the program are already established nationwide.

Relevant Programs in Agenda 21 on Soil Survey and Characterization

1. On Integrated Approach to the Planning and Management of Land Resources

This project under the Agenda 21 emphasized that multi-disciplinary teams must be fielded to be physically present in the project site. Pedologists or Soil Scientists, under this global outlook, are now advised to start retooling themselves for a new working conditions with other scientists and researchers with distinctly different but collaborative works on bio-physical resources.

This approach recognize the fundamental problem brought about by the ever increasing population and the subsequent conflicts in the use of the land resources. Integrated physical and land use planning and management is considered the best way to resolve the conflict arising from the increasing demand for land resources.

The Bureau of Soils and Water Management in the Philippines has adopted a 5 step-hierarchical analyses that will estimate the country's potential to handle her concerns for Food Security (Figure 1), as follows:

a. Agro-ecological Zone Analysis - the initial phase of the analysis appropriate for regional land use studies (map scale of 1:250,000 or smaller). The physical unit for mapping resources is the watershed which is divided into two major concerns:

(a.1) productivity, which is handled by the Pedo-ecological zones (zonal unit composed of soil types, temperature, elevation and slope situation);
(a.2) ecology, which is handled by the Hydro-ecological zones (zonal unit composed of vegetation cover-soil erosion status, run-off, and moisture status of a given river watershed areas).

b. Landscape analysis - Under each Agro-ecological zones, landscapes or physiographic units are defined and delineated as geomorphic units, and geo-
Figure 1: Map of Key Grains Areas, Philippines

- Key Rice Areas
- Key Corn Areas
- Key Rice and Corn Areas

*Representational only; does not reflect actual hectarage covered by the Program.
Figure 1. Soil Resource Survey for Sustainable Agriculture
coded for registration in the BSWM Geographic Information System. This phase make use of Remote Sensing facilities in the BSWM for vegetation and drainage analyses which are integrated with the Geographic Information System for spatial data analysis and management. At this stage the political units, province, or administrative regions are one of the map overlays for the GIS.

c. Land Use Analysis - Vegetation cover and economic landuses of each of the landscapes are identified and defined for project. Each of the major landuse categories are registered as a characteristic of a given geomorphic surface. At this stage of analysis and resource mapping, the geomorphic units are expressed into distinct land Management Units (LMU's), which are unique geomorphic land units with a given soil types, dominant land uses, slopes. The LMU's are properly coded and are now stored in the computer systems in the Soils Research and Development Center, a JICA assisted/Grant aid project with the BSWM.

d. Farming Systems Analysis - The LMU's are subdivided and are mapped with their respective phases or specific limitations like slope, drainage, acidity, erosion. The LMU's and their relevant management phases are linked with a range of dominant farming and cropping systems and the communities participation in field documentation are encourage. At stage, the LMU's and the equivalent Soil Taxonomic Units are recorded: the LMU's provide the observable attributes (slope, land use, erosion, drainage, surface soil textures, etc.) and the Soil Taxonomic unit provide the non-observable attributes such as chemical and physical soil characteristics obtained from soil laboratory analysis.

e. Development Impact Analysis - The impact of a given land use and farming systems in each of the LMU's are evaluated in terms of their sustainability in productivity. The expected degradation that may result over the extended use or misuse are reflected as off-site and on-site degradation or erosion. It is important to isolate off-site effects of land use from the on-site effects (river sedimentation/pollution) since the former provide the measurement of the broader ecological impact while the latter, is used to estimate future impact of the activities on the farm and the farmer himself (farm erosion).

f. Food Security Analysis - This is one of the major concerns and the type of analysis required in the Physical planning exercises now actively done in the Philippines. This particular analysis define the potential population carrying capacity of each of the administrative regions in the country.

2. On the Promotion of Sustainable Agriculture and Rural Development

It is estimated that by the year 2025, some 83 percent of the expected global population of 8.5 billion will be living in the developing countries. The enormous demand for food supply is a major challenge and will in fact put into acid test the
extent of global cooperation obtainable from each of the countries of all economic structure. Agricultural areas in all countries will be important in this global need for adequate and culturally-appropriate food supplies. Considerable efforts will be done for the soil conservation and fertility rehabilitation in most tropical countries since most agricultural activities in the future will involve significant upland marginal agricultural areas. The Philippines for instance, will have to contend two distinct problems of development: land use conversion and the increasing use of sloping lands. Under this conditions, the role of ground soil survey will be crucial to physical and land use planning.

The holistic approach for Sustainable Agriculture and Rural Development is formulated by the FAO and is illustrated in Figure 2. In summary the holistic approach requires four major considerations to attain sustainable agriculture and a balance rural development, as follows:

a. Natural resources management, with key efforts on residue recycling, appropriate and sustainable farming systems;
b. People's participation, which encourages farmer's organization to play a key role in land resource management;
c. Organization and support, where efforts on the entire exercises are institutionalized through appropriate flow of information from the farmer to the appropriate channels and the simultaneous strengthening of organizations and institutions.
d. Human resources development (People empowerment), where people are given broader access to information and were made as stake holders in the sustainability of the entire rural-agricultural integration mechanisms.

The results of the soil resources and landuse survey are credited by being the primary source in the identification of the Key Production areas (KPA). The KPA formalize the agenda of the Department of Agriculture in prescribing the simple instruction of putting land to best use where it was prescribed to plant the right crops in the right location. The resulting locations of the KPA for rice and corns areas are shown in Figure 3.
Figure 2. The Holistic Implementation of IPNS for Sustainable Agriculture and Rural Development.

3. On conservation of biological diversity

The ever increasing global populations and associated pressure on resources constitute a very serious threat to biodiversity conservation. The world’s biological diversity is threatened by over-harvesting, pollution, and the inappropriate introduction of foreign plants and animals. For instance, in the Philippines, the introduction of the Golden snail has become a serious problem in the rice growing provinces and lately, the introduction of the African catfish is creating apprehensions because of its threat to the local catfish. Several soil flora and fauna are known to be sources of pharmaceutical products and alternative sources of pesticides. Soil microbiological studies can become very important element of soil survey classification and characterization especially in our interests to include organic forms of fertilizers in our food security and crop production efforts.

Conclusions and Recommendations

1. Soil survey and characterization programs will need to review its minimum data sets in order to satisfy the cross-sectoral issues brought about by the concerns of Agenda 21 on Sustainable Agriculture and Rural development.

2. There is a need to establish a Global Network of Protected areas for Agriculture, Fisheries and Forestry to ensure global food security and sustainable development.

3. Country programs for soil survey and characterization must provide an understanding on the various soil ecological processes and responses to various technologies needed for the successful implementation of Sustainable development.
4. There is an urgent need to establish an international network of soil survey to establish the extent and location of human-induced soil and land degradation in support to the food security efforts of many developing countries.

5. Soil survey must play a central role in the establishment of balance fertilization guide for sustainable agricultural development.

6. Soil survey must play active roles in the formulation of environmental impact assessment as well in the disaster management.
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L' Evolution de la Coverture Pedologique et sa Distribution Spatial Dans une Region Montagneuse


Introduction. La Transformation de l'environnement par l'activité humaine provoque des modifications de la couverture pedologique et des changements constituent la recherche d'un nouvel équilibre naturel dans le rapport sol-paysage.

L'étude de ces portions du territoire est compliqué par la forte hétérogénéité édaphique en associée, dans ces conditions, la cartographie horizontale ou de volumes pédologiques (1) nous permet une meilleure compréhension des processus responsables. Le sondage par des transectes permet de diminuer le travail sur le terrain sans effectuer la précision des résultats (3); une fois les principes qui contrôlent la distribution spatiale des sols établis, il est possible de développer des modèles qui expliquent leur évolution et d'utiliser cette information pour l'étude d'autres territoires (2).

Ces critères ont été utilisés pour étudier une région agricole localisée dans la Sierra d' Arteaga (nord du Mexique) dont la topographie et l'abandon des parcelles sont à l'origine de l'érosion des sols et leur accumulation dans les parties les plus basses.

Matériels et Méthodes. Dans une portion de 4 ha (200 x 200m) nous avons tracé une maille de 40 x 40m. des sondages à la terre jusqu'aux 120 cm de profondeur ont été réalisés dans chacune des 36 intersections résultantes; des sondages additionelles nous ont permis d'établir une carte d' horizons. A partir de cette information et des sondages de vérification localisées par la méthode de cartographie libre, nous avons élaboré la carte de sols pour une surface de 60 ha. La mise au point des principes qui contrôlent la distribution spatiale des sols nous a permis, dans une troisième étape, de réaliser la carte des sols pour une surface de 400 ha, en appliquant des méthodes phisiographiques et des vérifications ponctuelles.

Résultats et Discussion. A partir des sondages cinq volumes pédologiques ont été identifiés: les vols 1 et 2 sont des sols calcaires a forte pierrosité et avec une texture moyenne; les vols. 3 et 4 sont formés par des conglomérats a couleur brun rougâtre, une moyenne pierrosité (15%) et une texture fine; Le vol. 5 est constitué par des alluvions et il présente une faible pierrosite, une granulométrie moyenne et la couleur est brun foncé. La présence ou l'absence de ces volumes, ainsi que leur position dans le profil, leur épaisseur et la combinaison entre eux, nous permet de développer des modèles d'évolution des sols identifiés.

Littérature Citee.
Formation and Classification of Anthrosols: China's Perspective

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Introduction. Human activity as a soil forming factor besides climate, vegetation, parent material, topography and time has been long recognized (1,2). In many places of the world, especially in ancient agricultural countries with long cultivation history, artificial transportation, tillage, fertilization and irrigation accelerated or retarded even negated natural soil forming processes, formed an unique soil type which is different from its counterparts of the same region, while original soils exist as buried soils or get strong modification in properties. This type of soil was considered as produced by human activities. Thus, definitively, anthrosols is the soil which get strong influence or was made out by human beings, possesses human-induced morphological features and chemical/biological properties, and must have specific anthric horizons and distinguished properties different from that of original soils.

Anthric soils were admitted in many classification systems. For example, as early in 1930's, Chinese soil scientists pointed out that paddy soils was an independent type of man-made soils (3). In 1978, irragric and tieric soils were set up as man-made soils (4). In the newly established Chinese Soil Taxonomic System (CSTC) (5), a separate soil order--Anthrosols was included in, it contains various anthropogenic soil types. Soil Taxonomy (6) set up anthropic epipedon to deal with anthropogenic soils in various levels of different soil orders. Soil Map of the World established Anthrosols in 28 major soil groupings (7). Two newly proposed Russian soil classification systems both included anthropogenic soil order/anthri-accumulative soil order(8,9). Updated German classification also founded terrestrial anthropogenic soils and semi-terrestrial anthropogenic soils (10). British soil classification system also set up diagnostic horizons of man-made soils:"thick anthropic A horizon" and "arrenic subsurface horizon" (11).

Distribution of anthric soils concentrate in regions of heavy human activities. Among them, 90 percent of paddy soils (most of them can be attributed to Hydragric soils) are in Asia, especially in the Yangtze and Pearl river deltas of China, the Ganges river delta and lower reaches of India and Bangladesh, while irragric mainly in inland of northeast China, the banks of the Nile River in Egypt, the mid-west Asia. As to cumulic, fimic soils, distribute mainly in plain areas with long agricultural history and suburbs of metropolis, such as European plain and the Wei river plain of China, and fimic soils of America and New Zealand are related to the habitats of aboriginal. The global distribution of Anthrosols is shown by the sketch map followed (Figure 1).

Formation and Classification. Formation of anthrosols was the result of human

a) Supported by the National Nature Science Foundation of China
activities, which have many forms since the very beginning of ancient agriculture, for the sake of sustaining even increasing soil fertility. These activities included classical terracing, stone clearing, strip cropping, bounding, and modern empoldering, silt accretion, dune stabilization; irrigation and drainage; application of organic and inorganic fertilizers; addition of chemical amendments (e.g. liming to acid soils, gypsum to saline-alkaline soils); land fixation, structure improvement by chemical products; modern tillage by heavy machinery. Anthropedogenesis represents the soil process occurred during these activities. The results cover the alienation of soil morphology, deepening of soil horizon, increase of soil nutrition, improvement of soil structure, increase of water supply and amelioration of adverse factors. Sometimes, soils were simply created in some places.

Anthropedogenesis could be divided into several types according to their expressions and natures. As for the formation of anthric soils, there are mainly four leading activities play determine roles, i.e., irrigation-accumulation, cumulative build-up, fimic process and wet cultivation.

Irrigation-accumulation is a ripening process occurs in the arid region by introduction of large amount of irrigation water containing suspended materials. In the arid land with annual precipitation less than 200 mm, irrigation water amounts to 9000-12000 cubic meter per hectare, which is 5-6 times of rainfall, it brings 3-7 tons/ha of sediments yearly, i.e., annual rise 2-6 mm. It forms deep irrigric horizon on original soils, and new soil structure and porous condition get developed with the disappearance of sedimentary stratification and the increment of soil fertility, under long-term intensified tillage and fertilization (12). Meanwhile, the accumulation of

Fig. 1. Sketch map of the global distribution of Anthrosols
organic matter and nitrogen, phosphorous in soils change their profile distribution function, which are even usually for well developed irrigagic soils. So do soil color, structure and texture. Fragments of coal, bricks and other artifacts as well as more worm holes and caste may appear in the profile.

Cumulative build-up is a ripening process occurs by the application of large amount of manured soil or soil rich in organic matter or other mud, through long-term cultivation. Generally speaking, there are several possible reasons for accumulation. (1). Deepen soil layer and improve nutrition supply; (2). Resist soil erosion process, especially in the Loess Plateau in northwest China; (3). Lower underground watertable, which is the usual case in the boggy and delta regions(13). In the process of accumulation, the amount of added materials possibly amounts 500-1000 tons per hectare in a year, which augment soil layer rapidly and may form a surface horizon more than 50 cm in several decades. It forms deep surface horizon on original soils. As the thickening of cumulated horizon, original plough and plowpan layers were buried, and above them formed new plough and plowpan (14). The properties of cumulated surface horizon are influenced by added materials.

Fimic processes is a ripening process occurs by the long-term application of soluble organic materials (e.g. human waste) and organic trash or manure, through intensive cultivation and frequent irrigation. Different from cumulative process, human influence on fimic process mainly expressed in the modification of soil properties, for example, the enrichment of phosphorous is determined by guided cultivation. Artificial guided cultivation accelerates alienation of various soils, and correspondingly, weakens the influences of nature. It forms darker surface layer rich in nutrition elements, and it is often connected with vegetable plantation. Soil properties get strong modification through above mentioned practices. Also, due to the characteristics of nutrition absorption of vegetable, the enrichment of elements has special regularities(15).

Hyd: agric ripening process is the result of rice plantation with wet-cultivation. Due to the requirement of rice growing, soil moisture meet "anthraquic" regime. In rice season, soil undergoes a series of tillage practices in surface management, such as leveling, puddling, fertilization and inter-tillage, periodic irrigation and drainage.

The basic reasons for including paddy soils as anthric soils lie in their man-induced soil forming factors, soil processes and unique soil properties. Viewed from soil forming conditions, regional differences of climate minimum due to long-term irrigation and smooth soil temperature change; soil microorganisms get accustomed to anaerobic condition; intensive cultivation and wet-dry alternation accelerate the activation and migration of soil components thus fasten the differentia of soil horizons. Viewed from soil genesis, soil processes taken in paddy cultivation include: rapid changes of physical-chemical properties such as Eh,pH, because of water saturation and reduction derived from anthraquic condition(16); activation and movement of elements due to chemical processes like dissolution, reduction, chelation and ferrolysis(17,18); re-oxidation of reducing substances after drainage; movement of fine soil particles (fine silt and clay); decomposition and re-synthesis of clay minerals.
It's necessary to point out that not all soils used for paddy be named "Hydragric Anthrosols". Only those have anthraquic moisture regime and have the development of plowpan and redoxic illuviation horizon could be called Hydragric Anthrosols, which are basically different from original soils (19).

Anthropedogenesis might co-worked in the formation of anthrosols. For example, there is also human addition of manured materials to soils when irrigation accumulation happens in some cases. Irrigation sediments also plays a role in the evolution of paddy soils in near river banks. Common features of anthric soil forming processes are expressed as follows:

1. Soil forming condition. Human factors outdo natural soil forming factors in much great extent in some occasions. The differences of climate (esp. rainfall), vegetation, parent material and topography are diminished due to artificial addition, irrigation, cultivation and land leveling.

2. Soil forming process. Rate and strength of soil development caused by human activities surpass that by natural pedogenesis. Characteristics of material cycling is also changed by fertilization and special culture, such as vegetable planting.

3. Soil properties. Human beings cultivate soils according to their own demands, which make soils have deep anthropogenic epipedon and unique physical, chemical, mineralogical properties, moreover, higher productive capability than original soils. Also, generally, soils contain more artificial intrusions.

Classification of anthrosols is based on the establishment of anthric horizons, i.e., irragric, cumulic, fimic and hydragric horizons, which are corresponding to the above mentioned anthric soil forming processes (5, 20). Cumulic horizon comprise plaggic and tieric horizons, they are different in resource materials, the former appear constantly in west Europe and later popular in northwest China. The diagnostic properties of these horizons are summarized as follows.

Irragric horizon is a surface horizon formed through gradual deposition of suspended particles during long-term irrigation and mixture of cultivation. Influenced by tillage, the sedimentary stratification disappeared. Usually, it has a clear lower boundary with buried original soils. It meet the following conditions:

1. A thickness of 40 cm or more with clear lower boundary.
2. Even distribution of clay and carbonates in profile, uniform texture in all sub-horizons, among fraction of 0.25-0.05 mm, 0.05-0.01 mm, 0.01-0.005 mm there is at least on fraction in which the maximum contents is less than 1.2 times that of minimum contents in all sub-horizons.
3. Has rounded or semi-rounded block mass of fine earth.
4. The weighted average organic matter content is more than 0.8 percent, and it decreases with depth, but at least 0.5% at the bottom.
5. No soluble salts.
6. Plenty of coal cinders, charcoal, brick or tile fragments and other artifacts through the horizon.
7. Available P,O, (0.5 M NaHCO,) is less than 100 mg*Kg' within 20 cm from the
Tieric Horizon is a surface horizon formed by long-term cultivation, application of manure or soils rich in organic matter or other mud. In different periods, materials used were different in color and texture, so the whole pedon show obvious "tieric" parallel layers. Organic matter content and soil color are depended on the resource. Tieric horizon meets the following requirements:
(1). A thickness of 40 cm or more with clear lower boundary.
(2). Has a non-uniform particle-size class with depth; the horizon may contain stones, randomly sorted and distributed.
(3). Organic matter decreased with depth, weighted average content is more than 0.8%.
(4). Has fragments of cinders, charcoal and other artifacts.
(5). Available $\text{P}_2\text{O}_5 (0.5 \text{ M NaHCO}_3)$ content is less than 100 mg*Kg$^{-1}$ within 20 cm from the surface.

Plaggic horizon is a surface horizon formed by application of sods and manure containing plant residues and insoluble mineral particles or abandoned materials. It meets the following requirements:
(1). A thickness of 40 cm or more with clear lower boundary.
(2). A uniform texture with depth, usually sandy or clay-sandy.
(3). Weighted average content of organic matter is more than 1.0%.
(4). Granular structure and soft consistency.
(5). Darker color, usually brown or gray.
(6). Has many artifacts.

Fimic horizon is a surface horizon formed by long-term application of human and animal wastes and other organic residues, under intensive fertilization and irrigation. With time going, the surface becomes soft and fluffy and has the appearance of well decomposed manure. It meets the following requirements:
(1). A thickness of 40 cm or more with vague lower boundary.
(2). Weighted average content of organic matter is more than 2.0%.
(3). The color value and chroma is 3 or less.
(4). Has a base saturation of 50% or more.
(5). Has more than 10% by volume of worm holes and worm castes.
(6). Has fragments of pottery, cinders and other artifacts.
(7). Available $\text{P}_2\text{O}_5 (0.5 \text{ M NaHCO}_3)$ is more than 100 mg*Kg$^{-1}$ within 20 cm from the surface.

Wet cultivation result in the formation of not only special surface horizon also subsurface horizon, i.e. Ap and B horizons, these two horizons make up "hydragric horizon sequence". Only both horizons exist can hydragric horizon be established. Ap: A surface horizon formed under wet cultivation and periodic submergence. Original soil structure is destroyed and new horizon is puddled. It meets:
(1). A thickness of 18 cm at least.
(2). The upper part is pudding for at least one month or more due to wet cultivation.
when soil temperature is more than 5°C.

(3) Soil saturated and in reduction for at least 90 days due to artificial submergence when soil temperature is more than 5°C.

(4) Has plenty of rusty streaks after drainage; has rusty spots on the void walls or on ped-faces, or with hue 2.5Y or yellower and the moist chroma is 2 or less at the bottom of plow layer.

(5) The ratio of bulk density of plowpan to that of top layer is more than 1.2 when drained.

Bm/Br/Bg: A subsurface horizon underlying Ap2, formed through translocation and illuviation of materials (Fe, Mn, clay) within pedons. It meets:

(1). A thickness of 12 cm or more.
(2). Redoximorphic features in pores such as coatings or grayed halos with hue 2.5 Y or yellower and chroma of 2 or less.

or

(3). Oxymorphic segerations of iron and/or manganese in the matrix.

or

(4). Dithionite citrate bicarbonate extractable iron and manganese is 1.5 times greater at least than that of Ap1 horizon.

B horizon may not appear directly under Ap2 horizon, sometimes it appear under an iron-depleted subhorizon which underlying Ap2 horizon and in which DCB extractable iron is much lower.

The relationship among these anthric horizons and their comparison could be summarized as in Table 1.

<table>
<thead>
<tr>
<th>Horizon Type</th>
<th>Formation Processes</th>
<th>Chief Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Art. add</td>
<td>Irrg. add</td>
</tr>
<tr>
<td>Cumulic</td>
<td>+++</td>
<td>++</td>
</tr>
<tr>
<td>Fumic</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Irragric</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Hydragric</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

The classification of anthrosols were based on the above listed anthric soil horizons, thus could be arranged as the following key:

- Anthrosols having a hydragric horizon sequence.
  - **Hydragric Anthrosols**

- Other Anthrosols having a irragric horizon.
  - **Irragric Anthrosols**

- Other Anthrosols having a plaggic or tieric horizon.
  - **Cumulic Anthrosols**

- Other Anthrosols.
  - **Fimic Anthrosols**

There are lots of soils which are affected by human activities but had not gained enough changes necessary for the recognize of Anthrosols, these soils are grouped in other major soil groups as lower units. For instance, soils showing evidence of deep
cultivation or deep mixing might be included in aric Regosols taxa.

**Distribution.** China has various anthric soil types which relate different soil management measures and they distribute widely over the country. Irragric Anthrosols usually appear in river branches or canal flood area of arid region, in which large amount of irrigation water is used. In China, they focus in Ningxia, Gansu and Xingjiang provinces, through the long-term introduction of water from the Yellow River or from melted glaciers of the Tianshan Mountains. Oasis agriculture builds heavily on irrigagric anthrosols in arid-desert area. Cumulic Anthrosols raised also in arid-semiarid northwest China, especially in loess region, where farmers use great amount of manured material to field, 'tieric' layers form rapidly. In cultivated delta or bog area, cumulic horizon may also form for the sake of artificial build-up to lower groundwater table. Hydragric Anthrosols are transformed from their original soils by wet cultivation, they developed from mainly three kinds of origins, i.e., alluvial materials, bog and zonal soils, especially in south and southeast parts of China. As for Fimic Anthrosois, they often are associated with intensified organic and inorganic fertilizers in urban area of cities, showing strong enrichment of some nutrient elements such as P and S. There is also study indicated that the fmic layer existed in ancient habitats. Generally, the distribution area of all kinds of anthric soils could be expressed as Table 2. A expansion of distributing area of anthric soils can be seen since 1950's, which mean a stronger human-induced changes of natural soils after 40 years.

<table>
<thead>
<tr>
<th>Soils</th>
<th>Main distributing region</th>
<th>area in 1950'(M ha)</th>
<th>area in 1990'(M ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydragric</td>
<td>South China(delta, low hills)</td>
<td>11.4</td>
<td>12.7</td>
</tr>
<tr>
<td>Irragric</td>
<td>Northwest China(arid region)</td>
<td>0.52</td>
<td>0.66</td>
</tr>
<tr>
<td>Cumulic</td>
<td>Northwest(Loess plateau)</td>
<td>0.49</td>
<td>0.49</td>
</tr>
<tr>
<td>Fimic</td>
<td>Sparsely in urban places</td>
<td>--</td>
<td>0.10</td>
</tr>
</tbody>
</table>

**Prospect and Research Needs.** Because of increasing food supply press faced by expansion of population, land reclamation and intensive use of soils are constantly needed, which might be reflected by the increasing area of human-affected soils, and most importantly, changes in soil properties especially those relate human health. These changes lead to deep-going modification of soils, by inevitable introduction of heavy metals, residue of pesticides, sludge, excrements from agriculture and husbandry and anthropogenic radioactive elements such as \(^6\)K, \(^8\)Rb, \(^86\)Po, \(^226\)Ra, \(^232\)Th, \(^238\)U from industry or nuclear test. Investigation showed Zn content in aged garden soils tripled that of original soils. It is of great priority to study material transfer through human-soil-plant system and their feedbacks with outer water/atmosphere environment, and more, technologically produced new soil types and their positions in an altered land cover.

Anthropogenic effects of increasing introduction of chemicals usually give no sign to

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soil morphological features thus no new morphologically altered horizon, but may change inside measurement of soil properties to a great extent. Chemically degraded soils have a fast expansion over the past several decades globally, the results cover acidification of soils, contamination of soils by harmful compounds, etc.. The consequences of these changes are diverse and many-sided, influencing the ecosystem as a whole and the status and sustainability of renewable natural resources. It should be considered for soil taxonomists that the establishment of some contaminated or acidified lower soil units within Anthrosols in a long-run.

Technologically produced soils also include those newly formed soil-like surface formations, such as land fills, mine spoil, urban fill, garbage dumps, dredging. These formations have not been subject to a sufficient period of time for pedogenesis, should not be grouped in Anthrosols until anthropopedogenesis has taken place. However, opinion existed indicating newly formed Replantozems and Construcozems as a part of anthropogenically transformed soils(2). Anyway, it can be predicted that stronger human activities, which have both positive and negative environmental consequences, will overlap their works to natural soil forming processes, and their results will confront soil classification system constantly.

Sediments Properties from San Josecito Cave, Nuevo León, México

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Abstract. Paleosols and cave sediments often represent an excellent record of past environmental conditions over a certain period of time. Reconstruction of paleoclimates from such environments requires a complete understanding of both fossil remains and surrounding sediments. San Josecito Cave located in Nuevo León, México is a paleontological site with well-known late Pleistocene fauna. To complement the information obtained through a comprehensive faunal analysis, the morphology, micromorphology, and the chemical and mineralogical properties of selected strata of San Josecito cave dated between 40000 to 25000 years B.P. have been described. The results indicate that the cave sediments have originated primarily from dissolution of limestone and breccia, and neoformed minerals (mostly varieties of apatite). Evidence of allochthonous material has not been found. Despite limitations, analysis of cave sediments can be a useful tool in determination of origin of the sediments.

Introduction. A clearer understanding of the forcing mechanisms and natural feedbacks of the glacial-interglacial cycles of the Quaternary period, including the role of hydrology, ocean circulation, and the biota, will clarify the understanding of the response of the Earth system to changes in radiative forcing -- an issue that is at the center of modern-day concerns about greenhouse warming (20).

Sedimentological studies have played a minor role in the interpretation of prehistoric cave sites prior to the 1950s (7). However, new developments in sedimentology have provided techniques that allow analysis of fine sediments from such environments. The goal of such studies is the interpretation of the paleoenvironment, and specifically the paleoclimate, under which the cave deposits accumulated (8). An independent source of information on paleoclimate is desirable to supplement interpretations based on fossil faunas. The sedimentary framework in which the bones occur is always present and has been found to be quite suitable to paleoclimatological interpretation in certain areas (14).

Paleosols represent an excellent record of past environmental conditions, usually integrated over a certain period of time. Soils generally respond to climate change somewhat slower than biota but are probably a better reflection of the regional climate than pollen, which seems to show considerable variation over a short time range (28).

Recent studies on soil dynamics are gradually assembling quantitative data on the state of soil formation and rates of changes of soil when subjected to new environmental conditions (28), but much remains to be done in this respect. Certain attributes like organic matter content respond rather rapidly (less than a hundred years) to change and may reach a steady state within a short time, while other attributes, like clay formation and clay movement, are relatively slow rate processes, and reach the steady state on the order of thousands of years.

The Late Pleistocene was a complex time of climatic shifts, changing faunal and floral communities, and impacted landscapes representing now extinct ecosystems. Climatic changes were initiated by global variations which resulted in deglaciation in North America. Localized fluctuations on a regional and microgeographic basis also were involved (19, 21). Therefore, the
building blocks toward understanding the Pleistocene and its environments must start with individual localities.

At the end of the Pleistocene, the Southern Plains ecosystem, mainly constituted by grassland vegetation, appears to have extended from southwestern Oklahoma and southeastern Colorado through western Texas and eastern New Mexico to the Texas Gulf Coastal Plains (16, 18) and into México through the Mexican Plateau, probably as far as the Valley of México (17). For the early or middle Wisconsin, however, studies of packrat middens (27) indicate a more humid environment prevalent prior to the beginning of the full glacial at 22,000 years B.P.; other studies, such as those based on paleofaunas (10, 13), seems to support this view.

The best database for Late Pleistocene climatic changes on the Southern Plains comes from the Lubbock Lake Landmark (15). This site, in the northern part of the region, has an extensive faunal representation for at least the past 12,000 years. Dry, U-Bar, and Pendejo caves (11, 12) have detailed records from 11,000 to 40,000 years B.P. in southern New Mexico. In order to work on a regional basis, a comparable time-transgressive database for the southernmost biotic section is needed. San Josecito Cave is one of a few localities available with a great potential for a detailed Late Pleistocene record in the area (2).

The general objective in this study is to develop a regional paleoclimate model dealing independently with both physical (sediments) and non-physical (fauna) aspects of the Earth system, and its integration into world-wide paleoclimatic models. The specific need is a detailed study of cave sediments in order to understand the different processes of formation and infer paleoenvironmental patterns from such processes. The hypothesis is that a complete sedimentological analysis would provide an independent data set for testing the assumptions of the paleoenvironment obtained through the comprehensive faunal analysis. This paper presents the properties of Late Pleistocene sediments from San Josecito Cave, Nuevo León, México.

Materials and Methods. San Josecito Cave is located on the western flank of the Sierra Madre Oriental in southern Nuevo León, México, at the edge of the Mexican Plateau at approximately 2240 m elevation (Fig. 1). It is about 1 km south of Ejido San Josecito, Municipio de General Zaragoza, at 23°57'21" latitude north, 99°54'45" longitude west. Precipitation is 800 mm and temperature averages range from 18°C in summer to 10°C in winter (23). Present vegetation is an oak and pine forest association. Soils around the cave are Lithic Hapludolls, which are shallow, dark soils overlying bedrock.

The cave is a single drop, multientrance fissure that occurs at the contact of folded and faulted Late Jurassic or Early Cretaceous limestone, including brecciated units. Dark limestone is found on the western side and on the ceiling of the cave while breccia was mapped in the eastern cave room wall (Stock, unpublished map). A sketch map (Fig. 2) documented that San Josecito Cave consisted of only one vertical room, 34 m long and 25 m wide, with three vertical shafts, two of which were high (30 m) above the present cave floor and the other consisted of a larger upper opening (20 m high) that probably served as the primary trap for the fauna. None of these entrances provided easy access today and probably did not in the past (2).

Personnel of the California Institute of Technology, under the direction of Chester Stock, excavated the upper part of the cave between 1935 and 1941 and recovered a rich vertebrate fossil fauna that included two species of reptiles, 52 species of birds, and 55 species of mammals, with at least 29 extinct species. Twelve extinct species were described, based on fossil specimens from this cave, including the great-footed extinct turkey (Meleagris crassipes) and the Pleistocene vampire bat (Desmodus stocki) (1, 24). The sediments studied by Stock (25) were younger than 25,000 years BP (9). Recent field observations by George Veni (personal communication, 1989) showed the presence of bones, mostly small, all along the wall of the subterranean shaft at the
Fig. 1. Geographic location of San Josecito Cave, Nuevo León, México (adapted from drawing made by Instituto Nacional de Antropología e Historia, México).
Fig. 2. Plan and profile of San Josecito Cave (adapted with permission from George Veni).
south of the cave (Fig. 2). These sediments indicate a detailed Pleistocene record remains to be studied.

Although fossil remains were relatively well studied, little was known about the provenance and deposition of San Josecito cave sediments. Stock (25: pp. 3) provided the only documented observation "The sediments consist for the most part of unconsolidated, grayish cave dirt, generally of a fine consistency. These deposits came from outside the cavern, and were either washed in or accumulated through aeolian action. Often thickly interspersed in these beds are fragments of limestone, varying greatly in size, that have fallen from the walls and ceiling." This observation was made for sediments above those selected for this study.

Test excavations were initiated in March and April, 1990, and a unit of 1 x 0.3 m (designated 533N197E) was used to square off the excavation grid at approximately 12 m deep of the original cave floor (3). The unit was located in the southern part of the room to the side of the eastern wall and adjacent to the north wall of a pit that made up the final test unit opened during previous excavations (named Stock's pit - Fig. 3). It was described and sampled down to 126 cm by stratigraphic levels. Sediments from each layer were collected for laboratory analysis. Samples from 12 layers were analyzed for selected physical and chemical properties.

Particle size distribution (PSD), except for samples for layers 810-780 and 695-650, was determined by a modified hydrometer method (5). The PSD analyses on samples 810-780 and 695-650 were determined by Laboratorio de Química y Suelos, Subdirección de Servicios Académicos, I.N.A.H., using a method based on settling time to determine clay and a 300-mesh sieve to measure sand. Sand fractionation was done by using nested sieves after removing carbonates with 10% acetic acid (HOAc). The pH, electrical conductivity (EC), and carbonates (CaCO₃) were analyzed following methods described in USDA Handbook 60 (26). Organic carbon was measured by chromic acid oxidation (22) and cation exchange capacity (CEC) was determined by the methylene blue method (4). The CEC was determined on whole samples and clays. X-ray diffraction (XRD) analyses were carried out on the clays from several layers. A Phillips-Norelco diffractometer, operated at 40 kv and 20 mA and with Ni-filtered Cu kα radiation, was used for the analyses.

Clays were separated for CEC determination and XRD after destruction of carbonates with 10% HOAc and removal of organic matter with hydrogen peroxide. After CaCO₃ and organic matter removal, the samples were dispersed using sodium hexamet phosphate. Clay samples were separated by sedimentation and repeated siphoning until the samples were essentially free of clay. Clays were oriented according to the method of Drever (6). One mount was saturated with Ca²⁺, dried at ambient temperature, x-rayed, then heated to 500°C for four hours, and x-rayed again. Powder samples, mostly sands, from selected layers also were x-rayed.

Optical studies of the very fine sand (0.05-0.10 mm) were carried out by mounting grains in oils with different refractive indices. Standard thin sections (30 μm thick) of undisturbed samples from selected strata were prepared and studied with a polarizing microscope. In addition, five samples from selected layers were dated radiometrically (¹⁴C).

Physical and chemical analyses were done in the Plant and Soil Science Department; XRD analysis was performed in the Geosciences Department, both at Texas Tech University.

Results and Discussion. Description of the layers studied reveal notable differences in color, texture, and consistence (Table 1). These differences arise primarily from the amount and kind of secondary mineral deposition. Weakly cemented layers impregnated with secondary CaCO₃, which had high value and low chroma, were found above the 630 layer, with the exception of the
FIG. 3. Stratigraphic profile of north wall of Stock's pit.
<table>
<thead>
<tr>
<th>Stratum</th>
<th>Depth (cm)</th>
<th>Range (cm)</th>
<th>Color</th>
<th>Texture</th>
<th>Consistence</th>
<th>Reaction to HCl(10%)</th>
<th>Boundary</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
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<td>810</td>
<td>00--10</td>
<td>8--10</td>
<td>10 YR 8/4</td>
<td>10 YR 8/4</td>
<td>CL</td>
<td>CM</td>
<td>AS</td>
<td>few black-stained bones</td>
</tr>
<tr>
<td>800</td>
<td>10--13</td>
<td>2--5</td>
<td>10 YR 3/3</td>
<td>L</td>
<td>CW</td>
<td>AW</td>
<td>few bones</td>
<td></td>
</tr>
<tr>
<td>790</td>
<td>13--15</td>
<td>2--4</td>
<td>10 YR 6/3</td>
<td>LS</td>
<td>CW</td>
<td>AW</td>
<td>few bones</td>
<td></td>
</tr>
<tr>
<td>780</td>
<td>15--16</td>
<td>1--4</td>
<td>5 BG 7/1</td>
<td>SL</td>
<td>CWCM</td>
<td>AW</td>
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<td>10 YR 7/1</td>
<td>SL</td>
<td>CW</td>
<td>EV</td>
<td>AW</td>
</tr>
<tr>
<td>760</td>
<td>18--21</td>
<td>3--5</td>
<td>10 YR 6/3</td>
<td>10 YR 7/1</td>
<td>SL</td>
<td>CW</td>
<td>EV</td>
<td>AW</td>
</tr>
<tr>
<td>750</td>
<td>21--24</td>
<td>1--5</td>
<td>7.5 YR 7/4</td>
<td>7.5 YR 5/4</td>
<td>SCL</td>
<td>CW</td>
<td>EV</td>
<td>CW</td>
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<td>24--35</td>
<td>9--15</td>
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<td>10 YR 6/1</td>
<td>SL</td>
<td>CM/DL</td>
<td>ES</td>
<td>CW</td>
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<tr>
<td>730</td>
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<td>4--10</td>
<td>10 YR 7/1</td>
<td>10 YR 7/2</td>
<td>SL</td>
<td>CM/DL</td>
<td>EV</td>
<td>CW</td>
</tr>
<tr>
<td>720</td>
<td>55--63</td>
<td>2.5--6</td>
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<td>10 YR 5/4</td>
<td>L</td>
<td>DL/DH</td>
<td>ES</td>
<td>AS</td>
</tr>
<tr>
<td>710</td>
<td>63--66</td>
<td>2--6</td>
<td>10 YR 6/1</td>
<td>10 YR 4/1</td>
<td>SIL</td>
<td>CW</td>
<td>AS</td>
<td>many bones</td>
</tr>
<tr>
<td>700</td>
<td>66--69</td>
<td>1--3</td>
<td>10 YR 6/1</td>
<td>10 YR 5/2</td>
<td>SL</td>
<td>CW</td>
<td>ES</td>
<td>AS</td>
</tr>
<tr>
<td>695</td>
<td>69--71</td>
<td>1--3</td>
<td>5 BG 7/1</td>
<td>7.5 YR 7/1</td>
<td>SIL</td>
<td>CW</td>
<td>ES</td>
<td>AB</td>
</tr>
<tr>
<td>690</td>
<td>71--73</td>
<td>1--2</td>
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<td>10 YR 5/2</td>
<td>SIL</td>
<td>CW</td>
<td>ES</td>
<td>AB</td>
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<tr>
<td>680</td>
<td>73--75</td>
<td>2--5</td>
<td>10 YR 7/3</td>
<td>SCL</td>
<td>CW</td>
<td>AW</td>
<td>few bones</td>
<td></td>
</tr>
<tr>
<td>670</td>
<td>75--77</td>
<td>2--5</td>
<td>10 YR 3/2</td>
<td>L</td>
<td>CW</td>
<td>AW</td>
<td>few bones</td>
<td></td>
</tr>
<tr>
<td>660</td>
<td>76--78</td>
<td>2--5</td>
<td>10 YR 6/2</td>
<td>10 YR 5/2</td>
<td>SIL</td>
<td>CW</td>
<td>AS</td>
<td>few bones</td>
</tr>
<tr>
<td>650</td>
<td>78--79</td>
<td>1--5</td>
<td>10 YR 7/2</td>
<td>SL</td>
<td>CW</td>
<td>AS</td>
<td>few bones</td>
<td></td>
</tr>
<tr>
<td>640</td>
<td>79--88</td>
<td>2--5</td>
<td>10 YR 8/1</td>
<td>10 YR 7/2</td>
<td>SL</td>
<td>CWCM</td>
<td>ES</td>
<td>AW</td>
</tr>
<tr>
<td>630</td>
<td>88--91</td>
<td>4--5</td>
<td>10 YR 5/4</td>
<td>10 YR 3/4</td>
<td>CL</td>
<td>CW</td>
<td>ES</td>
<td>AW</td>
</tr>
<tr>
<td>620</td>
<td>91--95</td>
<td>5--10</td>
<td>10 YR 6/1</td>
<td>10 YR 5/1</td>
<td>SCL</td>
<td>CWCM</td>
<td>EV</td>
<td>AW</td>
</tr>
<tr>
<td>610</td>
<td>95--101</td>
<td>5--10</td>
<td>10 YR 6/2</td>
<td>10 YR 4/2</td>
<td>SCL</td>
<td>DH/DVH</td>
<td>ES</td>
<td>AI</td>
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<tr>
<td>605(T)</td>
<td>101--118</td>
<td>7.5 YR 6/4</td>
<td>7.5 YR 4/4</td>
<td>SCL</td>
<td>DL</td>
<td>ES</td>
<td>AI</td>
<td>FEW BONES</td>
</tr>
<tr>
<td>605(M)</td>
<td>101--118</td>
<td>7.5 YR 6/4</td>
<td>7.5 YR 4/4</td>
<td>SCL</td>
<td>DL</td>
<td>ES</td>
<td>AI</td>
<td>FEW BONES</td>
</tr>
<tr>
<td>605(B)</td>
<td>101--118</td>
<td>7.5 YR 6/4</td>
<td>7.5 YR 4/4</td>
<td>SCL</td>
<td>DL</td>
<td>ES</td>
<td>AI</td>
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<tr>
<td>600</td>
<td>118--123</td>
<td>1--5</td>
<td>10 YR 3/2</td>
<td>CL</td>
<td>DL</td>
<td>CB</td>
<td>FEW BONES</td>
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</tr>
<tr>
<td>595</td>
<td>123--127</td>
<td>1--5</td>
<td>10 YR 5/6</td>
<td>10 YR 4/6</td>
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<td>DL</td>
<td>ES</td>
<td>CW</td>
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<tr>
<td>590</td>
<td>127--135</td>
<td>5--15</td>
<td>10 YR 5/6</td>
<td>10 YR 4/6</td>
<td>SIL</td>
<td>DSH</td>
<td>BM</td>
<td>AS</td>
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<tr>
<td>580(T)</td>
<td>135--144</td>
<td>1--15</td>
<td>10 YR 5/6</td>
<td>10 YR 4/6</td>
<td>SCL</td>
<td>DL</td>
<td>ES</td>
<td>AI</td>
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<tr>
<td>580(B)</td>
<td>135--144</td>
<td>1--15</td>
<td>10 YR 5/6</td>
<td>10 YR 4/6</td>
<td>SCL</td>
<td>DL</td>
<td>ES</td>
<td>AI</td>
</tr>
<tr>
<td>570</td>
<td>144--</td>
<td>10 YR 7/6</td>
<td>10 YR 5/6</td>
<td>SIL</td>
<td>DL</td>
<td>ES</td>
<td>AI</td>
<td>FEW BONES</td>
</tr>
</tbody>
</table>

Abbreviations for features: (Texture) L=loam, SiL=silt loam, SiCL=silty clay loam, SL=sandy loam, SCL=sandy clay loam, CL=clay loam; (Consistence) CM=moderately cemented, CW=weakly cemented, DL=dry loose, DH=dry hard, DVH=dry very hard, DSH=dry slightly hard; (Reaction to HCl 10%) EV=effervescence violent, ES=effervescence strong, EM=effervescence moderate; (Boundary) AS=abrupt smooth, AW=abrupt wavy, CW=clear wavy, GW=gradual wavy, Al=abrupt irregular, AB=abrupt broken, CB=clear broken.
layer, which had loose to very hard consistence. In contrast, sets of lamellae with intermediate value and high chroma and loose to hard consistence were found in the 610 and lower layers. It seemed that sediments of the upper strata were derived mostly from limestone, whereas the sediments of the lower layers were derived mainly from breccia. The contact between these two kinds of sediments was located between the 630 and 640 layers. Chemical, micromorphological, and mineralogical observations and coarse fragments of limestone and breccia in the 740 and 630 layers, respectively, supported this hypothesis.

The PSD of the samples studied is of limited value because CaCO$_3$ was not removed prior to analysis. Little correlation exists between the clay properties and whole soil CEC values, indicating that most of the clay-size particles are non-phyllosilicate minerals. In addition, little agreement is noted with the field texture (Table 1).

Chemical analysis showed that the pH was close to 8.0 and EC was lower than 0.8 dSm$^{-1}$ in all samples (Table 2). Organic carbon (OC) ranged from 1 g kg$^{-1}$ in the 760 stratum to 23.2 g kg$^{-1}$ in the 595 stratum. Unfortunately, the content of OC of layers with low chroma and value (usually indicative of higher organic matter content) is unknown because they were not selected for analysis. Although the OC of the limestone was relatively high and the OC of the breccia was very low, the OC content did not explain differences among layers (Table 2). These differences are likely due to biotic factors. The high CaCO$_3$ content in the limestone and breccia would be expected. Although some particles of the primary rocks occurred in the sediments, most of the CaCO$_3$ was of authigenic origin resulting in the formation of a tufa-like material, which often was mixed with apatite-rich materials. Values of CaCO$_3$ equivalent ranged from 248 to 648 g kg$^{-1}$. Moreover, these extreme values belonged to adjacent layers (750 and 740).

Considerable differences in the clay mineralogical composition of limestone and breccia are apparent. The CEC of the clay from the limestone is 3.5 cmol$_c$ kg$^{-1}$ while that in the clay from the breccia is 28.9 cmol$_c$ kg$^{-1}$ clay (Table 2). The CEC of the 640 stratum and upper layers (except for 700) varies from 11.4 to 15.9 cmol$_c$ kg$^{-1}$ clay, contrasting with the CEC of 630 and underlying layers which range from 8.0 to 22.3 cmol$_c$ kg$^{-1}$ clay. The higher CEC value of the 700 layer suggests a higher content of interstratified smectite/illite. The x-ray diffractogram of clay residue from the breccia (Fig. 4a) indicates that quartz (0.33 and 0.43 nm) dominates, followed by illite (1.01 nm) and smaller amounts of kaolinite (0.71 and 0.36 nm), smectite/illite (1.43 nm), and cristobalite? (0.40). This pattern is observed with some minor variation in diffractograms of clay from the lower samples. Goethite (0.42 nm) and lepidocrocite (0.62 nm) peaks are particularly prominent in the 580-590 and 630 samples, respectively. Hydroxyapatite diffraction (0.34 nm) is not as intense as in the diffractograms from the upper strata. The diffractogram of the clay extracted from the limestone (Fig. 4b) shows a broad, small intensity peak for illite and an intense quartz peak. Kaolinite and smectite peaks are not present. However, a rather sharp kaolinite and a cristobalite? peak are present in the 720 layer. Hydroxyapatite is especially prominent in the 640 and 720 layers and is small but distinct in the 700 and 650 layers.

The clay mineralogy of the upper horizons reflects a composition of the clay derived from both limestone and breccia. The CEC average is close to the mean value between breccia CEC and limestone CEC. Moreover, breccia is the only source of kaolinite. Simultaneous deposition of sediments derived from limestone and breccia could be possible as expressed by the strong contrast between the 760 and 720 layers.

Micromorphological descriptions indicate that fabrics of the upper strata differ from those of the lower strata. They are highly porous and contain many irregular vughs. They are characterized by a vo-cryptic fabric; random basic distribution, subcutanic referred distribution, and mostly vugh.
Table 2. Chemical and physical properties of sediments from selected strata.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Depth (cm)</th>
<th>PSD Sand(%)</th>
<th>Clay(%)</th>
<th>pH</th>
<th>CaCO3 (g kg⁻¹)</th>
<th>OC (cmolc kg⁻¹)</th>
<th>CEC(SOIL) (cmolc kg⁻¹)</th>
<th>CEC(CLAY) (cmolc kg⁻¹)</th>
<th>EC (dS m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>810</td>
<td>00-10</td>
<td>19.6</td>
<td>48.0</td>
<td>8.0</td>
<td>390</td>
<td>3.1</td>
<td>0.53</td>
<td>13.1</td>
<td>0.68</td>
</tr>
<tr>
<td>800</td>
<td>10-13</td>
<td>18.4</td>
<td>48.0</td>
<td>7.9</td>
<td>303</td>
<td>1.0</td>
<td>1.43</td>
<td>12.0</td>
<td>0.52</td>
</tr>
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<td>13-15</td>
<td>20.8</td>
<td>57.0</td>
<td>8.1</td>
<td>248</td>
<td>9.6</td>
<td>1.97</td>
<td>13.0</td>
<td>0.65</td>
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<td>15-16</td>
<td>35.1</td>
<td>37.0</td>
<td>8.1</td>
<td>548</td>
<td>5.9</td>
<td>0.49</td>
<td>13.0</td>
<td>0.58</td>
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<td>16-18</td>
<td>44.9</td>
<td>34.6</td>
<td>8.0</td>
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† Abbreviations: PSD=particle size distribution; OC=organic carbon, EC=electrical conductivity, CEC=cation exchange capacity. * reported PSD corresponds to residue after organic matter and carbonate extraction.
Fig. 4. X-ray diffractograms of clays saturated with Ca and solvated with glycerol.
A: lower layers, B: upper layers.
calcitans and few grain ferrans; many fine and very fine metavoids, and few to many fine and very fine sand-size apatite grains. Thin sections of the 770 through 750 layers show brownish, organic-stained calcitans, many fine voids, common partially decomposed bones, and a few apatite masses. Conversely, samples from the 740 and 730 layers have typical high birefringent calcitans around voids; many very fine voids; few bones; and many apatite masses. In contrast, the somewhat less porous lower layers exhibit crysyal fabric, banded and clustered basic distribution, and parallel referred distribution; many calcitans and brownish organic-calcitans, common grain ferrans; and many planar orthovoids. Apatite masses are common. Many partially to almost completely dissolved sparitic, fiber-shaped calcite crystals, and common partially decomposed bones are observed.

The grain (0.05 - 0.10 mm) mineralogy shows conclusively that the cave sediments have originated from two sources:
   (1) the residue from dissolution of the host limestone, including the breccia; and
   (2) neoformation.

Basically, four minerals occurred in the samples: calcite, apatite, quartz, and opaque Fe/Mn oxides. Calcite was destroyed by treatment with 10% HOAc to facilitate identification of the other minerals. Quartz was composed almost entirely of euhedral prismatic crystals and subhedral forms that occurred in the limestone and the breccia. Pitting, resulting from apparent dissolution, was common in some grains. Others were remarkably fresh appearing. Anhedral grains like many of those separated from the soil samples collected from outside the cave were extremely rare. Moreover, no feldspar, hornblende, or volcanic ash, which were identified in the "outside" soil, were identified in the cave sediments.

Conclusions. Mineral sediments in San Josecito Cave are composed of: (1) variable-sized fragments of primary limestone (including the brecciated unit); (2) residue from dissolution of the limestone; (3) authigenically formed calcite-cemented, tufa-like materials with varying degrees of porosity; (4) apatite-rich material likely formed in guano; and (5) mammal and bird bones. Individual layers are dominated by one or more constituents.

Both clay and very fine sand (0.05-0.10 mm) mineralogy indicates that additions to the mineral constituents from external sources have been very minimal, contrary to what Stock (25) proposed for the origin of the sediments. Morphological, micromorphological, chemical, and mineralogical observations indicate that the sediments of the upper layers, except for the 720 layer, are derived mostly from limestone and to a less extent from breccia, whereas the sediments from the lower layers plus the 720 layer were formed from breccia. The boundary of these sources is located between the 630 and 640 layers. Biological contributions (excreta and skeletal remains) have been also of considerable importance.

Despite limitations of this study, analysis of cave soils can be a useful tool in determination of origin of the sediments. This analysis, then, provides an independent data set for future testing of the paleoenvironmental assumptions obtained through comprehensive faunal analysis.

Acknowledgments. Funding for this study was provided by a 1993 Research Grant from the National Speleological Society to the first four coauthors. Other aspects of research on San Josecito Cave were funded by National Geographic Society (EJ), National Speleological Society (EJJAC), Cave Research Foundation (JAC), Instituto Nacional de Antropología e Historia (IN.A.H.), México, and the Graduate School and the Museum of Texas Tech University.
description of sediments was kindly provided by Mr. William T. Hartwell, formerly at Texas Tech University. The access and use of the XRD equipment and materials in the Dr. N. Guven's Laboratory, Department of Geosciences, is greatly appreciated. This manuscript represents part of the ongoing regional research of the Lubbock Lake Landmark into cultural adaptations to ecological change on the Southern Plains.

Literature cited.


Modelling Long Term Effects of Various Management Practices on Soil Physical Properties


Introduction. There is nowadays a growing interest in both agriculture and environment studies to investigate changes in the soil physical status as related to cropping pattern and techniques. Such changes are usually less obvious than similar modifications in soil chemical properties. This specific behaviour could be related to a more stable character of the soil physical characteristics, to difficulties in determining them on undisturbed samples, to their greater spatial and temporal variability, and also to more complex mechanisms of the interrelationships concerned. The objective of this paper is to suggest a model of the mechanisms involved and to show how some experimental results fit into the model.

The model. A summary of the suggested model, developed from some earlier versions (Canarache, 1987), is presented in Figure 1. The model includes management practices (cropping pattern, tillage, fertilization, irrigation etc) and their effects on root development, crop yields and plant residues (1), on humus and nutrient content, pH and other soil chemical properties (2) and on structure, tilth, water characteristics and other components of its physical status (3). Both chemical soil properties (4) and crop development (5) indirectly affect the soil
physical status, and both chemical and physical soil properties affect crop yields (6). Effects of initial soil properties and of seasonal weather conditions are also considered.

Experimental results (examples). Several long term field experiments have been selected from a more complete data base to show how the different mechanisms involved in the model could be described and quantified by stochastic equations (Table 1). Conventional digitizing of some of the experimental treatments and the discrete character of these conventional figures, although not convenient from a theoretical point of view, were considered acceptable in this case.

Table 1: Regression equations describing some of the relationships from the conceptual model in Figure 1.

<table>
<thead>
<tr>
<th>Location</th>
<th>Regressions equation</th>
<th>Corr. Coeff</th>
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<tr>
<td>Fundulea - Typic</td>
<td>( Y = 56 + 33 T_1 + 55 T_2 - 16 T_3^2 + 25 T_1 T_3 )</td>
<td>.91**</td>
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<td>Hapludoll, clay loam</td>
<td>( BD = 1.45 + .0011 Y - .68 \times 10^{-7} Y^2 )</td>
<td>.73*</td>
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<tr>
<td>Braila - Typic</td>
<td>( H = 1.85 + .32 T_3 - .057 T_4 - .049 T_4^2 + .021 T_1 T_3 )</td>
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<tr>
<td>Vermustoll, loam</td>
<td>( BD = 1.31 + .024 H - .0011 H^2 )</td>
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<tr>
<td>Urleasca - Oxiaquic</td>
<td>( BD = 1.48 - .27 T_4 + .18 T_5 + .065 T_5^2 - .064 T_6^2 - .022 T_3 T_6 )</td>
<td>.88**</td>
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</table>

\( T_1 \) - previous crop; \( T_2 \) - nitrogen; \( T_3 \) - rotation; \( T_4 \) - nitrogen + phosphorus; \( T_5 \) - kind of crop; \( T_6 \) - tillage; \( Y \) - yield, q.ha\(^{-1}\); \( BD \) - bulk density, g.cm\(^{-3}\).

In the Fundulea experiment, bulk density used as a parameter of the soil physical status is affected by the experimental treatments indirectly through a better crop development due to the presence of an improving crop in the rotation and to higher nitrogen application (mechanisms 1+5 in the model). A different mechanism (2+4) is to be noticed in the Braila experiment, where bulk density is indirectly affected through the effect of crop rotation and NP fertilization on soil humus content. A direct effect of specific management of various crops and of the tillage system on bulk density is described by data from the Urleasca experiment (mechanism 3).

Conclusion. The suggested model might be considered as a preliminary useful tool in describing in a coherent way the various mechanisms involved in alteration of the soil physical status under present-day (and perhaps future) agriculture practices, while a stochastic approach could be used to quantify these mechanisms.

Literature cited.
Model of physical and chemical processes in acid sulphate soils: principles, validation and application

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Abstract. Soil and water management are the key factors for sustainable use of acid sulphate soil areas for agriculture and nature development. Numerous complex physical and chemical processes are contributing to the genesis of acid sulphate soils and determine magnitude and rate of acidification or de-acidification and production/leaching of (toxic) compounds. Due to the complexity of physical and chemical processes in acid sulphate soils, prediction of effects of soil and water management and their practical consequences is only feasible by using simulation models. The principles of a simulation model for acid sulphate soils (SMASS) are explained. Further results of validation are presented, using measurements from undisturbed soil columns and field plots with both potential and actual acid sulphate soils, subjected to different water management strategies. The capability of the model is illustrated as a tool for evaluation of agricultural and environmental consequences of various water management strategies for an acid sulphate soil area in Indonesia. The validation showed a reasonably good agreement between measured and predicted pH, Al^{3+}, Mg^{2+} and SO_{4}^{2-} concentrations. Comparison of measured and predicted major ions yields a 1:1 relationship over a very wide range of concentrations. The pyrite oxidation could be predicted. Resulting pH-decrease and rise in Al^{3+} and SO_{4}^{2-} were reasonably well simulated. The examples of application showed how the model can be used to predict long-term effects of different water management strategies on changes over time and depth of element concentrations in the soil and of the contents of pyrite. Considering most relevant physical and chemical processes, the model enables to estimate progress and direction of the genesis of acid sulphate soils depending on the way of management. Agricultural and environmental consequences of management of acid sulphate soils can be evaluated. It is also shown how the model can be used to derive simple relationships or rules of thumb for specific situations.

Introduction. There are about 12 million ha of acid sulphate soils in the world [17]. These soils are found in coastal plains, with about 6 million ha in the humid tropics of Southeast Asia. Acid sulphate soils are formed in marine or brackish sediments in coastal plains, where sulphate from the seawater is reduced in the presence of organic matter to form pyrite (FeS_{2}). Acid sulphate soils have a favourable topography, suitable for (irrigated) agriculture. In addition, they generally occur near densely populated areas, which have a continuous pressure on land resources. The combination of favourable topography and population pressure would seem to make acid sulphate soils the logical solution to the problem of land shortage. However, these soils are problem soils. In their natural waterlogged and unripe state the soils have near neutral pH, but are unsuitable for agricultural use because of poor accessibility. Upon reclamation and in particular drainage, physical ripening and structure formation allow for penetration of oxygen into the soil, inducing oxidation of pyrite and acidification. A number of problems of chemical, biological and physical nature arise from this acidification: aluminum and ferric iron toxicity, decreased availability of phosphate, nutrient deficiencies, arrested soil ripening, hampered root growth, blockage of drains
by ochre and corrosion of metal and concrete structures [8]. Under these conditions, the diversity of crops that can be grown is restricted and yields are low. Moreover, the acid and toxic elements released adversely affect groundwater and surface water quality in and outside the reclaimed area. As a result, forest reserves and other ecologically valuable habitats located downstream of reclamation areas may be threatened.

Various international symposia and authors recognized the problems of acid sulphate soils and recommended adequate soil and water management as key measures for sustainable agriculture in acid sulphate soil areas [8,10,18]. Development of optimum water management strategies for new land reclamation projects or rehabilitation of existing projects requires knowledge about future consequences of the various possible water management options. Both the consequences for the local soil quality inside the reclaimed areas (agriculture) and downstream of the reclamation project (e.g. coastal mangrove forests) should be considered. Numerous complex physical and chemical processes are contributing to the genesis of acid sulphate soils and determine magnitude and rate of acidification or de-acidification and production/leaching of (toxic) compounds. Furthermore, the chemical processes may continue for a long time. For instance, complete oxidation of all pyrite present in a soil may take decades. Prediction of these slowly progressing complex chemical processes and their practical consequences is only feasible by using simulation models. Development of such models for acid sulphate soils was repeatedly recommended [8,10,18].

The objective of our study was to develop a computer simulation model for acid sulphate soils able to predict effects of water management strategies, such as drainage and irrigation, on acidification, de-acidification and release of toxic elements under various conditions of soil and climate [1]. This paper summarizes the basic principles and validation of the simulation model for acid sulphate soils (SMASS). Also its capability in evaluating agricultural and environmental consequences of various water management strategies for an acid sulphate soils area in Indonesia, is illustrated. The examples presented show how the model can be used to estimate progress and direction of soil genesis in acid sulphate soils, as well.

**Materials and Methods.** To obtain a simulation model for acid sulphate soils a joint Dutch-Indonesian research project was set-up in southern Kalimantan, Indonesia [1]. The project consisted of the following core activities: (i) column experiments, (ii) monitoring field plots, (iii) detailed experiments, (iv) model development, (v) model validation and (vi) model application.

(i) **Column experiments** aimed at studying basic physical and chemical processes to complete missing knowledge and to collect data for model calibration and validation. The experiments were carried out both in Indonesia and the Netherlands during two years and comprised seven undisturbed soil columns of 1 meter length and 25 cm diameter. Four columns contained sulphidic (potentially acid sulphate) soils and three columns ripe (actual) acid sulphate soils. The columns were subjected to the following hydrological conditions:
- drainage to study oxidation of pyrite and subsequent acidification;
- submerging/flooding to study reduction processes;
- leaching with fresh and brackish water to study the removal of acidity and chemical compounds.

Every fortnight the complete water balance, oxygen concentration, redox potential, chemical composition of soil moisture extracted from porous cups at five depths and element concentrations in drainage and ponding water were measured. In addition the initial and final soil properties such as texture, organic matter, pyrite, CaCO₃, and hydraulic characteristics were determined [1].
(ii) Monitoring plots have been installed on five different farmer fields located on both potential and actual acid sulphate soils on the Pulau Petak island, South Kalimantan, Indonesia. Research on these fields was carried out during three years and focussed on monitoring of main physical and chemical processes in acid sulphate soils at varying seasonal conditions and different water management alternatives. The sites were subjected to different hydrological conditions: tidal influence (daily flooding with brackish water) and little/no tidal influence (dropping water table in dry season, rising water table/flooded with both good and poor quality water in wet season). The same physical and chemical data as in the column experiments were collected with a frequency of every fortnight [1].

(iii) Detailed experiments have been carried out in addition to column and field experiments to quantify model parameters and to analyse phenomena and processes with specialist measuring techniques: oxygen diffusion coefficients, oxygen consumption rates of pyrite and organic matter, size/distribution of pyrite crystals and the nature of oxidation/reduction front in structured soils [1].

(vi) Model development was done including improvement and extension of existing soil water balance and solute transport submodels, development of an oxygen transport and a pyrite oxidation sub-model and a chemical submodel containing oxidation/reduction, complexation, adsorption/desorption and precipitation/dissolution processes [1,5].

(v) Model validation was extensively carried out by comparing model calculations with both results from the column experiments and with measurements from the monitoring field plots [1,2,6]. Additional validations were carried out specifically focusing on rates of pyrite oxidation and carbonate weathering [21] and oxygen transport and pyrite oxidation [6].

Here, four out of seven Indonesian columns, indicated as the columns 1 to 4, were used for validation. Columns 1 and 2 contained sulphidic (potentially acid sulphate) soil with pyrite from the soil surface downwards; while columns 3 and 4 were initially acid in the top (40 cm) and pyritic below. From day 1 until day 450, columns 1, 2, and 3 were subjected to drainage, keeping the groundwater table at 80 cm depth. During this period regular small irrigations with fresh (column 1) and brackish (columns 2 and 3) water were given to compensate for water losses by evaporation from the top and by soil moisture sampling. After day 450 the soil was submerged for one month with fresh (column 1) and brackish (columns 2 and 3) water. From day 480 onwards the columns were continuously leached with fresh (column 1) and brackish (columns 2 and 3) water, applying rates of 1 mm d\(^{-1}\) until day 500, 6 mm d\(^{-1}\) between days 500 and 715 and 12 mm d\(^{-1}\) from day 715 until 770. Column 4 was subjected to fresh water submergence from day 1 until 480. After day 480, the soil was leached with fresh water with the same leaching rates as the other columns.

Conditions in the columns differ considerably from those in the field. Owing to rather extreme water management practices applied, the concentrations of some major elements (Al\(^{3+}\), Mg\(^{2+}\), SO\(_4^{2-}\)) were much higher in the columns than in the monitoring field plots. To investigate the capability of the model under normal field conditions, SMASS was also extensively validated by comparing model calculations with two year measurements from the five field plots in Indonesia [1,26]. In this article only the validation by the field plot at Tabunganen will be presented. Tabunganen is located in the coastal plain close to the sea. The soil is potential acid sulphate, with pyrite up to the soil surface (Typic Sulfaquent), used for growing rice. The land is flooded daily with brackish water. Only during the dry period (two to three months a year), the groundwater table drops below the soil surface with a maximum depth of 15-20 cm below surface.

(vi) Model application aimed at the illustration of the capability of the model as a tool to evaluate
agricultural and environmental consequences of various water management strategies for an acid sulphate soil area [1,26]. Here, the Barambai area located in the coastal plain Pulau Petak, South Kalimantan, Indonesia, was chosen for this purpose. The area is a poorly drained backswamp, used for rice cultivation. It lies above springtide level and is not subjected to tidal flooding. Tidal movement only slightly affects the groundwater level. The area is submerged for about seven months of the year. The soil is a potential acid sulphate soil (Typic Sulfaquent) with a peaty topsoil of 15 cm and pyrite starting from 15 cm downwards. Every year in situ acidification due to pyrite oxidation occurs in the dry season because the groundwater level drops into the pyritic layer. Rice yields in this area are very low, sometimes only a few hundred kg per ha, because of acidification and release of toxic elements such as iron and aluminum in the dry season [2,16].

To apply the SMASS model in a specific area, various model parameters have to be quantified for the prevailing local conditions in that area. Methods of determination and values for each required model parameter for the Barambai area, are described in [1]. Because pyrite is present close beneath the soil surface, and water for water conservation is not available during the dry season, new water management strategies should generally aim at improved drainage and deeper groundwater levels to enhance removal of pyrite from the soil profile by oxidation. The following water management strategies were selected for further evaluation:

1. Continuation of the present water management;
2. A drainage strategy with a groundwater level of 40 cm below the soil surface throughout the year;
3. A drainage strategy with a groundwater level of 60 cm below the soil surface throughout the year;
4. A moderate drainage strategy with a groundwater level of 40 cm below the soil surface during the dry season (145 days) and above the soil surface in the wet season (220 days);
5. A moderate drainage strategy with a groundwater level of 60 cm below the soil surface during the dry season (145 days) and above the soil surface in the wet season (220 days);
6. A combined drainage/irrigation strategy with a groundwater level of 40 cm below the soil surface throughout the year (equal to strategy 2), combined with irrigation with good quality water at the end of the wet season (90 days, pH 5, 30 mm d⁻¹). This good quality water is available at present in the tertiary canals at the end of the wet season, but is not yet been used for irrigation.

The strategies 1 to 5 were evaluated for the future development of the pyrite profile in the soil. The strategies 1, 2 and 6 were evaluated for the course of pH and aluminum concentration at a depth of 5, 25 and 65 cm.

Model principles

General. The computer simulation model SMASS consists of a number of mutually linked sub-models in which the various physical and chemical processes occurring in acid sulphate soils are described with mathematical equations (Fig. 1). To solve these equations, the soil profile is divided into compartments which may be of variable size (Fig. 2). The initial physical and chemical conditions in each compartment must be given as model input. For the complete simulation period, values for the boundary conditions, as given in Figure 1, are required as input as well. The physical and chemical conditions in each compartment, together with the water and solute fluxes at the boundary of the soil system are computed at selected time intervals. Figure 1 illustrates the sequence in which the various physical and chemical processes are computed:
The water transport submodel computes vertical water transport. This yields the water content profile in the soil. The air contents in the soil are complementary to the water content profile.
In the oxygen transport and pyrite oxidation submodel, air contents are used to compute oxygen diffusion coefficients in the air-filled soil macropores. Oxygen consumption values in the soil are calculated from pyrite and organic matter contents. Subsequently, the oxygen content profile in the soil macropores is computed.

Depending on the oxygen concentration at a given depth, the rate of pyrite oxidation at that depth is now calculated in the oxygen transport and pyrite oxidation submodel. For each depth, the oxidized amount of pyrite is converted into amounts of produced H⁺, Fe³⁺, SO₄²⁻. The remaining amount of pyrite in the soil is used for calculations in the next time step.

The solute transport submodel computes solute fluxes between soil compartments, in dependence on the calculated water fluxes (from step 1).

In the chemical submodel, first the production/consumption terms for the non-equilibrium processes (such as iron reduction) are calculated. Then the total concentrations of each chemical component are calculated in the soil compartments by summing for each component the production/consumption terms, the inflow/outflow (from step 4), and the total amounts at the end of the previous time-step. From these total concentrations, the equilibrium concentrations in the soil solution, the composition of the exchange complex, and the amount of minerals and precipitates are computed for each compartment.

Time steps for computations of the water and solute transport submodels are in the order of hours. Pyrite oxidation, oxygen profiles and chemical equilibria are computed once every day. The output of the model SMASS and its submodels is generally given on a daily basis. Model predictions can be carried out for one or more decades, so that the long-term effects of various water management strategies can be evaluated quantitatively. The model is described in detail in [1,5].

Water transport submodel and solute transport submodel. The water transport submodel is based on the SWATRE model [3,11]. SWATRE calculates one-dimensional vertical transient water flow in soils. The basic flow equation of SWATRE is:

\[
\frac{\partial h}{\partial t} = \frac{1}{C(h)} \frac{\partial}{\partial z} \left[ K(h) \left( \frac{\partial h}{\partial z} + 1 \right) \right] - \frac{S(h)}{C(h)}
\]  

in which: \( h \) = soil water pressure head (cm), \( t \) = time (d), \( C \) = differential moisture capacity \( \partial \theta/\partial h \) (cm⁻¹), \( z \) = vertical coordinate (positive upwards) (cm), \( K(h) \) = hydraulic conductivity (cm d⁻¹), and \( S \) = water uptake by roots (d⁻¹).

Solving Equation (1) yields the flux of water through the upper and lower boundary of each soil compartment (Fig. 2). For the top and bottom compartment boundary conditions determine the flux at the upper and lower boundary of the soil profile. The complete set of equations is solved by an implicit finite difference scheme, applying a Thomas algorithm. With respect to the boundary conditions at the top (precipitation/irrigation, evaporation, evapotranspiration) and the bottom of the soil system (groundwater level, pressure heads, free drainage, fluxes) various options are possible, which makes the model flexible and generally applicable.

The solute transport submodel is based on the existing TRANSOL model [15]. Within the soil compartments (Fig. 2) complete mixing of the solutes has been assumed. For each compartment a mass conservation equation is formulated according to:
\[
V(n,t) \frac{dC(n,t)}{dt} + C(n,t) \frac{dV(n,t)}{dt} + q_{out} \cdot C_{out}(n,t) = q_{in} \cdot C_{in}(n,t)
\]

in which: \(C(n,t)\) = concentration of a solute in layer \(n\) at time \(t\) (mol cm\(^{-1}\)), \(V(n,t)\) = volume of water in layer \(n\) at time \(t\) (cm), \(q_{in}\) = incoming flux in layer \(n\) (cm d\(^{-1}\)), \(q_{out}\) = outgoing flux from layer \(n\) (cm d\(^{-1}\)), \(C_{in}\) = concentration of incoming flux (mol cm\(^{-1}\)), \(C_{out}\) = concentration of outgoing flux (mol cm\(^{-1}\)).

**Oxygen transport and pyrite oxidation submodel.** The principles of the oxygen transport and pyrite oxidation submodel have been outlined by [1,5,6]. In the model, it is assumed that in natural soils with pH-values of about 3 and higher, pyrite is mainly oxidized by oxygen via the following reaction:

\[
\text{FeS}_2 + \frac{3}{4} \text{O}_2 + \frac{1}{2} \text{H}_2\text{O} \rightarrow \text{Fe}^{3+} + 2\text{SO}_4^{2-} + \text{H}^+
\]

The fate of the produced \(\text{Fe}^{3+}\), \(\text{SO}_4^{2-}\) and \(\text{H}^+\) is considered in the chemical submodel. Neglecting oxidation by ferric iron is justifiable because above pH 3 ferric iron has a low solubility. Furthermore, oxidation of pyrite by ferric iron in natural soils will be inhibited by complexation of ferric iron by organic substances, as was found for sewage sludge [20]. Finally, in the case of pyrite oxidation by ferric iron, the concentration of ferric iron must be sustained by the oxidation of ferrous iron by oxygen, and thus oxygen is still the driving force for pyrite oxidation. In the model approach two main processes were distinguished: vertical diffusion of gaseous oxygen through air-filled macropores and lateral diffusion of dissolved oxygen from macropores into the saturated soil matrix (Fig. 3). The two processes interact at the walls of the macropores where gaseous oxygen dissolves into the matrix soil solution. The equilibrium between gaseous and dissolved oxygen at the walls of the macropores is described by Henry’s law: \([\text{O}_2]_{\text{water}} = K_H \cdot [\text{O}_2]_{\text{air}}\), in which \(K_H\) is Henry’s constant. This constant is temperature dependent. At 20°C, \(K_H = 29.7\), at 30°C, \(K_H = 52\).

In SMASS, the gaseous oxygen concentration profile in the air-filled pores is calculated by:

\[
\frac{\partial}{\partial x} (D_{\alpha}(x) \frac{\partial C_{\alpha}(x)}{\partial x}) = \alpha
\]

Fig. 3 Model approach for the distribution of oxygen in a structured acid sulphate soil, as applied in SMASS. Pyrite is still present in the anaerobic zones. \(R\) is the radius of the soil aggregates (m), \(r_a\) is the radius of the anaerobic zone (m).
where $C_a(x) = \text{concentration of O}_2 \text{ in air-filled macropores (m}^3 \text{ O}_2 \text{ per m}^3 \text{ air)}$, $D_s(\varepsilon_a) = \text{diffusion coefficient of oxygen in air-filled pores (m}^2 \text{ d}^{-1})$, $x = \text{distance (m)}$, $\alpha = \text{oxygen consumption rate in the soil (m}^3 \text{ oxygen per m}^3 \text{ soil per day)}$, and $\varepsilon_a = \text{air-filled porosity}$. The relation between diffusion coefficient $D_s$ and air content, $\varepsilon_a$, is described in the model by:

$$D_s(\varepsilon_a) = F(1 - (1 - \varepsilon_a)^{2.5})D_o$$

(5)

where $D_o = \text{diffusion coefficient of O}_2 \text{ in the atmosphere (m}^2 \text{ d}^{-1})$, $F = \text{an empirical tortuosity factor (dimensionless)}$ and $D_o = \text{oxygen diffusion coefficient in air (m}^2 \text{ d}^{-1})$. To solve differential Equation (4), the oxygen consumption term $\alpha$ must be quantified. In the model, oxygen is consumed by two processes inside the soil matrix: decomposition of organic matter and oxidation of pyrite. According to [5,6] the steady state diffusion equation for the aerobic part of the soil matrix can be written as:

$$D_w \frac{d^2C_w(x)}{dx^2} = \frac{0.311262 X_{FeS2}}{\rho d} \sqrt{C_w(x)} + Q$$

(6)

where $D_w = \text{diffusion coefficient of O}_2 \text{ in the soil matrix (m}^2 \text{ d}^{-1})$, $C_w = \text{concentration of dissolved oxygen (kg m}^{-3})$, $X_{FeS2}$ is the pyrite content (kg m$^{-3}$), $\rho = \text{density of pyrite (kg m}^{-3})$, $d = \text{average diameter of the pyrite crystals (m)}$, and $Q = \text{oxygen consumption rate by organic matter (kg m}^{-3} \text{ d}^{-1}$). According to Christensen $Q$ is taken constant [7]. Solving this equation with appropriate boundary conditions yields expressions for the steady state oxygen concentration profile in the aerobic part of the soil matrix, for the radius of the (an)aerobic zone, and for the total oxygen consumption per volume of soil. Subsequently this oxygen consumption is used to solve Equation (4) numerically.

The steady state oxygen consumption by pyrite oxidation is then computed as the difference between the total oxygen consumption and the (constant) oxygen consumption by organic matter. Next, from the stoichiometry of Equation (3) the amount of oxidized pyrite is computed, together with the produced quantities of $\text{Fe}^{3+}$, $\text{H}^+$, and $\text{SO}_4^{2-}$.

**Chemical submodel.** The important chemical processes occurring in acid sulphate soils are listed in Table 1. Pyrite oxidation is computed in the oxygen transport and pyrite oxidation submodel. All other chemical processes are modeled in the chemical submodel. This submodel is based on the existing EPIDIM model [12]. In the chemical submodel, changes in solution concentration, changes in adsorbed amounts, and changes in amounts of minerals and precipitates as a result of cation exchange and precipitation/dissolution reactions are calculated. Because cation exchange and precipitation/dissolution reactions are related to ion activities, ion association is considered as well. Each time-step, for each compartment, total amounts for each chemical component in solution and at the exchange complex are calculated from the amounts at the end of the previous time-step, the amounts released into the soil solution due to pyrite oxidation, and the net amounts transported to or from that compartment. From these total amounts, new concentrations, new adsorbed amounts and new amounts of minerals and precipitates are calculated.

Ion association and cation exchange are modeled as equilibrium processes, while precipitation and dissolution of minerals and precipitates are modeled as a kinetic process. The equations describing
Table 1 Chemical processes and their effects in acid sulphate soils. Processes included in SMASS are indicated

<table>
<thead>
<tr>
<th>Process</th>
<th>Effects</th>
<th>Included in SMASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate limited</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrite oxidation</td>
<td>acidification, produces Fe$^{3+}$ and SO$_4^{2-}$</td>
<td>+</td>
</tr>
<tr>
<td>Iron oxidation</td>
<td>acidification, lowers Fe$^{2+}$-concentration</td>
<td>-</td>
</tr>
<tr>
<td>Iron reduction</td>
<td>de-acidification, raises concentration of Fe$^{2+}$</td>
<td>+</td>
</tr>
<tr>
<td>Sulphate reduction</td>
<td>de-acidification, raises sulfide concentration</td>
<td>-</td>
</tr>
<tr>
<td>Weathering of primary minerals</td>
<td>produces base cations, consumes protons</td>
<td>-</td>
</tr>
<tr>
<td>Weathering of secondary minerals/precipitates</td>
<td>consumes protons, regulates Fe and Al$^{3+}$ concentrations</td>
<td>+</td>
</tr>
<tr>
<td>Instantaneous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cation exchange</td>
<td>buffers pH and determines concentrations of Ca$^{2+}$ and Mg$^{2+}$</td>
<td>+</td>
</tr>
<tr>
<td>Ion association</td>
<td>raises equilibrium concentrations, especially of Al$^{3+}$</td>
<td>+</td>
</tr>
</tbody>
</table>

these different processes, are solved simultaneously. In various application of the SMASS model precipitation/dissolution has been modeled for Al(OH)SO$_4$ (jarosite), Al(OH)$_3$ (gibbsite), Fe(OH)$_3$ (goethite), CaCO$_3$ (calcite), CaMg(CO$_3$)$_2$ (dolomite), and CaSO$_4$ (gypsum). If necessary for a specific situation, other minerals can easily be included as well. It has been assumed that the dissolution/precipitation rate of these minerals and precipitates is proportional to the difference between the actual activity product ($Q$) and its particular solubility product ($K_r$) (e.g. [14]). The rate expression is formulated as follows:

$$\frac{dB_i}{dt} = K(Q - K_r) - \frac{\theta}{\rho}$$

(7)

where $B_i$ = amount of a precipitate (mol kg$^{-1}$), $K$ = a rate constant, $\rho$ = dry bulk density of the soil (kg m$^{-3}$) and $\theta$ = volumetric water content. This differential equation is approximated with finite differences.

Because the concentrations of NO$_3^-$ in acid sulphate soils are often small and amounts of Mn(III/IV)-oxides are generally negligible, the most likely electron acceptor in redox reactions is Fe$^{3+}$. Reduction of ferric oxide is described by:

$$\text{Fe(OH)}_3 + \frac{1}{4}\text{CH}_2\text{O} + 2\text{H}^+ \rightarrow \text{Fe}^{2+} + \frac{1}{4}\text{CO}_2 + \frac{11}{4}\text{H}_2\text{O}$$

(8)

in which Fe(OH)$_3$ represents any reducible ferric oxide and CH$_2$O represents organic matter. In
SMASS iron reduction starts when a soil layer is saturated with water. The model distinguishes two forms of ferric oxides: reducible ferric oxide and non-reducible ferric oxide. Reducible ferric oxide is formed when Fe^{3+} precipitates. The transformation of reducible ferric oxide into non-reducible ferric oxide is described according to:

\[ \Delta [Fe(OH)_3^{R}] = -k_1(pH) [Fe(OH)_3^{R}] \Delta t \]  \hspace{1cm} (9)

in which \([Fe(OH)_3^{R}]\) = amount of reducible ferric oxide (mol kg\(^{-1}\)) and \(k_1(pH)\) = rate constant (h\(^{-1}\)). In the model the pH dependency of the rate constant \(k_1(pH)\) is described with an exponential function which fits the data of [22].

If reducible ferric oxide is present in a soil layer and this compartment is saturated with water, the reduction of reducible ferric oxide is described by:

\[ \Delta [Fe(OH)_3^{R}] = -k_2 \Delta t \]  \hspace{1cm} (10)

in which \(k_2\) = rate constant (mol kg\(^{-1}\) h\(^{-1}\)). New amounts of reducible ferric oxide are calculated by combining Equations (9) and (10) and adding the amount of precipitated Fe(OH)_3 calculated in the precipitation/dissolution subroutine. From the amount of ferric oxide reduced, the produced amounts of Fe^{2+}, OH, and HCO_3\(^{-}\) are calculated using the stoichiometry of Equation (8).

Cation exchange is modeled according to the Gaines-Thomas expression (see [4]).

**Model validation**

Comparing model results with measurements from column experiments. The time span during which the model simulation was carried out, was similar to the monitoring period of the column experiments, while applying the same drainage, submergence and leaching/irrigation regimes. The daily measured actual evaporation of the columns was given as top boundary condition in the model validation. This evaporation ranged from 1 to 1.7 mm d\(^{-1}\). Furthermore, daily groundwater levels inside the columns were given as bottom boundary condition together with the groundwater quality. Ionic concentrations, pH and redox potentials measured at the start of the monitoring period of the columns were used as initial condition for different model compartments. Measured values of the cation-exchange capacity at different depths were used for model input. Other required input parameters and their values used have been given in [1].

During the validation some problems were encountered. First, due to drying of the upper layers of the columns during the drainage phase, it was not always possible to extract enough soil solution from the porous cups to carry out a complete chemical analysis. In that case, the pH was estimated with indicator paper which yielded only a very rough indication. Although great care was taken with the samples, a continuous series of measurements of high quality cannot be guaranteed. Especially pH, SO_4^{2-} and Al^{3+} were sensitive to erroneous measurements [13,24]. Sometimes measured pH values of reduced bottom layers were low due to oxidation of Fe^{2+} in the sampling bottles. Samples with high ionic strength sometimes exhibit great differences between sum of cations and sum of anions; sum of anions often exceeds sum of cations, sometimes with a few hundred percent. SO_4^{2-} concentrations seemed to be too high, and aluminum too low [24].

Figure 4 summarizes the results of the model validation. All data available on pH, Al^{3+}, Mg^{2+} and SO_4^{2-} from the four columns have been plotted against values computed for corresponding days using SMASS. Calculated and measured pH agree reasonably well within the range pH 2.5 to 7. The scattering of pH-values is obviously increased by the unreliable pH-paper measurements (which can be recognized as vertical columns of symbols at pH 3, 3.5, 4.5 and 5). Measured and
Fig. 4  Comparison of model simulations of pH, Al$^{3+}$, Mg$^{2+}$ and SO$_4^{2-}$ concentrations with measurements at depths of 5, 45 and 85 cm in four columns with two undisturbed acid sulphate soils subjected to drainage, submergence and leaching with fresh and brackish water.

calculated Al$^{3+}$ concentrations exhibit more variability. Apart from uncertainties in measured data, other reasons may be:
- a relatively slight difference in measured and calculated pH results in a much more pronounced difference between measured and calculated Al$^{3+}$ concentrations;
- in the model calculations, equilibrium between concentrations of H$^+$, Al$^{3+}$ and SO$_4^{2-}$ with jurbanite, Al(OH)SO$_4$, is assumed to take place over the whole pH range, while, in reality, Al-hydroxides are becoming important above pH 5;
- constant exchange coefficients are used in the model simulations, sometimes leading to poor agreement between predicted and measured values, in particular during leaching.

The measured and predicted Mg$^{2+}$ concentrations also indicated some dispersion. The main reason may be that the soil in the model was uniformly leached, not accounting for macropore flow, leading to an overestimation of leaching efficiency. Measured and predicted SO$_4^{2-}$ concentrations showed a high similarity.

In conclusion, in spite of some noise, the relationship between the measured and computed major elements can be described by a 1 : 1 line over a very wide range of concentrations. This indicates that the model is theoretically sound based and therefore widely applicable.
Comparing model results with measurements from monitoring field plots. In the model simulation the daily flooding regime and precipitation measured at the Tabunganen field site were used as the top boundary condition. During flooding, brackish water of the same quality as measured in the nearby tertiary canal is infiltrating through the top boundary of the model with a rate of 10 mm d\(^{-1}\). Potential evapotranspiration was obtained from open pan evaporation measurements and were completed with estimates for missing periods [9]. Groundwater levels measured at the field plot were used as the bottom boundary condition. Ionic concentrations, pH and redox potentials measured at the start of the monitoring period were used as initial condition for different model compartments. Measured values of the cation-exchange capacity at different depths were used for model input. Other required input parameters and their values used have been given in [1]. Because groundwater levels at Tabunganen were high throughout the year, all chemical processes in Tabunganen occur in the upper 30 cm. Therefore, only the field observations and model com-

Fig. 5 Comparison of model simulations of pH, Al\(^{3+}\) and SO\(_4^{2-}\) concentrations with measurements at depths of 5 (left hand side) and 25 cm (right hand side) from a monitoring field plot on a potential acid sulphate soil (Tabunganen, Indonesia) subjected to daily flooding with brackish water.
putations for 5 and 25 cm depth will be presented. SMASS nicely computed the oxidation of pyrite upon aeration of the soil during the dry period in the first year of field measurements. The computed drop in pH around day 250 (Fig. 5) and the corresponding rise in Al\(^{3+}\) and SO\(_4^{2-}\) concentrations, agreed with the field measurements. The leaching process in the successive wet period (starting around day 350) was shown by both computed and observed pH rise and decrease in SO\(_4^{2-}\) concentration. The model predicted aeration and pyrite oxidation in the dry period of the second year, starting around day 580 by a drop in pH at 5 cm depth, and rise in SO\(_4^{2-}\) concentration. In the second dry period, the model predicted a rise in SO\(_4^{2-}\) concentrations at 25 cm depth due to leaching of compounds out of the topsoil. In reality, however, concentrations at 25 cm depth were much more stable. Part of the SO\(_4^{2-}\) produced in the topsoil was, possibly, leached horizontally into the field ditches. As a result, the subsoil received less compounds from the topsoil than was computed with the one-dimensional model. In general, however, there was a good agreement between modeled and actual conditions.

**Model application**

**General.** For each of the six selected water management strategies a period of ten years was simulated, starting with the initial pyrite, organic matter, pH and Al\(^{3+}\) profiles, which were measured at the beginning of the field monitoring at Barambai (1 November 1988). The top boundary condition for the simulations consisted of daily precipitation and potential evapotranspiration measured in the field between 1988 and 1990. To arrive at a period of ten years, these two-year measurements were repeated five times, because of lack of reliable long-term weather records. In case of strategy 6 an irrigation gift of 30 mm.d\(^{-1}\) with good quality water was added to the top of the model, in addition to the daily precipitation and potential evapotranspiration, during 90 days at the end of the wet season. The bottom boundary condition applied for each of the six strategies was according to the drainage strategies described before. For strategy 1 the present course of the groundwater level such as measured in the field during two years, was repeated five times. Model simulations concentrated on the following output:

- future development of the pyrite profile in the soil;
- future course of pH and Al\(^{3+}\) concentration at depths of 5, 25 and 65 cm.

**Pyrite oxidation in dependence of water management.** Figure 6 shows the computed future pyrite profiles for the water management strategies investigated. The intensive drainage strategies 2 and 3 (groundwater levels 40 and 60 cm below soil surface respectively) will result in a rapid decrease in pyrite content of the topsoil. Within five years, nearly all pyrite above the groundwater table will be oxidized. The moderate drainage strategies 4 and 5 (groundwater levels 40 and 60 cm below soil surface for only part of the year respectively) result in a slower oxidation of pyrite in the topsoil. After five years, there will still be considerable amounts of pyrite present in the topsoil, but after ten years, nearly all pyrite will be oxidized. However, the present water management strategy results in the slowest oxidation of pyrite, which even after ten years will leave considerable amounts of pyrite in the topsoil.

In Figure 7 the predicted course of the starting depth of the pyritic layer over the next ten years is pictured. It is clear that drainage plays the major role in the future development of the pyrite profiles. The most extreme drainage strategy, i.e. strategy 3 (groundwater level 60 cm throughout the year), will lead to a pyrite-free topsoil of 40 cm in 3.3 years and a pyrite-free topsoil of 60 cm in 4.5 years. In strategy 2 (40 cm groundwater throughout the year) it will take approximately 2.8 years to achieve a pyrite-free topsoil of 40 cm. Obviously, in the strategies in which the water
Table is below the soil surface for only part of the year (strategies 1, 4, 5) it will take a longer time for the topsoil to become free of pyrite. Under the present water management (strategy 1) the decrease in pyrite content is slow: in ten years only the top 30 cm of the soil will be free of pyrite. From Figure 7 it can be concluded that deeper groundwater levels do not automatically result in a more rapid pyrite oxidation in the topsoil.

The various water management strategies should also be evaluated from an environmental point of view. Different strategies will result in different pyrite oxidation rates (Fig. 8). The right hand axis of Figure 8 gives the quantities of released H+ per m² of soil, assuming, for a first approximation, that oxidation of one mole of pyrite results in the release of 4 moles of H+, as is the case during complete oxidation of pyrite to ferro-hydroxide [8]. Obviously, in reality only part of the
Fig. 7 Computed course of the pyrite depth in the Barambai soil over the next 10 years for various water management strategies (1 = present water management; 2 = groundwater level -40 cm whole year; 3 = groundwater level -60 cm whole year; 4 = groundwater level -40 cm dry period, 0 cm wet period; 5 = groundwater level -60 cm dry period, 0 cm wet period)

Fig. 8 Computed pyrite oxidation and acid production in the Barambai soil over the next 10 years for various water management strategies (1 = present water management; 2 = groundwater level -40 cm whole year; 3 = groundwater level -60 cm whole year; 4 = groundwater level -40 cm dry period, 0 cm wet period; 5 = groundwater level -60 cm dry period, 0 cm wet period)

Acidity will be transported to the groundwater and surface water, while the remaining part will be buffered and retained in the soil profile. However, the amounts involved are enormous. The produced acidity is highest in the intensive drainage strategy 3 and lowest in the moderate drainage strategies. Once the pyrite is depleted from temporarily aerated layers, acid production stops. The more intensely drained situations show shorter periods of acid production. In strategy 2 and 3, further acid production would stop after about 5 years. Under the present water management, acid generation will still continue even after ten years.
Soil and water quality. If the present water management is continued for another ten years (strategy 1), the pH will rapidly decrease every dry season, because of in situ pyrite oxidation, while the reverse will occur in the wet season as a result of leaching and reduction (Fig. 9a). Concurrently, Al$^{3+}$ concentrations will also change (Fig. 9b). In the dry season maximum concentrations of some 10 mmol, l$^{-1}$ can be expected. Toxic levels for rice lie around 2 mmol, l$^{-1}$ [23]. After ten years, soil conditions will remain as poor as they are at present. Water management strategy 2, i.e. groundwater level at 40 cm below soil surface, will result in lower pH-values in the soil. The pH will drop as low as 2.4 in the whole profile in the dry seasons of the first two years. After about three years, however, the pyrite in the top 40 cm will be completely oxidized (Fig. 7) and the pH in the topsoil will slowly rise to values around 4, mainly because of leaching with precipitation water. The predicted Al$^{3+}$ concentrations show a similar trend. During the first

![Fig. 9](images/fig9.png)

Computed course of pH (a) and aluminum concentration (b) at three depths in the Barambai soil over the next 10 years for various water management strategies (1 = present water management; 2 = groundwater level -40 cm whole year; 6 = groundwater level -40 cm + irrigation)
three years, extremely high concentrations will occur, thereafter concentrations will drop to lower
levels. After ten years, a less unfavourable soil will be achieved if strategy 2 is implemented
rather than the present water management. The main disadvantage of strategy 2, however, is the
strong acidification of the soil during the initial years. Water management strategy 6 is identical
to strategy 2, except for the application of 30 mm.d⁻¹ good quality irrigation water to leach the
released acidity and toxic elements from the soil profile. Additional irrigation has a moderate
effect (Fig. 9). During the first three years of strategy 6, pH and Al³⁺ concentrations will be
slightly better than with strategy 2 (without irrigation), especially in the topsoil. After complete
oxidation of pyrite (4-5 years), the pH values will rise and Al³⁺ concentrations will descend more
rapidly to acceptable levels with irrigation.

**Concluding remarks.** The simulation model for acid sulphate soils (SMASS) has been developed
to predict effects of water management strategies, such as drainage, submergence and leaching, on
acidification and de-acidification, and on the release and movement of elements in acid sulphate
soils. The output consists of the soil water balance, oxygen concentration in the soil air, solute
concentration in the soil solution and amount of minerals, including pyrite, in the soil. The
validation of the model by comparison of model calculations with measurements from column ex­
periments and field plots showed a reasonably good agreement between measured and predicted
pH, Al³⁺, Mg²⁺ and SO₄²⁻ concentrations. Comparison of measured and predicted major ions yields
a 1:1 relationship over a very wide range of concentrations. The greatest variability was found for
Al³⁺ and Mg²⁺, which can be ascribed partly to erroneous measurements and partly to some
shortcomings of the model, related to our assumptions about leaching. The pyrite oxidation could
be predicted. Resulting pH-decrease and rise in Al³⁺ and SO₄²⁻ were reasonably well predicted.
The examples presented show how the model can be used to predict long-term effects of different
water management strategies in acid sulphate soil areas on changes over time and depth of
element concentrations in soil and drainage water, and of contents of pyrite. Considering most
relevant physical and chemical processes, the model enables to estimate progress and direction of
the genesis of acid sulphate soils depending on the way of management. Agricultural and
environmental consequences of management of acid sulphate soils can be evaluated. For instance,
periods during which iron and aluminum concentrations exceed levels toxic to crops and element
loads of drainage water contaminating surface waters, can be predicted. In the evaluation
presented, the consequences of various water management strategies are predicted without
discussion their implementation in practice. The success of promising strategies depends on
technical, economic and social factors as well. The feasibility of their implementation must be
subsequently assessed by an technical, economic and social evaluation.

Compared to simple and empirical models process-based models such as SMASS are often more
accurate and much wider applicable. However, in general, complex deterministic models have a
higher data demand. With respect to SMASS the system parameters, e.g. hydraulic functions are
soil-specific and have to be measured or obtained by using pedotransfer functions. Chemical
system parameters, such as cation exchange coefficients, rate constants for precipitation/dissoluti­
on and redox reactions are not soil-specific and can be found from literature and model calibrati­
on. Initial conditions such as water, pyrite and organic matter contents, initial pE, pH and element
concentration in the soil solution can be obtained from field measurements and chemical analysis.
Boundary or variable conditions, e.g. groundwater levels, daily weather records and concentrations
in irrigation, precipitation and groundwater are site-specific and are sometimes available or have
to be measured as well.
The average groundwater level is computed as $\frac{\sum_{n} h(n) - Z_{FeS2}}{365}$, in which $h(n)$ is the groundwater level at day $n$, and $Z_{FeS2}$ is the starting depth of the pyritic layer. For days that the groundwater table is above the pyritic layer $h(n) - Z_{FeS2} = 0$. The graph contains model computations, laboratory measurements and field measurements.

An other disadvantage of simulation models is that they may be too complicated for non-specialists. To overcome this problem simulation models can be used to fit complex processes into simple relationships or to derive rules of thumb for specific situations. Figure 10 presents an example of such approach of going back from complex models to simple tools. In the Barambai area we have found a reasonable relationship between the yearly average of the groundwater levels in the pyritic layer and the computed yearly pyrite oxidation rate. In the figure measurements from various laboratory and field experiments in Indonesia [1], have also been included, supporting the validity of the relationship found with the model. A quick estimation of yearly pyrite oxidation can now be made quite simply for any water management strategy. Figure 10 also shows that, under continuously aerated conditions, the maximum pyrite oxidation rate is about 1 weight % of pyrite per year. Alternatives to modeling to predict future effects of water management are either expert knowledge or extensive field experimentation. Expert knowledge is indispensable for applying a model in an area, but remains mainly qualitative and restricted to local conditions. Moreover, the time dependence of processes in reaction on variations in soil, water and climatic conditions is difficult to assess in this way. Field experimental research is often prohibitive in terms of costs and duration required to run experiments with different water management strategies on different soil types over a series of years, to get reliable results reflecting both soil and climatic influences.

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Pedodynamics: An Approach to Study and Quantify Soil Forming Processes

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Introduction. Many different types of models have been utilized in the history of pedology. In a recent paper, Hoosbeek and Bryant (1992) presented a framework for the classification of pedogenetic models based on relative degree of computation, complexity, and level of organization (Fig. 1). The relative degree of computation distinguishes between qualitative and quantitative models. The second characteristic, complexity of the structure used in the model, distinguishes between functional and mechanistic models. The third distinction is based on the organizational hierarchy which describes at which level a model aims to simulate a natural system. The pedon was placed at the central i-level. Positive i-levels include the polypedon (i+1), catena or catchment (i+2), and the soil region (i+3). Negative i-levels comprise of the horizon (i-1), peds and aggregates (i-2), and molecular interaction (i-3).

The dominant paradigms of pedology are based on qualitative models, e.g., Jenny's (1941) 'Factors of Soil Formation', positioned in the framework as a qualitative-functional-positive i-level model, and Simonson's (1959) 'Generalized Theory of Soil Genesis', which is primarily concerned with the differentiation of horizons in a profile, positioned as a qualitative-functional-negative i-level model. Data for these qualitative models are usually obtained from the soil-landscape at one point in time. These static observations provide a 'snapshot' of the soil system. This paper presents a new approach to study and quantify the dynamic soil processes in a pedon. We coined the word "pedodynamics" and defined it as: "The quantitative integrated simulation of physical, chemical, and biological soil processes acting over short time increments in response to environmental factors." (Hoosbeek and Bryant, 1994a) A pedogenetic study was designed to quantify processes over short time increments reflecting seasonal fluctuations in temporal properties. Newly developed and adapted soil process submodels were used as building blocks in an integrated pedodynamic computer simulation model. The pedodynamic ORTHOD model was developed to study and quantify soil forming processes in a Typic Haplorthod. The model aims to study and simulate at the pedon (i) and horizon (i-1) level. It therefore needed to consider physical, chemical, and biological soil processes at the horizon (i-2) and molecular (i-3) level. Algorithms to describe these processes were based on the current mechanistic understanding available in soil science. The ORTHOD model may be classified as a quantitative-mechanistic-negative i-level model.

The pedodynamic ORTHOD model was used to study the dynamics of carbon (Hoosbeek and Bryant, 1994b). The study of carbon in soils received much attention in recent years due to its importance to the issue of greenhouse gas warming. A better insight into the
Figure 1. Classification of pedological models based on relative degree of computation, complexity and level of organization.
dynamics of CO₂ respiration rates, DOC movement, and DOC adsorption, may benefit ecological models aimed at predicting global changes.

The model was also used to test several hypotheses describing podzolization processes (Hoosbeek and Bryant, 1994c). Two major podzolization theories exist to explain the formation of non-agric Spodosols. The more traditional "organic" theory describes the formation of organic acids in the O horizon, complexation of Al, and the downward migration of these Al-organic complexes. The C:Al ratio is observed to decrease upon precipitation which is attributed to increased complexation of Al and/or the microbial decomposition of organic acids (De Coninck, 1980; Buurman, 1984 and 1985). In 1980, Farmer et al proposed an "inorganic" theory in which a soluble positively charged Al₂O₃-SiO₂-H₂O sol migrates from the E horizon to the Bs horizon to precipitate as proto-imogolite. In a second stage, a negatively charged organic sol precipitates on the positively charged surfaces of the Bs horizon. Both podzolization theories were modeled and simulated results were compared with measured field data.

This paper gives an overview of the construction of a pedodynamic model, describes its application to ecological and pedological studies, and discusses the role of the pedodynamic approach in studies of pedogenesis.

Materials and Methods. A detailed study site was installed in the Adirondack Mountains, New York. The site was located 21 km northwest of the village of Tupper Lake at an elevation of 458 m. The combination of climate and vegetation, predominantly Red Spruce (Picea rubens) and Balsam Fir (Abies balsamea), classified as Boreal forest. The parent material consisted of deep sandy glacial outwash deposited shortly after the glaciers retreated some 11,000 years ago (New York State Museum/Geological Survey, 1991). The soil was a member of the Adams series, a well expressed Typic Haplorthod (sandy, mixed, frigid) (Hoosbeek and Bryant, 1994c).

Two pits were dug, about ten meters apart, for soil characterization and collection of minimally disturbed samples for use in laboratory experiments. Three sets of tensiometers, soil solution samplers, thermistors, and platinum electrodes were installed in 1990. Each set consisted of 6 tensiometers (Oa, E, Bhs, Bs, BC, and C horizons), 5 soil solution samplers (Oa, E, Bhs, Bs, and C horizons), 6 thermistors (Oi, Oa, E, Bhs, Bs, and BC horizons), and 3 platinum electrodes (Oi, Oa, and E horizons). One set was installed adjacent to the 'north' pit, the two other sets were installed at each side of the 'south' pit. One precipitation collector was installed in an open spot in the vegetation approximately 50 m from the monitoring site. Four throughfall collectors were installed on the site adjacent to the three sets of monitoring instruments.

The soil profiles of each pit were described according to USDA-SCS guidelines. Bulk samples from each horizon were collected for particle size analyses, organic carbon determination, several extractions, and X-ray analyses. Particle size percentages were
determined with standard sieves and the pipet method (NSSL, 1991). Organic Carbon percentages were determined with a Leco Corporation induction furnace.

Ring samples were carefully excavated from each horizon to measure bulk densities and establish moisture retention curves. The ring samples were equilibrated on pressure plates (Soil Moisture Corporation) at pressures of 0.1, 0.2, 0.3, 0.5, 1.0, 2.0, 3.0, 5.0, and 15 bar. Measurement of the water content at each pressure resulted in $\theta$-$h$ relations for each horizon.

Precipitation, throughfall, and soil solution samples were collected every 4 weeks during the 1991 and 1992 frost-free seasons. The solution samples were transported and stored at low temperatures (1-4°C) to minimize microbial activity. All major cations were determined with inductively coupled plasma optical emission spectrometry (ICP-OES). Organic and inorganic carbon was analyzed with an IR Corporation Carbon Analyzer.

The ORTHOD model simulated soil processes per layer using a layer thickness of 0.025 m. Each layer was assumed to be physically and chemically homogeneous. Each profile contained 44 layers to a depth of 1.1 m, and each soil horizon consisted of two or more layers. Chemical fluxes and budgets were calculated for soil volumes with a square horizontal area of 1.0 m$^2$ and a vertical dimension of 0.025 m. The development and description of the submodels used in the ORTHOD model was presented elsewhere (Hoosbeek and Bryant, 1994a and 1994b) and will therefore be summarized briefly in the following paragraphs.

**Water Movement.** Several deterministic models have been developed that simulate the flow of water in the unsaturated zone based on Darcy’s law and the continuity principle:

$$ q = -K \frac{\delta H}{\delta z} \left( \text{cm.day}^{-1} \right) $$

$$ \frac{\delta \theta}{\delta t} = - \frac{\delta q}{\delta z} \left( \text{day}^{-1} \right) $$

Combination yields a partial differential equation in terms of hydraulic head, called the Richard’s equation:

$$ \frac{\delta \theta}{\delta t} = \frac{1}{C} \frac{\delta \psi}{\delta z} $$

Using the pressure head form of the flow equation and the differential moisture capacity ($C$), defined as $C = \delta \theta/\delta \psi$, the flow equation for predicting water movement in layered soils is:

$$ \frac{\delta \psi}{\delta t} = \frac{1}{C(\psi)} \frac{\delta \psi}{\delta z} $$

The sandy soil at the study site permitted the use of a model based on the Richard’s equation. The LEACHM model (Wagenet and Hutson,
uses a numerical solution to the Richard’s equation and was selected for use in the ORTHOD model.

Real-time weather data were obtained from the nearby Tupper Lake Sunmount weather station. Undisturbed core samples of each horizon were used to determine bulk densities and water retention curves. The water retention curves were established by equilibrating the undisturbed cores on pressure plates at pressures ranging from 10 kPa to 1500 kPa. Measurement of the water content at each pressure resulted in 0-h relations for each horizon.

Simulated values gave a good fit for measured values (Hoosbeek and Bryant, 1994a). Given precipitation and evaporation input, this submodel gave a relatively good representation of soil moisture conditions and water movement in all horizons at any point in time and over the full range of soil moisture conditions.

**Solute Movement.** Solute movement consists of three components: convective, diffusive, and dispersive transport. Combining the equations of these three processes leads to the following expression for solute flux ($J_s$):

$$J_s = -\theta D(\delta C/\delta x) + qC$$  

(van Genuchten and Wierenga, 1986)

where $\theta$ is the volumetric water content, $C$ is the volume averaged solute concentration, $x$ is distance, $q$ is the volumetric fluid flux density, and $D$ is the summation of the molecular diffusion and mechanical dispersion coefficients. Both the diffusion and dispersion coefficients were assumed to be negligible for a sandy soil with a relative large downward convective flow throughout the year. The solute movement between two layers is then dominantly convective flow, which is the product of the volumetric fluid flux density and the volume averaged solute concentration (Wagenet, 1986):

$$J_s = qC$$

This simplification significantly reduced computation time and did not cause significant error when using relatively thin layers (25 mm) in the simulations.

**Soil Temperature.** Heat transfer and soil profile temperatures were simulated with LEACHM as described by Tillotsen et al. (1980). The heat flow equation is:

$$\rho C_p \delta T/\delta t = \delta (K_t(\theta) \delta T/\delta z)/\delta z$$

where $\rho$ is bulk density (kg.m$^{-3}$), $C_p$ is gravimetric heat capacity of the soil (J.m$^{-3}$.°C$^{-1}$), $T$ is temperature (°C), $t$ is time (s), $z$ is depth (m), and $K_t(\theta)$ is the thermal conductivity of the soil (J.m$^{-1}$.s$^{-1}$.°C$^{-1}$) at water content $\theta$ (m$^3$.m$^{-3}$). The volumetric heat capacity was calculated from:

$$\rho C_p = \rho_s C_s + \theta \rho_w C_w$$
where \( p_s \) and \( C_s \) are the bulk density and the gravimetric heat capacity of the solid phase and \( p_l \) and \( C_u \) are the density and the gravimetric heat capacity of the liquid phase.

Simulated temperature profiles gave a good fit for the measured soil temperatures. Simulated temperature profiles were used in other submodels to adjust respiration rates and chemical constants.

**Mineral dissolution.** The rate of dissolution of clay minerals and metal hydrous oxides is surface controlled and is observed to follow zero-order kinetics and can be expressed by the equation (Stumm et al., 1985; Sposito, 1989):

\[
\frac{d[A]}{dt} = k
\]

where \([A]\) is the aqueous-phase concentration of an ion, and \( t \) is time. The parameter \( k \) is a function of temperature, pressure, mineral surface area, proton concentration \([H^+]\), and, in the presence of a strong chelator, the ligand concentration \([L']\). In a controlled laboratory experiment at constant temperature, pressure, and for a given soil material of some specific mineralogy and mineral surface area, \( k' \) is then a function of \([H^+]\) and \([L']\):

\[
k = k'[H^+]^m[L']^n
\]

where \( m \) and \( n \) are fractional order constants. Combination of the two equations yields:

\[
\frac{d[A]}{dt} = k'[H^+]^m[L']^n
\]

An experimental set-up was designed to resemble the natural field conditions of mineral dissolution as closely as possible (Hoosbeek and Bryant, 1994a). The following dissolution rates (mole/l/h) were obtained:

- \( d[Na^+]/dt = 2.63E-06[H^+]^{0.17}[L']^{0.03} \) \( r^2=0.99 \)
- \( d[K^+]/dt = 2.23E-06[H^+]^{0.11}[L']^{0.04} \) \( r^2=0.99 \)
- \( d[Ca^{2+}]/dt = 8.58E-03[H^+]^{1.09}[L']^{0.03} \) \( r^2=0.98 \)
- \( d[Fe^{2+}]/dt = 2.55E-03[H^+]^{1.63} \) \( r^2=0.98 \)
- \( d[Al^{3+}]/dt = 7.62E-04[H^+]^{0.89}[L']^{0.03} \) \( r^2=0.94 \)
- \( d[Si^{4+}]/dt = 1.19E-03[H^+]^{0.87}[L']^{0.02} \) \( r^2=0.97 \)

The mineral dissolution submodel is specific for the Typic Haplorthod at our monitoring site. Mineralogy, surface areas, and mineral surface conditions were not specifically defined but were embodied in the \( k' \) values of the rate equations.

**Microbial Decomposition of Organic Matter.** This submodel distinguishes three carbon pools; soil organic carbon (SOC), dissolved organic carbon (DOC), and carbondioxide (\( CO_2 \)). Decomposition products are SOC, DOC, and \( CO_2 + H_2O \). The ratio in which these products are produced depends on the volumetric water
Field measurements of redox potentials indicated aerobic conditions throughout the year. A laboratory experiment was designed to determine rates of microbial CO$_2$ and DOC production in horizons of the Typic Haplorthod at our field monitoring site (Hoosbeek and Bryant, 1994a). The following polynomials were obtained:

\[
\begin{align*}
\frac{d\text{CO}_2}{dt} &= 38.2 + 89.8 \theta - 138.8 \theta^2 & r^2 &= 0.99 \\
\frac{d\text{DOC}}{{}_{01}}}{dt} &= 10.0 + 22.0 \theta - 9.4 \theta^2 & r^2 &= 0.82 \\
\frac{d\text{DOC}}{{}_{02}}}{dt} &= 2.9 + 2.1 \theta - 3.8 \theta^2 & r^2 &= 0.97 \\
\frac{d\text{DOC}}{{}_{03}}}{dt} &= 2.1 + 10.7 \theta - 11.9 \theta^2 & r^2 &= 0.50
\end{align*}
\]

where \( \frac{d\text{CO}_2}{dt} \) is the CO$_2$ respiration rate (\( \mu g \text{ C day}^{-1} \text{ g}^{-1} \text{ soil} \)). DOC production rates could be described with linear equations:

\[
\begin{align*}
\frac{d\text{DOC}}{{}_{01}}}{dt} &= 2.9 + 19.1 \theta & r^2 &= 0.88 \\
\frac{d\text{DOC}}{{}_{02}}}{dt} &= 4.0 + 4.1 \theta & r^2 &= 0.97 \\
\frac{d\text{DOC}}{{}_{03}}}{dt} &= 1.6 + 3.2 \theta & r^2 &= 0.92 \\
\frac{d\text{DOC}}{{}_{04}}}{dt} &= 11.0 + 3.7 \theta & r^2 &= 0.85
\end{align*}
\]

where \( \frac{d\text{DOC}}{dt} \) is the DOC production rate (\( \mu g \text{ C day}^{-1} \text{ g}^{-1} \text{ soil} \)).

These CO$_2$ and DOC production rate equations were established with respiration data measured at 20°C. For use in the microbial decomposition submodel, these rates needed to be adjusted for the particular soil temperature of each simulated layer. A Q$_{10}$-type temperature response was used to calculate the corrected temperature, \( T_{corr} \):

\[
T_{corr} = Q_{10}^{0.1(T_{soil} - T_{base})}
\]

where \( Q_{10} \) was assumed to be 2, \( T_{soil} \) is the soil temperature (°C), and \( T_{base} = 20°C \).

**DOC Adsorption.** DOC adsorption was described by the Freundlich equation (Bohn et al., 1985; Sposito, 1989):

\[
A = K \times C^n
\]

where \( A \) is the weight of adsorbate per unit weight of adsorbent (kg C/kg soil), \( C \) is the equilibrium concentration of adsorbate in solution (kg C/m$^3$), and \( K \) and \( n \) are empirical constants. The linear form of the equation, with \( n=1 \), was used in the submodel. The \( K \) value for each horizon was obtained through calibration.

**Ion Exchange.** Different exchange equations have been proposed to describe the exchange between cations of unequal charge. The most general form of an exchange equation is based on the mass action equation (Bohn, 1985), e.g:

\[
3\text{Ca}^2+ + 2\text{Al}^{3+} = 2\text{Al}^3+ + 3\text{Ca}^{2+}
\]
with the selectivity coefficient:

$$K = \frac{(A_1X)^2 (Ca^{2+})^3}{(CaX)^3 (Al^{3+})^2}$$

where $X$ denotes the ion in the adsorbed phase. Vanselow (1932) substituted the mole fractions of the exchangeable ions in the above exchange equation. The mole fraction, e.g. $N(A_1)$, is defined as:

$$N(A_1) = \frac{n_{Al}}{n_{Al} + n_{Ca}}$$

where $n$ is mole of exchangeable ions per g soil. The Gapon equation is widely used for $Na^+\text{-Ca}^{2+}$ exchange (Bohn, 1985). The mass action equation for $Ca^{2+}\text{-Al}^{3+}$ exchange, which is an important exchange reaction in a Spodosol, is written as:

$$CaX + \frac{2}{3}Al^{3+} = (Al)_{2/3}X + Ca^{2+}$$

with the exchange coefficient:

$$K_{Gapon} = \frac{[(Al)_{2/3}X] [Ca^{2+}]}{[CaX] [Al^{3+}]^{2/3}}$$

Exchange equations based on mass action equations assume that the activities of the adsorbed ions are proportional to their equivalent or mole fraction in the adsorbed phase. However, data from a $Ca^{2+}\text{-Al}^{3+}$ exchange experiment on Montmorillonite at low pH showed a large preference of the clay for the trivalent ion (McBride and Bloom, 1977). An exchange model based on a statistical thermodynamic approach was derived to better describe the activity of $Al^{3+}$ at the mineral surface. The equation relates the $Al^{3+}$ in solution and the equivalent fraction of adsorbed $Al^{3+}$ as:

$$(Al^{3+}) = K_{McBride} N(A_1)/(1 - N(A_1))$$

This equation emphasizes the lack of dependence of $Al^{3+}$ adsorption on the $[Ca^{2+}]$ in solution, a result of the more solution-like nature of adsorbed $Ca^{2+}$ in comparison to the strongly adsorbed $Al^{3+}$.

To represent a field situation, soil samples from the major horizons were equilibrated by slowly leaching with different base ion and $AlCl_3$ solutions. The CEC of the O horizons is primarily the result of the ionization of functional groups on organic matter. Exchange reactions on organic matter could best be described by a mass action type equation using $K_{Vanselow}$ or $K_{Gapon}$ (Table 1). The B horizons have a higher clay content and are rich in sesquioxides and could be modeled successfully with the McBride equation. Given solution chemistry and solute movement fluxes as input, the ion exchange submodel calculated the change in solution chemistry for each layer on a daily basis.

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Table 1. Exchange coefficients used in the ion exchange submodel.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Exch coeff.</th>
<th>Mean</th>
<th>Std Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oi</td>
<td>K_{Vanselow}</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>Oa</td>
<td>K_{Vanselow}</td>
<td>0.13</td>
<td>0.10</td>
</tr>
<tr>
<td>Bh</td>
<td>K_{McBrine}</td>
<td>0.38</td>
<td>0.03</td>
</tr>
<tr>
<td>Bhs</td>
<td>K_{McBrine}</td>
<td>0.29</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Chemical Speciation and Precipitation. Since the objective of the pedodynamic model is to simulate the chemistry and movement of the major chemical components, a chemical speciation and precipitation submodel was needed. The chemical equilibrium program MINEQL+ (Westall, 1976; Schecher, 1991) was selected to calculate chemical speciation and the precipitation of solid phases.

Aluminum in solution may be present as free aqueous Al, hydroxide, fluoride, and sulfate complexes. The thermodynamical constants of these complexation reactions are known and the speciation can be calculated with a chemical equilibrium program. In natural waters aluminum also forms complexes with organic matter and with amorphous silica (Buurman, 1984; David and Driscoll, 1984) which strongly influences all other chemical equilibria (Schnitzer and Kodama, 1977; Farmer and Fraser, 1979). The chemical formulae of organic ligands and amorphous silicates are variable and not exactly known. It is therefore impossible to obtain thermodynamical data for use in equilibrium equations to calculate the exact speciation of a solution.

Different submodels were developed to simulate the speciation, movement and precipitation of aluminum according to two different hypotheses. Hypothesis one is based on the traditional organic podzolization theory, in which Al is complexed with DOC, moves as an Al-DOC complex, and precipitates due to DOC adsorption. Hypothesis two represents the inorganic theory in which Al movement is assumed to take place in the form of a $\text{Al}_2\text{O}_3\text{-SiO}_2$ sol. Precipitation was modeled with the following pH dependent reaction:

$$\text{Al}_2\text{O}_3\text{-SiO}_2 + \text{OH}^- \rightarrow (\text{HO})\text{Al}_2\text{O}_3\text{SiOH}$$

The reaction may go both ways, allowing for dissolution and precipitation of proto-imogolite.

Results and Discussion. Simulated DOC concentrations provided a good fit to the measured data for all horizons of the three monitoring sites (Fig. 2). The adsorption coefficients for the Freundlich adsorption isotherms differ considerably for the Oi/Oa, E, Bh/Bhs, and Bs horizons within each profile, but are in close range across the three sites (Table 2). The O horizons retained a part of the DOC by adsorption. Only a small amount of the DOC passing through the E horizon is adsorbed. Most of the DOC was adsorbed in the Bh/Bhs horizons which makes the Bh/Bhs horizon an effective barrier to DOC leaching leaving relatively low DOC concentrations in the C horizon. The north profile lost $2.1 \times 10^{-3}$ kg
Figure 2. Measured and simulated DOC concentrations of the E and Bhs horizons.

Figure 3. Cumulative DOC drainage from the bottom of 1.0*1.0*1.1 m³ profiles.
Table 2. Adsorption coefficients, $K$, for the Freundlich equation: $A = K \cdot C_{D0C}$ with $A$ (kg C/kg soil) and $C_{D0C}$ (kg C/m$^3$ solution).

<table>
<thead>
<tr>
<th>Horizon</th>
<th>north site</th>
<th>central site</th>
<th>south site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oi/Oa</td>
<td>60.0E-06</td>
<td>90.0E-06</td>
<td>70.0E-06</td>
</tr>
<tr>
<td>E</td>
<td>13.0E-06</td>
<td>17.0E-06</td>
<td>13.0E-06</td>
</tr>
<tr>
<td>Bh/Bhs</td>
<td>140.0E-06</td>
<td>145.0E-06</td>
<td>115.0E-06</td>
</tr>
<tr>
<td>Bs</td>
<td>1.5E-06</td>
<td>4.0E-06</td>
<td>10.0E-06</td>
</tr>
</tbody>
</table>

C m$^{-2}$ y$^{-1}$ through drainage while the central and south profiles lost $0.4 \times 10^{-3}$ kg C m$^{-2}$ y$^{-1}$ (Fig. 3). Simulated net DOC fluxes for each layer over a 365 day period showed a large DOC flux into the Bh horizon and relatively small fluxes into the Bs and BC horizons (Fig. 4).

CO$_2$ was assumed to diffuse into the atmosphere over time. Simulated cumulative CO$_2$ production rates for the north, central, and south profiles were respectively $0.20$, $0.25$, and $0.24$ kg C m$^{-2}$ y$^{-1}$ (Fig. 5). These rates are in agreement with rates compiled by Raich and Schlesinger (1992) for boreal forests. The rate differences for the three profiles could be explained by differences in carbon pool size of each profile.

The ORTHOD model simulated the Al concentrations in the O and E horizons reasonably well using the organic hypothesis. The inorganic hypothesis overestimated Al concentrations in the O and E horizons by about one order of magnitude. The organic hypothesis consistently underestimated Al in the Bhs, Bs and C due to the strong adsorption of DOC in the Bhs. The inorganic hypothesis overestimated Al in the Bhs, but showed good agreement in the Bs horizon (Fig. 6). In horizons with relatively high DOC concentrations the Al activity was found to be regulated by DOC dynamics. In horizons with relatively low DOC concentrations, below the Bhs, the Al activity was found to be governed by the proto-imogolite equilibrium. Simulated net Al balances over a 365 day period per layer showed significant losses of Al from the E horizon, losses from the Bhs, and accumulations of Al in the Bs and BC horizons (Fig. 7).

The Role of Pedodynamics in Pedological Research. The dominant paradigm of pedogenesis is based on the "Factors of Soil Formation" (Jenny, 1941). Jenny’s model has especially been successful in describing the distribution of pedons at the catena (i+2) and soil region (i+3) levels (Fig. 1). However, some pedological and environmentally related questions involving soil forming processes cannot be answered by applying the factors of soil formation. In the case of Spodosols, some of those questions include: How much DOC, produced in the O horizon, will be sequestered in the B horizon, and how much DOC will leave the profile per year? Which mechanisms regulate Al activity in the rootzone? Which podzolization mechanisms govern the accumulation of Al in the Bs
Figure 4. Simulated net DOC fluxes for each layer over a 365 day period.

Figure 5. Cumulative CO₂ respiration from 1.0*1.0*1.1 m³ profiles.
Figure 6. Measured and simulated Al concentrations of the Bhs and Bs horizons.

Figure 7. Simulated net Al balances for each layer over a 365 day period.
horizon and how do these rates vary throughout the year?

A pedodynamic approach addresses these questions through the use of interactive submodels which can be gradually improved as individual submodels are refined. For instance, a water movement submodel based on the Richards equation might be replaced by a model capable of dealing with preferential flow in structured soils without affecting the other submodels of a pedodynamic model. The choice of submodels depends on the character of the pedon as well as the research objectives.

The ORTHOD model addresses these questions by quantitatively describing the dynamics of a representative pedon of a Haplorthod at the horizon (i-1) and molecular (i-3) levels. In its present stage, the ORTHOD model is limited to a one dimensional, vertical, representation of soil processes in a pedon. A pseudo multidimensional representation may be obtained by applying the model to adjacent points in a soil landscape. A truly two or three dimensional pedodynamic approach would have to include multidimensional soil process algorithms, e.g. vertical and lateral solute movement.

Although the "Factors of Soil Formation" and the pedodynamic models differ in approach (qualitative versus quantitative and functional versus mechanistic), they complement each other in respect to organizational hierarchy (Fig. 1). Depending on the level of the soil system under investigation, the models can be used complementary in pedological research.

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Modeling Soil Genesis from a Landscape Perspective

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Abstract. The variability of the soil continuum at the landscape level affects a wide range of human activities. Mapping this variability is one of the major challenges of pedology. While our understanding of the soil forming processes that are responsible for soil variability at the landscape level is mainly qualitative, geographic information system and allied technologies provide the tools to approach the genesis of soil-landscapes quantitatively. We conducted this study to quantify soil-terrain relationships and to test the hypothesis that the spatial pattern of variability in the depth of the A-horizon and depth to carbonates can be explained by spatial patterns of terrain variability. We described 191 soil profiles at 10-m spacing along a series of transects running both parallel and perpendicular to direction of the maximum slope gradient for a 20-ha study site in west-central, Minnesota, USA. Slope gradient, curvatures, drainage paths, specific catchment area, elevation, wetness index, elevation above and horizontal distance to the nearest drainage path and the wetness, stream power, drainage proximity, and accumulated flow indices were estimated from the 10-m DEM derived from a field survey of the study site. Linear models were developed to quantify the relationships between these terrain attributes and A-horizon and carbonate depth. The wetness and drainage proximity indices explained 51% of the variation in A-horizon depth and the wetness, drainage proximity, and accumulated flow indices explained 44% of the variation in depth to carbonates. Spatial patterns of A-horizon and carbonate depth for the site were estimated by applying the linear models to the database of terrain attributes derived from the DEM. We concluded that terrain attributes could explain approximately half of the spatial variation in A-horizon and carbonate depth and the spatial distribution of these soil properties are strongly influenced by the dynamics of water flow and accumulation. These results suggest that, for this site, hydrologic modeling will be an important component of a processed-based approach to model soil genesis at the landscape level.

Introduction. Soil-forming processes occur at many scales and can be modeled using a variety of techniques. Hoosbeek and Bryant (1) classify soil genesis models based on model complexity (functional vs. mechanistic), the degree of computation required (qualitative vs. quantitative), and the level of the soil system being simulated (molecular through the soil region). This research focuses on functional, quantitative models at the soil catena level with a goal of developing mechanistic models linking patterns of soil and terrain variability to soil-forming processes. The factors of soil formation (climate, organisms, relief, parent material, time, ...) (2,3) provide the conceptual framework to approach catena level studies of soil genesis. The combination of these factors defines the equilibrium state of the soil system and the active pedogenic processes. We are working under the hypothesis that the spatial variability of soil properties is correlated to the spatial variability of these soil-forming factors. Environmental gradients where one state factor varies while the others...
remain relatively constant provide the opportunity to study the influence of individual soil-
forming factors on pedogenesis.

In order to explain soil genesis from a landscape perspective, we must be able to explain
why soil properties vary across the landscape. If we assume that soil property variability is
a function of soil-forming factor variability, then we need a means to depict and explain the
spatial variability of the soil-forming factors. For our current research areas, relief
(topography) is the state factor with the greatest variability and is assumed to be the major
factor contributing to soil variability. The spatial variability of topography can be depicted
with a digital elevation model (DEM) which is a regular grid of elevation observations.

Algorithms have been developed to estimate slope gradient, plan curvature, profile curvature,
aspect direction, specific catchment area, and a variety of surface drainage proximity
variables from DEMs (4,5,6). Several researchers (4,5,6,7,8) have found a high correlation
between changes in these terrain variables and changes in soil drainage characteristics, A-
horizon depth, organic matter content, extractable-P, pH, sand, silt, and soil
taxonomic classes.

Quantitative models of soil-landscape relationships have been developed by numerous
researchers (9,10,11,12). At the time of their development, these models were of somewhat
limited applicability because the spatial information required to apply these models to the
landscape for practical purposes were not available. The relatively recent development of
geographic information system (GIS) technology and digital terrain analysis provides the
tools to quantitatively define landscape attributes and to simultaneously define the spatial
patterns of multiple landscape attributes using digital overlay techniques. More recent work
(4,5,6) demonstrate how statistical models of soil-landscape relationships can be used to map
spatial patterns of soil properties. The importance of this work is that spatial patterns of soil
properties are derived from spatial patterns of landscape attributes. This creates the
opportunity to quantitatively link spatial patterns of landscape attributes and soil-forming
processes at the landscape level.

Objectives. This work was performed as an initial step to identify landscape level processes
contributing to soil genesis on a hillslope in west-central Minnesota, USA, and to examine
the applicability of digital terrain analysis for landscape level studies of soil genesis. We
will test the hypothesis that the spatial pattern of variability in the depth of the A-horizon
and depth to carbonates can be explained by spatial patterns of terrain variability. The
specific objectives of this research are to (i) define the statistical relationships between
terrain variables and the depth of the A-horizon and depth to carbonates, (ii) use these
statistical relationships to map A-horizon depth and depth to carbonates for the 20-ha study
site and (iii) based on the results, suggest the landscape processes that could be responsible
the genesis of A-horizon and carbonate depth for future research at this site.

Methods. The 20-ha study site is located on the Alexandria glacial moraine of west-central
Minnesota, USA, at 46°10'20" N, 95°56'15"W (Fig. 1). The hillslope that we studied
is south to west facing with slope gradients ranging from 0 to 16% and approximately 30 m
of topographic relief. This site was selected because the hillslope is representative of
soil-landscape conditions found in this part of the Alexandria moraine complex. The soil parent material is glacial till of late Wisconsinan age (10,000 to 14,000 ybp) from the Des Moines Lobe of the Laurentide ice sheet. The soils within the catena are classified as fine, mixed, frigid Typic Endoaquolls, Udic Argiaquolls, Pachic Haploborolls, and Typic Eutrochrepts. The climate is humid, continental with a mean annual precipitation of 597 mm including 1092 mm as snowfall and monthly mean temperature of 21.6°C in July and -14.5°C in January. The site is located in the forest-prairie ecotone with the native vegetation being a mixture of tall grass prairie and deciduous forests. After European settlement, the site was used for agricultural production and is currently in a mixture of grasses as part of the U.S. Department of Agriculture Conservation Reserve Program. Our overall methodology for determining statistical relationships between soil and terrain attributes and for creating predictive maps of soil attributes is illustrated in Figure 2. This approach includes field descriptions of soil profiles along several transects, the calculation of terrain variables from a DEM, statistical modeling to define empirical relationships between soil and terrain attributes, and application of the statistical model to the DEM to map A-horizon and carbonate depth. The following sections describe the specific procedures used for each stage of this process.

Field Sampling. We described 191 soil profiles at 10-m intervals along a series of transects running both perpendicular and parallel to the direction of the maximum slope gradient (Fig. 3). This strategy provided continuous sampling across all hillslope positions plus repeated observations within the summit, shoulder, sideslope, toeslope, and depressional hillslope positions. Soil cores were extracted using a hydraulic, truck-mounted soil probe to depths of 1 to 2.5 m such that the bottom of the A-horizon and a horizon containing free carbonates was observed at each location. Standard nomenclature (13) was used to describe the morphology of all soil profiles. Depth to carbonates was defined as the depth to a soil horizon containing carbonate masses with a strong or violent reaction to 10% HCl. The geographic coordinates (universal transverse mercator (UTM)) of each soil profile description were recorded using a global positioning system (GPS) receiver with differential correction from a base-station at a known geographic location.

Digital terrain analysis. We conducted a ground survey to measure elevations on approximately a 10- x 10-m grid across the 20-ha site using a geodometer (electronic surveying device). The coordinates of all elevation observations were transformed to UTM coordinates by referencing the field survey to two U. S. Geological Survey benchmarks in the vicinity of the study site. The measured elevations at 1500 points were interpolated into a regular grid using a universal krigging procedure (14) to create a 10-m DEM consisting of 1978 points. Primary terrain attributes were calculated directly from the DEM whereas secondary terrain attributes were derived from combination of the primary attributes to characterize specific processes or landscape geometries. In order to estimate primary terrain attributes, we applied a second-order, central finite-difference scheme using a 3 x 3 moving window to calculate slope gradient (S), plan curvature (C_plan), and profile curvature (C_prof) (6). The algorithm described by Jenson and Domingue (15) traces flow across the landscape based on elevation differences and was used to calculate flow directions, to determine drainage paths, and specific catchment area (A). For this hillslope, drainage paths were
Figure 1: Location of the study site (Dalton, MN).

Figure 2: Flowchart for soil-terrain modeling methodology.

Figure 3: Locations of the sampling transects for the Dalton study site.
defined as grid cells receiving flow from more than 100 upslope cells (1 ha area). This flow simulation assumes that the surface is impermeable and that water movement is solely a function of elevation gradients. While this assumption is unrealistic for this landscape, the algorithm can be used to separate regions of the landscape that will respond differently in regard to the collection or transportation of soil water based on topography. The elevation above nearest drainage path and horizontal proximity to nearest drainage path were calculated according to the procedure described by Bell et al. (4). Four secondary terrain attributes (wetness index, stream power index, depression proximity index, accumulated flow index) were derived to separate landscape regions based on water flow characteristics. The wetness index (WI) identifies landscape positions where water is likely to accumulate and has been used to characterize the soil water content in landscapes (6,16). The stream power index (SPI) is a measure of the erosive power of overland flow. The wetness index and stream power index are calculated as:

\[ WI = \log(A / S) \]
\[ SPI = \log(A * S) \]

where \( A \) is the specific catchment area (m\(^2\)) and \( S \) is the slope gradient (%) (6). The drainage proximity index (DPI) and accumulated flow index (AFI) distinguish portions of the landscape that are likely to collect water based on hillslope geometry and are calculated as:

\[ DPI = (E_t / P_t) * 100 \]
\[ AFI = (A_t / E_t) \]

where \( E_t \) is the elevation above the nearest drainage path, \( P_t \) is the horizontal distance to the nearest drainage path, and \( A_t \) is the specific catchment area (A) for the nearest drainage path. Computer programs to calculate primary and secondary terrain variables were written and implemented using the software tools of the Khoros image processing system (17). The primary and secondary terrain attributes for each soil profile description were found based on the geographic coordinates of the soil observations in the field.

Statistical Modeling. Correlations among all soil and terrain variables were calculated using Pearson's correlation coefficients. Logarithmic transformations were used for wetness index and stream power index to achieve normal distributions for these data. A split-sample approach was used to develop multivariate linear models to define relationships between soil and terrain attributes where 146 randomly selected observations were used to develop regression models and the remaining 45 were used to obtain an unbiased estimate of model performance. A stepwise procedure was used to select the optimal set of terrain variables for inclusion in the regressions. In order to be entered into or to remain in the model, terrain variables had to be significant at the 0.01 level (18). Once regression equations were developed for A-horizon thickness and depth to carbonates, these equations were applied to the 45 observations in the model validation set to evaluate the regression models.

**Results.** A three-dimensional, wire-frame representation of the study site topography is shown in Figure 4. Subsequent maps of terrain and soil variables are draped over this surface to elucidate relationships between the spatial pattern of the variables and the shape
of the land surface. For example, the derived map of slope gradient (Fig. 5a) indicates, as expected, that the highest slope gradients (light shades) occur on the sideslope positions with the lowest gradients (dark shades) at the summit and depressions. The high values for specific catchment area delineate the drainage pathways quite well (Fig. 5b). The diagonal striping on the hillslope is an artifact of the particular algorithm that was used which traces flow in an unrealistic manner in the uplands. However, the algorithm does separate regions of the landscape receiving little, moderate, and high quantities of cumulative flow from upslope contributing areas. Proximity to the nearest drainage path (Fig 5c) and elevation above the nearest drainage path (Fig 5d), define the geometry of the landscape in relation to the drainage paths and separates low depressional areas (dark shades) from the uplands (light shades). Slope curvatures in the plan and profile directions were also calculated, but are not presented here because these two primary terrain variables were not significant in defining the regression models.

Figure 4: Three-dimensional, wireframe view of the DEM for the Dalton study site.
Figure 5: Primary terrain attributes derived from the DEM draped over the terrain model (Fig. 4) for the Dalton study site.
The wetness index (Fig. 6a) segregates regions of the landscapes where water is likely to collect based on the morphology of the land surface. High values were found in drainage paths and depressional areas with low values on drainage basin divides. The stream power index (Fig. 6b) separates areas of the landscape where high volumes and/or velocities of flowing water are likely to occur, such as drainage paths and steep sideslopes (high values), from gently sloping areas on short hillslopes and drainage divides that potentially could receive lower quantities of flow from upslope areas. The drainage proximity index (Fig. 6c) is essentially the mean slope gradient from any point on the landscape towards the nearest drainage path. Hence, this index provides another means of separating low, depressional areas on the landscape (low values) from the uplands (high values). The accumulated flow index (Fig. 6d) identifies depressional areas that could potentially accumulate water flow within the landscape (high values). These four secondary terrain indices are based on different combinations of the slope gradient, specific catchment area, elevation above the nearest drainage path, and horizontal distance to the nearest drainage path.

Field sampling revealed consistent relationships between A-horizon and carbonate depth with topographic position. These relationships can be examined in a qualitative fashion by constructing cross-sectional diagrams of the hillslope based on the observations along transects perpendicular to the hillslope (Fig. 7a,b,c). These observations indicate that A-horizon and carbonate depth decreases on steeply sloping and convex portions of the hillslope and increase in concave, toeslope, and depressional positions. Pearson correlation coefficients (Table 1) indicate that the highest individual correlation with A-horizon and carbonate depth occur with the wetness and drainage proximity indices. These two indices

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<th>E_d</th>
<th>S</th>
<th>C_pro</th>
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*depths for A-horizon depth (AHD) and depth to carbonates (DTC) are expressed as negative values.
Figure 6: Secondary terrain attributes derived from the DEM draped over the terrain model (Fig. 4) for the Dalton study site.
Figure 7. Cross-sectional view of A-horizon depth relative to elevation for sampling transects A, B, and C at the Dalton study site.
suggest that the residence time and the flow of water both over and within the soil continuum are important factors in the formation of these soil properties. Additionally, A-horizon and carbonate depth are highly correlated suggesting that the genesis of these soil properties may be controlled by similar processes. While cause-and-effect relationships cannot be conclusively determined from statistical correlations, we speculate that a combination of: (i) erosion and sedimentation, (ii) the inhibition of organic matter decomposition by wet, anaerobic soil conditions, and (iii) the extent of vertical leaching of soluble soil constituents are responsible for the spatial pattern of A-horizon and carbonate depth across this hillslope.

Multivariate linear regression indicated that two terrain variables could explain 51% of the variability in A-horizon depth and three terrain variables could explain 44% of the variability in depth to carbonates (Table 2). The percent of explained variability is within the range found by Moore et al. (6) in a similar study, who speculated that it may be unrealistic to expect that these techniques could explain more than 70% of soil property variability. A certain portion of the variability cannot be explained due to limitations of scale. For example, the cell size used to calculate the terrain variables was 10 x 10 m. Consequently, the variability within this 10 x 10-m area cannot be considered due to limitations of scale. The use of smaller cell sizes would allow for the explanation of more variability, however, the marginal increase in explained variability must be balanced against i) the additional expense of collecting terrain data at a higher spatial resolution, ii) the purpose for which the soil property information is required, and iii) the spatial scale of the pedogenic processes of interest. The optimal spatial scale for studying pedogenic processes at the landscape level is unknown and probably varies among different climatic-physiographic regions.

Table 2. Coefficient and $R^2$ values for the regression equations relating A-horizon depth and depth to carbonates to terrain variables.

<table>
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<th>Terrain Variable</th>
<th>A-horizon Depth</th>
<th>Depth to Carbonates</th>
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<tr>
<td>Intercept</td>
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<td>Wetness Index</td>
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<td>Depression Proximity Index</td>
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<td>Accumulated Flow Index</td>
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<td>0.26</td>
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<td>$R^2$</td>
<td>0.51</td>
<td>0.44</td>
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*R^2 is an unbiased estimate determined from the validation data set.*

The regression analysis identified the wetness index and depression proximity index as the best predictors of A-horizon depth and carbonate depth. The wetness index was the terrain variable accounting for the largest portion of variability in A-horizon and carbonate depth followed by the depression proximity index and accumulated flow index. These indices distinguish topographic positions where hydrologic processes on the hillslope are different.
suggesting that hillslope hydrology is a major factor influencing variability in the A-horizon and carbonate depth for the soil continuum at this site.

A comparison of the predicted vs. observed A-horizon and carbonate depths (Fig. 8a,b) indicates the regression predicts the A-horizon carbonate depth within 20 cm of the observed depth for approximately 70% of the model validation observations. The largest residuals were underestimates associated with the three deepest observations of A-horizon and carbonate depths. If these observations were considered to be outliers and were eliminated from the analysis, then the $R^2$ would improve to 0.63 for A-horizon depth and to 0.48 for depth to carbonates. This also suggests that a non-linear model may be appropriate in this situation. However, we did not pursue further refinements in curve fitting because our objective was to find the optimal set of terrain variables that could be used to predict these soil properties. Additionally, while more sophisticated curve fitting would improve the results for this hillslope, it may be of dubious value if the regression were applied to other hillslopes in the same climatic-physiographic region.

The wetness, drainage proximity, and accumulated flow indices were estimated for each 10 x 10-m grid cell for the study site and combinations of these indices were used to predict spatial patterns of A-horizon and carbonate depth using the regression equations described in Table 2 on a cell-by-cell basis. This procedure creates a digital map of A-horizon and carbonate depths based on spatial patterns of topography and provides a means to extrapolate point observations to the three-dimensional landscape and hence generate a spatial model of A-horizon and carbonate depths for the soil continuum. We draped the predicted maps of A-horizon and carbonate depths over the three-dimensional view of the site (Fig. 4) to help visualize the predicted spatial pattern of these soil properties in relation to the shape of the land surface (Fig. 9a,b). As expected, the spatial patterns for A-horizon and carbonate depth are very similar. The estimated depths for both soil properties is greatest (dark shades) in the drainage paths and depression areas where water is likely to accumulate and move downward through the soil. The shallowest depth (light shades) for these soil properties are predicted to occur on steep and convex slopes in the uplands. These soil-terrain relationships agree with those observed on the sampling transects (Fig. 7). There is always the possibility that these statistical correlations are fortuitous in nature and may not be related to physical processes leading to soil genesis. In this case, the statistical correlations and estimated spatial patterns confirm our intuitive understanding of the landscape processes that could account for soil genesis in this setting. For example, the secondary terrain indices separate areas of the landscape that we would expect to have different hydrologic processes (erosion vs. deposition, lateral water flow vs. infiltration and vertical leaching, etc.) which would lead to the development of soils with different properties. The predicted locations of deep A-horizons are associated with deposition landscape positions and/or potentially wet positions where organic matter is likely to accumulate. Shallow A-horizons are predicted for steeper slopes and convex, water-spreading slopes. Similarly, deeper depths to carbonates are predicted in depressional areas and toeslopes where more vertical movement of water through the soil profile is expected and shallower depth to carbonates on sideslopes and convex slopes where more lateral movement of water would be expected. These relationships suggest a depression focused recharge situation where the groundwater is
Figure 8: Observed vs. predicted A-horizon and carbonate depths using the regression model for the Dalton study site.

Figure 9: Predicted A-horizon and carbonate depths draped over the terrain model (Fig. 4) for the Dalton study site.
primarily recharged from water that collects in depressional areas from either surface or interflow (19). We would expect that the relationships between soil properties and topography would be quite different in landscapes with flowthrough or groundwater discharge hydrology.

Discussion. The extent to which the soil-terrain relationships for the hillslope in this study site would apply to other hillslopes within Alexandria glacial moraine is unknown at this time and will be the subject of future work. Previous studies (1,20) suggest that it is difficult to extrapolate statistical correlations to other sites because the calibration site may not be completely representative of soil and terrain conditions for the broader geographic area. Statistical correlations most certainly could not be extrapolated to other climatic-physiographic regions where the soil-terrain relationships are likely to change or where other combinations of soil-forming factors may be of more importance. We view the identification of statistical relationships between soil and terrain attributes as one of the first steps towards developing process-based models of soil genesis at the landscape level. Statistical correlations, when combined with our existing knowledge of soil genesis, suggest possible mechanisms for the formation of specific soil properties. The results of this study suggest that the processes affecting A-horizon thickness on this site are related to water flow and retention both over and through the soil continuum. A process-based approach for A-horizon thickness would include modeling water flow and retention, erosion and depositional processes (geologic and contemporary), organic matter accumulation as a function of the soil moisture regime, climate, and vegetation. If we assume that the predominant source of carbonates in the Alexandria moraine is the calcareous till, then the depth to carbonates could be considered as a surrogate for landscape differences in soil leaching intensity. Consequently, horizontal and vertical water flow and retention, erosion and deposition, and carbonate dissolution and precipitation processes would be of importance. A process-based approach requires consideration of the temporal variation in the states of the soil-forming factors as well. Late Wisconsinan glacial drift provides a good opportunity for process-based modeling because a clear starting point for soil genesis can be identified and the climatic record during the past 10,000 years is relatively well known and similar to the contemporary climate. The expansion of quantitative soil-terrain modeling approaches to broader geographic areas, such as the midwest of North America, would require the consideration of additional soil-forming factors (climate, vegetation, parent material, relative soil age, human influence, etc.) and associated genetic processes. While this may be technically feasible, the background research and complexity required for such regional models of soil genesis would be considerable.

This and related research by other scientists (4,5,6,21,22) suggests a new paradigm for describing the spatial distribution of soils at the landscape level based on the spatial extent of soil horizons and defines the soil continuum in terms of stratigraphy, rather than as discrete pedons and polypedons (map units). Consequently, the soil catena is the experimental unit for studies of soil genesis at the landscape level rather than the pedon. The pedon and soil mapping unit are conceptual constructs that were invented to help us convey information about the spatial variability of the soil continuum when pen and paper were the only means to convey this information. These constructs have served pedology
well, however, geographic information system technology and high-speed computing capabilities present new and innovative opportunities to both depict and understand the spatial dimension of soils and landscapes. We now have the ability to depict the continuously varying nature of the terrain quantitatively as a three-dimensional surface (Fig. 4). Consequently, to the extent that changes in the terrain are associated with changes of the soil continuum, we can model and depict the spatial variability of soil horizons in reference to the topographic surface (Fig. 9a,b).

The practical application for theories of soil genesis from a landscape perspective has been for mapping soils. Traditional soil mapping efforts, in most countries, rely on qualitative relationships gained through years of experience. Unfortunately, much of this qualitative information is not documented and, consequently, it is not available to the scientific community, and cannot be shared or verified. The ability to quantify soil-landscape relationships presents the opportunity to publish and debate them in the scientific literature and to quantify what many pedologist have learned from field experience, but have been incapable of efficiently articulating to other scientists. The quantification of soil-landscape relationships also provides a means to link pedology at the landscape scale to other quantitative sciences such as hydrology and climatology.

The approach described here is appropriate for regions where topography is the predominant factor controlling soil genesis. The optimal spatial scale will vary depending on local landscape conditions and the desired results. The spatial patterns of soil properties, illustrated in Figure 9a,b, could be either used with existing soil survey information to estimate locations of map unit inclusions and to estimate the range of soil properties found within the map unit. Quantitative soil-terrain modeling approaches have the potential for mapping soils for large scale (<1:12,000) applications such as site specific crop management for certain landscapes. The use of quantitative soil-terrain modeling techniques are not intended to replace field work by qualified pedologist for soil mapping. These techniques provide tools to the assist the field scientist with the organization of information about the soils and landscape and rely on considerable field work to develop and validate the quantitative models.

Conclusions.

1. Terrain variables derived from a 10-meter DEM explained 51% of the variability in A-horizon depth and 44% of the variability in depth to carbonates for this study site.

2. The spatial pattern of variability in A-horizon and carbonate depth can be estimated for the entire hillslope from spatial patterns of the wetness, drainage proximity, and accumulated flow indices for this study site. These indices were calculated from combinations of slope gradient, specific catchment area, elevation above the nearest drainage path, and horizontal distance to the nearest drainage path derived from a 10-m DEM.
3. The terrain variables that are most highly correlated to A-horizon and carbonate depth suggest that the movement, distribution, and residence time of soil water across the hillslope are driving factors for the genesis of these soil features.

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Mobilisation, Segregation Precoce Du Fer Conduisant Au Cuirassement Et a L' Allitisation en Milieu Ferrallitique Hydromorphe
L' Exemple des "Llanos Orientales" de Colombie.


Introduction..

Les processus précoces de mobilisation géochimique du fer et les mécanismes corrélatifs de transformation des minéraux argileux au sein de séquences de sols ferrallitiques affectés par l'hydromorphie ont été étudiés dans les régions de savanes tropicales humides des Llanos de Colombie (bassin de l'Orénoque). L'approche de l'évolution pédologique est facilitée par l'origine récente des sédiments alluviaux à partir desquels se sont modelés les paysages et différenciées les séquences pédologiques.

La région d'étude : l'Altillanura, un plateau modelé par un réseau hydrographique très dense.

Cette unité physiographique de plusieurs milliers de kilomètres carrés domine de quelques dizaines de mètres les grands affluents de l'Orénoque issus des Andes. Dans son ensemble elle forme un plan faiblement incliné vers l'Est. Le réseau hydrographique qui la draine est très dense et ramifié. Il est relié à un système de nappes superficielles, fluctuantes, mais présentes en tous points et en toutes saisons, qui l'alimente abondamment et de façon permanente en raison des abondantes précipitations (environ 3000 mm) qui tombent sur la région bien que la répartition annuelle de ces dernières soit soumise à de forts contrastes saisonniers : une saison sèche de 3 à 4 mois (décembre à mars) alterne avec une période intensément pluvieuse (Avril à Novembre) au sein de laquelle les précipitations vont en s'accroissant jusque vers juillet-août et diminuent ensuite.

L'incision plus ou moins importante des axes de drainage entraînant les épaisses formations pédologiques conditionne la position des nappes au sein de ces dernières et l'apparition de phénomènes de cuirassement. Il en résulte l'existence de deux types de paysages:

- "l'altillanura peu disséquée" (Altillanura poco disectada) dans laquelle les nappes sont relativement superficielles et les phénomènes de cuirassement absents,

- "l'altillanura disséquée" (Altillanura disectada) où les nappes sont beaucoup plus profondes et l'ensemble du réseau hydrographique est oublé par des cuirasses qui traduisent l'induration, à proximité des axes de drainage, de certains horizons pédologiques enrichis en fer.
Ces deux types de paysages paraissent dériver l'un de l'autre, aussi est-il important de saisir les mécanismes pédologiques dans les stades de jeunesse du paysage. Pour cette raison, dans le cadre d'une étude plus large la distribution, les propriétés et le fonctionnement des sols ont été étudiés de façon détaillée dans l'altillanura peu disséquée.

**Toposéquence de sols caractéristique d’un interfluve de "l'Altillanura" peu disséquée.**

*a) Organisation au niveau du paysage :*

Les sols se répartissent de façon assez identique d’un interfluve à l’autre. De la partie sommitale de chacun de ces derniers en direction des axes de drainage hydrographiques ("caños") il existe de véritables toposéquences. En tous points de ces dernières on distingue la succession verticale de cinq grands ensembles qui peuvent correspondre suivant les cas à un ou plusieurs horizons pédologiques.

De haut en bas s'étalent successivement les ensembles (Figure 1a):

- jaune (J), poreux en raison d’un travail faunique intense,
- de transition jaune-rouge (JR) puis rouge-jaune (RJ),
- rouge (R), plus compact, peu affecté par la faune,
- rouge nodulaire (Rn) qui passe progressivement à un ensemble encore très riche en nodules mais qui cette fois se détachent sur une matrice de couleur blanchâtre très déferrifiée (Ar).

Tous ces ensembles à l'exception du plus profond s'amenuisent et sont de plus en plus marqués par l'hydromorphie de l'amont vers l'aval.

*b) Caractères hydrologiques.*

Deux nappes affectent ces ensembles (Figure 2):

- l’une profonde et permanente fluctue amplement au rythme des saisons, de plusieurs mètres au centre de l'interfluve. Sa zone de battement annuel correspond approximativement avec l'ensemble le plus profond (Ar). En effet le toit de cette nappe coïncide lors des hivernages les plus forts avec la limite supérieure de cet ensemble. La frange capillaire dans ces périodes de hautes eaux affecte jusqu’à l'ensemble rouge nodulaire (Rn).
- l’autre superficielle temporaire voire fugace car liée aux grands épisodes pluvieux se localise au sein de l'ensemble Jaune (J). A partir de cette nappe des infiltrations vers la profondeur existent en des sites très localisés.

Entre ces deux zones affectées par les nappes l'ensemble rouge constitue une zone relativement sèche. Vers l’aval les deux types de nappes se rapprochent puis finissent par converger, l'ensemble rouge, ou plutôt sa continuation n'occupe plus alors qu'un volume très réduit.

*c) Caractères morphologiques et micromorphologiques des différents ensembles. Relations avec l’hydromorphie et le travail de la faune.*

(Figure 1c)

- L’ensemble jaune superficiel est très poreux en raison d’un travail très intense de la faune. Vers l’amont il apparaît homogène sur le terrain mais l’étude micromorphologique indique qu’il est en fait constitué par la juxtaposition de volumes déferrifiés et de zones d’accumulation ferrugineuses brunâtres qui sont l’expression d’une hydromorphie ménagée.
Vers l'aval alors que la couleur d'ensemble devient de plus en plus claire les volumes déferruginisés prennent de plus en plus d'importance. Les amoncellements ferrugineux se résument à quelques rares concrétions.

- L'ensemble Rouge (R) dont la texture est identique à celle de l'ensemble jaune est beaucoup plus compact : les traces d'activité biologique se limitent à quelques chenaux verticaux localisés, la structuration résulte surtout de phénomènes de fragmentation produisant des agrégats de type polyédrique. En amont à toute échelle d'observation cet ensemble est très homogène et présente une couleur uniforme. Vers l'aval il devient progressivement hétérogène : la périphérie des agrégats se décolore tandis que leurs cœurs se ferruginisent.

- Dans les ensembles de transition Jaune-Rouge (J-R) et Rouge-Jaune (R-J) on assiste à une juxtaposition de volumes possédant toutes les caractéristiques de l'ensemble Rouge et d'autres qui possèdent toutes celles de l'ensemble Jaune superficiel et notamment une microstructuration et une porosité liées aux actions fauniques. En fait les volumes jaunes très poreux sont en continuité avec l'ensemble superficiel. Au niveau du profil ils présentent une forme d'entonnoir allant en se rétrécissant vers le bas et se prolongeant au travers de l'ensemble rouge. C'est l'origine des étroits chenaux qui parcourent localement ce dernier ensemble. D'amont vers l'aval les volumes rouges présentent les mêmes caractéristiques que ceux de l'ensemble du même nom, d'une répartition homogène du fer on passe progressivement dans les éléments structuraux à une ségrégation centrifugée des composés ferrugineux. Les volumes jaunes ont une évolution identique à celle de l'ensemble superficiel : ils se déferruginisent.

Les volumes les plus travaillés par la faune, les plus poreux, sont ceux qui dans les ensembles de transition et l'ensemble rouge, sont le plus facilement pénétrés et saturés par l'eau. C'est en leur sein que les effets de l'hydromorphie sont le plus rapidement sensibles. Vers l'aval c'est à partir d'eux que la déferruginisation progresse repoussant une partie des composés ferrugineux vers le cœur de la plupart des agrégats. Actions fauniques et hydromorphie combinent leurs effets pour conférer au sol ses caractères morphologiques.

- Les ensembles de profondeur (Ar et Rn) sont beaucoup moins affectés par le travail de la faune. Leurs caractères morphologiques sont essentiellement liés aux effets de l'hydromorphie. L'ensemble le plus profond saturé par l'eau une grande partie de l'année possède une matrice déferruginisée de couleur grisâtre dans laquelle s'individualisent des concrétions ferrugineuses. L'observation micromorphologique indique qu'en profondeur les dépôts ferrugineux s'effectuent dans les plans de litage du sédiment original donnant des nODULES dont la structure interne alterne bandes argileuses grisâtres et ferrugineuses rouges. Vers le haut le fer oblitère progressivement les parties argileuses aboutissant à des nODULES pratiquement opaque au microscope. C'est ce dernier type de figures qui caractérise principalement l'ensemble rouge nodulaire.

Il existe deux modes de fonctionnement hydrique dans une séquence de ce type

- les ensembles supérieurs, J, J-R, R-J et R s'apparentent à une dynamique de type pseudo-gley voire pseudo gley glossique : présence d'une nappe temporaire superficielle, pénétration en profondeur de l'eau par des cheminements préférentiels, dynamique centrifugée du fer dans les agrégats lorsque vers l'aval l'intensité de l'hydromorphie s'accroît.

- les deux ensembles inférieurs et notamment le plus profond ont un mode de fonctionnement plus proche de celui d'un gley : déferrification intense de la matrice, individualisation du fer dans des espaces préexistants, dans ce cas, les plans de litage du matériel alluvial.
1. Fonctionnement de type pseudogley
2. Fonctionnement de type gley

Figure 1 - Organisation verticale et latérale des ensembles dans une toposéquence de référence.

a - Schéma général de la toposéquence.
   1. Ensembles de surface (J, JR, RJ et R) affectés par un fonctionnement de type pseudogley (nappe temporaire, voir figure 2).
   2. Ensembles de profondeur (Rn et Ar) affectés par un fonctionnement de type gley (nappe permanente, voir figure 2).

b - Légende : couleur Munsell.

c - Aspect micromorphologique. On notera la progression de la nodulation de l'amont vers l'aval. (Les rectangles en a, représentent les emplacements approximatifs des sites de prélèvement dans la séquence).
Dans la partie amont et moyenne de la séquence ces deux dynamiques sont parfaitement individualisées. Les ensembles supérieurs sont affectés par une hydromorphie ménagée. Vers l'aval, le rapprochement puis la jonction des nappes, l'intensification et la généralisation de l'hydromorphie qui en résulte, aboutissent à des interférences entre ces deux processus. Seule une lecture approfondie du sol aux échelles les plus fines permet d'en saisir la coexistence.

Figure 2 - Position des nappes durant les saisons sèche (février) et humide (novembre).

Aspects minéralogiques et géochimiques.

a) - Nature et dynamique des composés ferrugineux.

Les quantités de fer libre, proches de celles du fer total, augmentent progressivement vers la profondeur. En haut de séquence les taux varient de 3,5% à des valeurs voisines de 8% en profondeur alors que dans l'ensemble rouge ils sont proches de 5%.

A l'intérieur d'un même ensemble les valeurs globales varient peu latéralement à l'exception de l'ensemble de surface et des parties travaillées par la faune qui le prolonge vers le bas : les taux de fer y sont environ 10 fois plus élevés en amont qu'en aval.
Ce sont essentiellement la répartition et la nature des composés ferrugineux, et surtout la proportion relative de goethite et d'hématite, à l'intérieur d'un ensemble qui conditionnent l'aspect du sol : les parties rouges quelle que soit l'intensité de cette couleur contiennent un mélange de ces deux formes, alors que dans les parties jaunes, qu'elles soient foncées ou claires, seule subsiste la goethite.

Les goethites présentes dans ces milieux possèdent toujours des taux de substitutions élevés, proches de ceux admis comme maximaux pour cette espèce minéralogique.

L'apparition d'une couleur jaune dans les zones affectées par des conditions d'hydromorphie correspond, ainsi que l'ont amplement démontré des travaux expérimentaux effectués sur ces mêmes sols à une dissolution sélective de l'hématite sous l'influence de microorganismes capables de vivre en anaérobiose. Le jaunissement du sol est l'expression d'une hydromorphie modérée (MACEDO et BRYANT, 1989 - JEANROY et al, 1991). Lorsque les conditions d'hydromorphie s'accentuent la goethite est également dissoute. Cette dernière est alors d'autant plus résistante aux conditions réductrices engendrées par les phénomènes de saturation hydrique que les taux de substitution alumineux qui la caractérisent sont élevés.

Une partie du fer dissout migre pour reprécipiter dans des sites plus oxygénés : plan de litage du sédiment dans les zones affectées par un fonctionnement de type gley, cœur des agrégats, dans lesquels l'air se trouve comme emprisonné de la manière d'une bulle lorsque les volumes rendus poreuses par le travail de la faune sont saturées d'eau, pour les parties caractérisées par une dynamique hydrique de type pseudo-gley.

Les figures d'accumulation d'abord molles et correspondant à des taches lorsque les quantités de fer sont modérées s'indurent quand il augmente pour former de véritables nodules qui se séparent aisément de leur matrice argileuse. Quel que soit le type de figures considéré les produits ferrugineux qui la composent correspondent pratiquement exclusivement à des formes cristallisées : seulement près de 1% du fer total est extrait par le réactif de Tamm considéré comme un agent d'extraction spécifique des formes non ou peu organisées.

Le fer qui reprécipite s'individualise majoritairement sous forme d'hématite, d'où la couleur rouge de ces taches et concrétions y compris dans les milieux hydromorphes, ce qui peut apparaître en contradiction avec le fait que ce minéral est considéré comme caractéristique des milieux secs.

Une possible explication de l'existence de l'hématite dans ces milieux consiste à admettre comme l'on fait TARDY et al. (1988) qu'une faible activité de l'eau nécessaire à la formation de ce minéral peut exister sous deux conditions :

- dans les milieux secs c'est à dire lorsque dans presque tout le système poral existent au moins momentanément des conditions de sécheresse;

- dans les milieux humides à l'intérieur des pores de très petite taille. L'eau liée y est très fortement retenue, elle possède alors une très faible activité et ne peut plus participer aux néosynthèses minéralogiques, d'où la formation d'oxyde déshydraté comme l'hématite.

Les observations au microscope électronique de la conformation interne des nodules montrent que les pores les plus fins subsistant en leur sein sont progressivement oblitérés par ce minéral.
b) - Nature et évolution du cortège argileux.

En tous points de la séquence les deux minéraux qui dominent sont la kaolinite et le quartz. Le premier diminue de la profondeur vers la surface passant d'environ la moitié à un quart de la masse totale du sol. Dans les termes situés en amont de la séquence cette diminution n'est réellement sensible qu'à partir des horizons de transition et dans l'horizon de surface, plus en aval elle se manifeste plus profondément dans le profil, affectant principalement les volumes déferrifiés. Le second augmente naturellement, en sens inverse, de la profondeur vers la surface.

Pour les minéraux de moindre importance pondérale, à coté des composés ferrugineux figure la pyrophyllite considérée comme inaltérable et donc totalement héritée, la muscovite, qui de bas en haut se transforme progressivement et intégralement en vermiculites hydroxyalumineuses (HIV) et enfin la gibbsite. Les nodules ferrugineux de toutes origines possèdent toujours des teneurs en argile élevées qui dans les positions situées en aval contrastent avec celles de la matrice qui les entourent. La nature du cortège argileux emprisonné dans ces nodules est très voisin de celui présent dans les ensembles inférieurs et médians en amont de la séquence. La composition interne des nodules est un témoign de la composition du sol au moment de leur formation ce qui signifie que la diminution du taux d'argile dans la matrice s'est produit postérieurement à leur formation.

L'accumulation d'aluminium sous forme de minéraux alumineux, HIV et Gibbsite, s'effectue dans la séquence suivant deux directions :
- verticalement, atteignant en chaque point de la séquence des taux maximaux dans les ensembles les plus superficiels.
- latégalement, dans ces mêmes ensembles de l'amont vers l'aval, par l'augmentation de gibbsite. L'aluminisation se produit donc préférentiellement dans les volumes touchés par l'hydromorphisme et la déferrification.

La formation des HIV se produit par évolution des muscovites qui perdent potassium et silice et qui en revanche s'aluminisent. Les HIV qui caractérisent ces sols correspondent à des formes fortement aluminisées. Une partie de cet aluminium peut provenir de la dissolution des oxydes et des hydroxydes de fer qui possèdent des taux de substitution en aluminium plus ou moins importants.

Fait important HIV et Gibbsite coexistent au sein des mêmes sites et s'accroissent simultanément. Dans ces milieux l'aggradation d'aluminium dans les édifices micacés n'apparaît donc pas antagonique de la formation de gibbsite comme l'avait suggéré JACKSON (1963) en invoquant "un effet antigibbsitique " des HIV.

Cependant la seule dissolution des oxydes et hydroxydes de fer ne suffit pas à expliquer toute l'alumine accumulée dans ces milieux.

Alors que HIV et gibbsite s'accroissent dans les mêmes sites les kaolinites diminuent. Une part non négligeable disparaît par appauvrissement probablement en relation avec les actions fauniques, une autre de moindre importance par désilification. Plusieurs faits plaident en faveur de cette hypothèse :
- un mauvais degré de cristallinité des kaolinites attesté par des études en spectroscopie infra-rouge.
- des teneurs élevées en silice dans les eaux qui drainent ces milieux.
- la dénudations des kaolinites suite à la déferrification résultant des conditions d'hydromorphie qui met ces argiles au contact avec la solution du sol facilitant les réactions d'équilibre.
- le fait que l'autre seule source possible d'aluminium dans ces milieux à savoir les HIV fortement alumineuses apparaissent dans ces conditions de milieu comme beaucoup plus stables que les kaolinites.

En effet le diagramme de stabilité du système SiO2-Al2O3-H2O établi par KARATHANASIS (1988) pour des sols acides du même type démontre que les HIV fortement alumineuses à la différence de vermiculites peu aluminisées sont beaucoup plus stables que la kaolinite. Dans ces conditions, l'équilibre thermodynamique s'établit entre le couple HIV-Gibbsite, la genèse de ce dernier minéral étant alimenté par la désilification des kaolinites, phénomène facilité par la mauvaise cristallinité de ces argiles.

Les observations réalisées au microscope électronique confirment largement cette hypothèse : les kaolinites des volumes déferrifiés présentent des figures de corrosions très importantes alors que celles existant dans ceux qui ne le sont pas échappent à ce phénomène. La gibbsite formée au cours de ces processus de désilification finit par s'individualiser sous forme de fines concrétions qui restent molles mais qui néanmoins peuvent se séparer parfaitement de la matrice qui les entoure.

Conclusions :

Les milieux récents des Llanos orientaux de Colombie correspondent à des sites très favorables pour saisir les mécanismes de mobilisation et de redistribution du fer et les effets que ces processus induisent sur les autres constituants minéralogiques dans les milieux latéritiques hydromorphes. Le long des toposéquences caractéristiques dans la partie supérieures des sols la dynamique hydrique étroitement liée au travail de la faune induit un mode de fonctionnement de type pseudo-gley qui s'oppose à un autre de type gley en profondeur.

Les processus hydromorphes entrainent la solubilisation préférentielle des hématites par rapport aux goethites surtout si ces dernières sont très alumineuses, phénomène qui se traduit initialement par un jaunissement du sol. Une partie du fer solubilisé reprécipite à courte distance dans des sites plus aérés sous forme d'hématite qui participe à la formation de taches et de nodules.

Ces processus s'accompagnent d'une stabilisation des édifices micacés qui se transforment en HIV fortement alumineuses. Les kaolinites évoluent par désilification laissant un résidu alumineux qui s'individualise sous forme de gibbsite.

Outre une ségrégation du fer, tous ces processus aboutissent finalement à un enrichissement du milieu en aluminium qui se concentre dans trois types de minéraux différents : les HIV, les goethites alumineuses et enfin la gibbsite.

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**Symposium B**  
**Thursday, July 14**  
**morning session**

**Micromorphological Indicators of Anthropological Effects on Soils**

Convener: L. P. Wilding (USA)  
Co-convener: Klaudia Oleschko (Mexico)

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Micromorphological Indicators of Anthropologenic Effects on Soils

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Micromorphology is the science that studies microfabrics of undisturbed materials by microscopy (light optical and less frequently submicroscopy) methods, commonly using thin-section techniques. This tool is employed to elucidate supplemental information about the environmental setting, micromorphological features, and physical, chemical, mineralogical and biological habitat in an in situ architecture. While the technique was develop by the geological sciences over 100 years ago, it has gained recognition as a powerful tool in other earth sciences only since the early 20th century.

Historically in its early development, and to some extent today, micromorphology was steeped in fabric terminology, mostly unintelligent to ancillary scientists. A major focus was on a descriptive science with heavy application to pedology. The multidisciplinary problem-solving orientation was underemphasized. However, since the middle 1970's micromorphology has seen a dynamic surge in utilitarian applications. For example, it has been used to: (1) trace pathways of water and solute movement; (2) to quantify degradation of soil structure with consequent formation of crusts, hard pans and tillage pans; (3) to identify shear-strength failure and land instability; (4) to elucidate chemical degradation and remediation of lands by heavy metals, pesticides, petroleum organics and salts; (5) to verify microsite chemical, physical and hydrological alterations of drained and undrained wetland habitats; (6) to establish lifestyles and cultural patterns of ancient people; (7) to determine paleoenvironments and climatic changes from paleopedology records; and (8) to quantify the anthropogenic effects on the above phenomena. It is the latter which stimulated this Symposium in concert with the theme of the International Congress of Soil Science entitled, "Soil Utilization in Harmony with Nature". Papers of the Symposium not only support the theme of this Congress but illustrate the modern emphasis and focus of micromorphology. They nicely illustrate that micromorphology represents only one of the contributions to resolution scales from submicroscopic to megascopic. The papers are at the cutting-edge of science, but are realistic in the limits of information content that can be gained from micromorphology without incorporation of other multi-faceted analytical tools.

In Mexico and other Latin American countries there is a rich heritage of cultural history. The blend of both modern and ancient civilizations has taken its toll on soil, air and water resources in these countries as elsewhere in the world. Micromorphology provides a simple, rapid, inexpensive and non-destructive analytical tool to identify early warning signals of land degradation and soil health demise. A training center is needed in this sector of the hemisphere that offers the opportunity to teach faculty and students the applications of micromorphology in the context of a holistic soil system. A workshop that integrates soil micromorphology with soil taxonomy, pedogenic processes and soil behavioral responses from alternative land management practices is in order. Such a workshop, headquartered in Mexico City, Mexico, that addresses the sustainability of land resource issues as mandated in Agenda 21 would be well received by the International Soil Science Society and Subcommission B: Micromorphology. We offer this invitation as a challenge to be met in the future.
Micromorphological indicators of anthropogenically induced soil structural degradation


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Abstract. The impact of human activity on soils has had profound effects on a wide range of soil structural properties, which in turn impacts on runoff and erosion, the soil water balance and plant growth and thus productivity. This paper reviews how micromorphology has been used to describe and quantify anthropogenic effects on soil structural properties. Particular emphasis is placed on soil crusting, but hardsetting, compaction and the impacts of tillage and stubble management on both surface and subsurface horizons are also discussed. The focus is placed on developments in the last decade and some recommendations for future research are presented.

Introduction. This paper reviews the contribution of micromorphology to the enhancement of understanding of a number of soil structural changes generally caused by anthropogenic activities. Whilst much of the literature focuses on relatively recent changes to soil structure, it is pertinent to note that studies by Valentine and Dalrymple and more recently McPhail amongst others have used micromorphology as a tool to recognize the effects of anthropogenic disturbance of soils in the England and Italy dating back to the Neolithic period. Once formed many soil properties change very slowly. Micromorphology therefore provides a methodology for both the explanation of the effects of various current anthropogenic influences on soils and for exploring past changes in land use practice, for which no other records often exist. The aim of this paper is to determine the soil micromorphological properties which are useful as diagnostic features of structural change and which can be used to enhance our understanding of the effects of past and present changes in cultivation practice and land use. It is important to note that the term soil structural degradation is poorly defined and often not determined quantitatively. In this review, we take it to mean a change in soil physical properties that leads to slower water entry, increased runoff and bulk density, higher soil strength and compaction all of which can result in reduced plant production and potentially serious off-site environmental consequences.

Anthropogenic influences include cultivation, grazing and uses of the soil resource are considered in terms of the development of surface crusts and, to a lesser extent, hardsetting, compaction and changes accompanying the development of sodicity. Attention is given to changes in morphological and associated soil physical, biological and chemical properties which accompany soil structural degradation.

The review commences with a flow chart summarising the procedures for thin section and polished block preparation to assist with their systematic preparation, description and analysis in studies of soil structural changes. A model for crust development and evolution is then presented along with descriptions of the micromorphological properties of the different forms of soil crusts. The role of micromorphology in describing processes and properties in hardsetting, compaction and sodic soil horizons is also considered. The review concludes with discussion of the impact of land use practices on micromorphological properties and with some suggestions for the future directions of research.
Sample preparation and analysis methodology. Sample preparation and handling which minimise post-sampling structural damage is paramount in investigations which aim to characterise treatment/management effects on soil properties including porosity, soil fabric and soil microstructure. Sampling, sample drying and sample impregnation procedures must be chosen to minimise artefacts. A number of techniques have, however, been developed in recent years which can help overcome these problems and some of which greatly accelerate sample preparation. These are shown in flow chart form in Figure 1, which contrasts various thin section and polished block production methods and time required. Options to minimise sample disturbance include in situ impregnation with water-miscible epoxy resins containing fluorescent dye and an opacifier (3, 4) and encasement of the sample in plaster of Paris to facilitate transport back to the laboratory. Minimising shrinkage is of major importance during sample drying and impregnation. In field impregnated samples this problem is overcome, but in the laboratory other techniques including water replacement using either acetone (5) or dioxane (6, 7) can also be used. Care needs to be taken in both cases because some soil clays are dispersive and/or swell in water-acetone mixtures and both reagents are relatively toxic. Once samples have been successfully dried and impregnated other potential problems arise in terms of how measurements should be made. Generally, the choice is between thin-sections and polished blocks. Murphy and Kemp (8) demonstrated that the finite depth of thin-sections could cause errors in estimation of pore size and clay contents. Studies by Ringrose-Voase and Bullock (9) have shown that polished blocks offer an accurate and effective means of determining many of the pore space properties required. Polished blocks have to be digitised by using either direct video imaging, or via an intermediate photographic process. The choice of system used depends upon preference and cost. Following image capture, the next stage is image analysis. There are now many software packages which can analyse either grey levels or colour scenes using the principles of mathematical morphology. These range in complexity and price. A wide range of structural features can be determined from processed images. These include pore area, pore perimeter, pore and pore neck diameters, and shapes of pore and solid features. The most serious difficulty encountered in image analysis is usually related to the determination of 3-dimensional shape of the imaged 2-dimensional features. This difficulty can be overcome by the use of stereology (9), or by the analysis of sequential polished surfaces to build a 3rd dimension. The limits of these techniques are determined by their ability to resolve optically fine porosity. Scanning electron microscopy (10) can be used to extend their application into the submicron pore size range. Small sampling volumes and limited replication may also be of concern in a number of studies (11, 12), in which generalisation of local results to wider areas are required. A more detailed treatment of sampling, laboratory treatments, description and analysis of soil microstructure is given by Ringrose-Voase (13). Whilst image analysis has greatly improved our ability to quantify soil microstructure, conventional thin section descriptions should not be overlooked, because many important structural properties can be determined from the soil fabric. As colour image processing and pattern analysis techniques are applied in micromorphology increasing opportunities will appear for the quantification of soil fabric.

Micromorphological indicators of soil crusting. Soil crusting can be a natural phenomenon, but there are numerous instances in both arid and humid environments where anthropogenic activities have caused crusts to form with major consequences both for on and off-site activities in terms of crop losses, erosion and sedimentation. Soil crusting affects most parts of the world. Arid and semi-arid areas are the most exposed to this form of surface degradation since nearly the whole landscape is permanently affected, including croplands and rangelands. In the humid tropics, crusting occurs
extensively where the soil is left uncovered after land clearance, during the crop preparation period and the early fallow period. In temperate areas, surface crusts only develop on unstable soils, mainly as a result of crop management practices. Soil surface crusting strongly reduces infiltration rate,
which not only decreases soil water storage but also triggers and favours runoff and hence soil erosion hazards. Moreover, surface crusts can induce failure of seedlings to emerge and hamper crop establishment. Predicting soil surface crusting in the field and preventing its consequences requires knowledge of soil processes, management practices and climatic conditions. Cultivation, whether by hand or machine significantly affects the soil surface and its propensity to crusting. However, whether crusting occurs depends on exposure to rainfall intensities high enough to induce aggregate breakdown and on a range of soil properties including chemical properties such as exchangeable sodium percentage and other chemical properties, organic matter content, particle size and mineralogy which all affect dispersibility and thus crusting potential. Micromorphological investigations of soil surface crusts have been found useful for fifty-five years (eg 14). Recently, West et al. (15) summarised the morphological characteristics of surface crusts and their genesis in relation to soil, rainfall and topographic characteristics. A detailed literature review from the period 1939–1991 of more than sixty papers involving micromorphology (16) assessed the specific contribution of micromorphology in our understanding of the various processes which are involved in crust formation. Microscopically-defined crust types can be identified in the field using morphological diagnostic features (17). Since these types are genetically related, such a classification helps to assess the crusting rate as well as the processes involved, thus gives some insight into predicting soil degradation and selecting the most suitable control techniques (18). In the following sections crusting processes are discussed in terms of a dynamic model and crust typology and related diagnostic features are presented.

**Soil crusting processes.** Humanity's greatest effect of soil crusting may be in the way soils are tilled for the cultivation of crops. Soils that have undergone traditional European cultivation are left in an open and porous condition and have high saturated hydraulic conductivities. When rainfall occurs, even at low intensities, the rate of water intake becomes less and runoff and erosion can occur. This is due to a number of processes acting in conjunction which lead to a sealed surface when wet and crusted when dry. A number of tools may be used to study the surface crusting processes including micromorphology (19), microtopographers (20) and infiltrometers (21). The most effective way to elucidate the various processes is to use all of these tools together. Microtopographers can be used to study the associated changes in surface form that occurs with surface crusting. A rough surface form is important for reduction of wind speed and erosion, causing high water depressional storage and friction to slow runoff water. Microtopographic changes from the freshly tilled surface condition were monitored (Fig. 2) through the growing season with natural rainfall for a midwestern mollisol from the USA (20). The initial change in microtopography actually causes the surface roughness to become greater than the freshly tilled condition, even with a small amount of rainfall. This is because the fine material consolidates in the interstices while the large scale roughness produced by the larger clods does not change. Dispersion of the finer material by the low electrolyte content of the rainwater and mechanical energy of the raindrops (21) and slaking (22) further reduce the small scale roughness while the larger clods remain. As additional wetting and drying cycles occur and the mechanical beating of the raindrops continues, the large scale roughness begins to be reduced and the fine material produced fills the interstices between the clods. The end result is an almost completely sealed smooth microtopography after just 231 mm of rainfall (Fig. 2d) and a crusted surface with low saturated hydraulic conductivity.
Surface sealing was studied on this same soil in the laboratory under simulated rainfall using an infiltrometer and the procedure of Bradford et al. (23). Freshly packed soil sieved to pass 4mm was packed into the infiltrometer and saturated from below. Following saturation and equilibration replicate control and treated surfaces received constant rainfall at a rate of 37mm/hr for two hours, a total amount intermediate between Figures 2b and 2c. The treated surface received a surface treatment of 5 t/ha phosphogypsum to remove the chemical dispersion effect of the low electrolyte water (21).

Figure 2. Changes in microtopography under natural rainfall of a midwestern Mollisol from the USA (after Huang and Bradford (20))
Figure 3. Infiltration rate as a function of cumulative rainfall during the sealing process. The dashed line represents 5MT/ha addition of phosphogypsum and the solid line control.

For each treatment the infiltration rate was initially greater than the rainfall rate which decreased asymptotically to a low steady state rate very quickly (Figure 3). The difference between the control and phosphogypsum treatments represent the conductivity caused by dispersion in the rainwater treatment because of the low electrolyte content of the water. In contrast the phosphogypsum treatment quickly releases electrolytes. Although addition of phosphogypsum doubled the low (~3mm/hr) infiltration rate to around 7 mm/hr, the chemical effect for this soil was minor compared to the reduction in infiltration (> 37mm/hr) from the mechanical effects of the rainfall.

The micromorphology of this soil was also studied following addition of 128 mm rain to freshly tilled soil with a rainfall simulator in the field (Figure 4). Thin sections shows that the soil has developed a continuous compacted zone representative of a "mechanical" crust (19) and little evidence was seen of a "washed-in zone" (24). Micromorphological examination supports the evidence from the microtopographic, and infiltrometer studies, that for this soil, the mechanical processes leading to crusting are dominant over the chemical effects of dispersion. Although as evidenced by the infiltrometer study, chemical processes do occur, and micromorphological study using 30 micron thick thin sections may not be the best way to see its redistribution of soil materials affecting infiltration. However, all three studies demonstrate that for this soil mechanical processes dominate the formation of a crust. Therefore, conservation practices that will prevent the impact of raindrops and prevent slaking in this soil would improve the water intake rate.

A crusting model. Soil crusting is a dynamic process, but one in which the various stages of crusting and crust forms are frequently genetically related. and form time- and space-dependent sequences as discussed by Valentin (25, 26) and Boiffin (27, 28). These authors indicate that microtopography plays a critical role in controlling the crusting process, a point which has been seldom considered by others with the exception of Falayi and Bouma (29), Norton (19) and Levy et al. (30). The dynamics of the crusting process involve the following stages: (1) sealing of the surface by a structural crust, then (2) development of a depositional crust. The change from the first to the second stage mainly depends on a decrease in infiltration rate due to the structural crust properties, which induces
microrunoff (25, 27, 28). These two stages can be identified in the field, using simple macroscopic features (27, 26) which can also be used to quantify the crusting rate (28).

Structural crusts generally develop faster where aggregates are finer, which explains why crusts observed in the field do not uniformly cover the seedbed surface (31, 32). Depositional crusts first form in microdepressions or interstices between large clods. As the soil surface flattens, the deposited microbeds become thinner but tend to expand more extensively over the former structural crust (31). In sandy soils Valentin (33) and Valentin and Bresson (18) have demonstrated that surface roughness is usually more transitory and the spatial variability of crusts occurs at a larger scale: structural crusts can be observed upslope, erosion crusts midslope and depositional crusts downslope.

**Major types of crusts.** From their studies of loamy and sandy soils, which involved more than 400 thin sections from more than 100 soils, Valentin and Bresson (18) suggested a typology of crusts based on macro- and micro-morphological characterisation (Table 1): (1) structural crusts including slaking (and swelling), infilling, coalescing and sieving (and coarse pavement) sub-types; (2) erosion crusts and (3) depositional crusts, with two sub-types, runoff- and still-. Such a morpho-genetic classification of crusts appeared to be relevant to the prediction of infiltration rates (31, 34, 35).

This typology seems to account for most of the crusts described in the literature (16), with the exception of cryptogamic crusts (36, 37) and rain impact crusts characterised by silt layer compaction (38).
Table 1. Crust types and diagnostic features

<table>
<thead>
<tr>
<th>CRUST TYPE</th>
<th>SUBCLASS</th>
<th>DIAGNOSTIC MICROMORPHOLOGICAL FEATURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural crusts</td>
<td>Slaking</td>
<td>Reduced aggregate size, increased microporosity, no textural separation of skeleton and plasma</td>
</tr>
<tr>
<td></td>
<td>Swelling</td>
<td>Banded skeleton grains within superficial parts of clods</td>
</tr>
<tr>
<td></td>
<td>Infilling</td>
<td>Textural separation, net-like infillings of silt grains</td>
</tr>
<tr>
<td></td>
<td>Coalescing</td>
<td>Porous, coalescence of aggregates decreasing with depth</td>
</tr>
<tr>
<td></td>
<td>Sieving</td>
<td>Surface skeleton grains overlying translocated clay</td>
</tr>
<tr>
<td>Erosional crusts</td>
<td></td>
<td>Poorly oriented fine particles, absence of relationship between layer thickness and surface microtopography</td>
</tr>
<tr>
<td>Depositional crusts</td>
<td>Runoff</td>
<td>Silty surface seals, loose aggregates</td>
</tr>
<tr>
<td></td>
<td>Ponding</td>
<td>Clay and silt laminae</td>
</tr>
<tr>
<td>Rain impact crusts</td>
<td></td>
<td>Compacted silt layers</td>
</tr>
<tr>
<td>Cryptogamic crusts(1)</td>
<td></td>
<td>Mosses, lichens, liverworts and algae, subsurface hyphae</td>
</tr>
</tbody>
</table>

(1) It is considered that cryptogamic crusts can develop under appropriate conditions on a wide range of other crust types.

**Slaking crust.** Slaking was one of the breakdown processes invoked by McIntyre (24). Aggregate slaking due to entrapped air compression was well documented by Robinson and Page (39), but few clear micromorphological illustrations of slaking-induced crusts were given before Le Bissonnais et al. (22) and Le Souder et al. (40). In the early stage of the crust formation, Onofik and Singer (41) described a reduction in the size of the aggregates in the upper 0.4 mm and a corresponding increase in micropores, which is good evidence of the model of aggregate breakdown suggested by Valentin (25) and Farres (42). Typically, slaking crusts consist of a thin dense layer which do not show clear textural separation between coarse particles (skeleton) and fine particles (plasma), even in sodic soils (18). Slaking crusts predominate when the soil is dry before rainfall (19, 22, 25, 28).

'Swelling crusts', observed in arid loamy soils (33), can be considered as a particular form of slaking crust (18). Such crusts are characterised by the banded distribution of skeleton grains within superficial parts of clods. Upon wetting, clay lattices expand, turn into a slurry and fill the interstices between clods (33). The latter process can be related to coalescing, as well as to the early stage of depositional crust formation ('muddy flow' (31)).

**Infilling crust.** Boiffin (28) described in the field a structural crust with net-like infillings of bare silt grains. Such crusts were clearly due to silt illuviation. Raindrop impact, rather than physico-chemical dispersion, induces textural separation at the top of surface aggregates and the resulting separated silt grains illuviate a few millimetres deeper into the interaggregate packing voids (43). Further laboratory studies (22) showed that such features developed only if the soil was wet before rainfall and that, with air dried samples, a slaking crust quickly sealed the surface. The washing-in process, defined by McIntyre (24) as the 'plugging of the large pores by washed-in material', might be similar to 'infilling'. Unfortunately, the literature is so confusing that no clear relationship can be established (16). McIntyre did not provide any information (description or illustration) about what
he called 'fine material', i.e. aggregates fragments or clay particles, but most later authors, quoting McIntyre, clearly considered the washing-in process as clay particle illuviation. However, only a few convincing illustrations of clay coatings related to crusting can be found in the literature (43, 44).

**Coalescing crust.** Bresson and Boiffin (31) described structural crusts which were rather porous and showed a diffuse boundary with the underlying undisturbed layer. Macropores were typical polyconcave packing voids at the bottom, but their amount and roughness gradually decreased towards the surface, as convexities developed. The main process involved was a gradual coalescence of the initial aggregates by raindrop compaction under plastic conditions. Coalescing crusts occur on soils which are wet before rainfall and are most developed in sodic soil (31). Ahmad and Roblin (45) and Moss (46) also described crusts where compaction was mainly due to aggregate deformation. Some of the crusts described in the literature look similar to coalescing crusts (47, 48).

**Sieving crust.** In arid sandy soils, Valentim (26, 33) described structural crusts with a surface layer of coarse skeleton grains, overlying a thin plasmic layer. Using a close time-dependent sequence of sampling, this author showed that textural differentiation mainly results from mechanical winnowing and sieving so that the finer the particles, the deeper they are deposited. Moreover, the downward translocation of clay through the coarse grained top layer can be enhanced by percolating water. Fine particles then accumulate, probably due to entrapped air within the underlying layers (49). In the wet tropics, such sieving crusts have been observed in cultivated sandy soils (50). This type of crust has also been called 'filtration pavement' (33) or 'layered structural crust' (35). Crusts with various names were related to sieving crusts by some authors, e.g. 'quartz crust' surface layers (51) and 'physical crusts' (52). Some of the coarse textured top layers described in the literature, especially when developed on sandy soils, seem to be similar to sieving crusts (14, 53, 54, 55). Also, some of the washed-in layers described in the literature might be part of sieving crusts.

In arid areas, pebbles are often embedded within a crust similar to the sieving crust described above (26, 33) with a pronounced vesicular structure, especially below the coarse fragments (56). Such a crust, called 'coarse pavement crust', can be considered as a particular form of sieving crust. Water infiltration through these crusts is very slow and is negatively correlated with increasing amounts of stone embedded in the crust (57). These crusts have also been described as vesicular crusts in the Australian arid zone soils by Jessup (58), Mabbutt (59) and Chartres (60) amongst others. Elsewhere, similar crusts have been described by Marbut (61), Thorpe (62). In most of these instances vesicular crusts appear to be associated with the occurrence of discontinuous stony surface layers known as desert pavements. In Australia, the soils associated with these desert pavements are often desert loams of variable depth. The A horizons of desert loams are generally shallow (2.5 to 10 cm) and characterised by extremely low organic matter contents, loamy texture and massive, pulverulent structure (63). In both hand specimen and in thin section surface crusts containing closed pores (vesicles) are common.

**Erosion crust.** Erosion crusts were defined by Valentim (25, 33) as thin, smooth surface layers enriched in fine particles. The fine particles are usually poorly oriented. Voids are generally restricted to some cracks and vesicles. The thickness of this plasmic layer is rather regular and is not related to the surface microtopography. Such crusts often resulted from erosion of the coarse textured top layer of sieving crusts (26). They form a rather resistant surface against further wind or water erosion, and therefore often cover large patches of land. Erosion crusts form first on the higher points, then expand over the surface as the global surface roughness diminishes. Some authors used the term of 'skin seal' (53, 55) to describe a similar type of layer enriched in clay particles compared to the underlying material as a result of preferential erosion of coarser particles by high energy raindrops (33, 53, 64). Greene and Ringrose-Voase (51) also described 'clay crust'
surface layers which relate to erosion crusts. Erosion crusts can be recognised from after rain deposits and eroded depositional crusts using not only their spatial distribution in the field but also micromorphological features of their plastic surface layer, namely (i) the poor orientation of the fine particles and (ii) the absence of relationship between the layer thickness and the surface microtopography (16). Erosion crusts are usually better developed in semi-arid to arid rangelands rather than in cultivated fields, presumably because the velocity of overland flow is not limited by the surface roughness of the seedbed. Moreover, rangeland crusts are not rejuvenated by tillage practices and often develop over many years (18).

Coarse textured layers can develop as a result of clay removal by overland flow (14, 65, 66). Such clay depleted microlayers were frequently described using the term 'washing out' (19) which was introduced by Onofiok and Singer (41). However, they were mainly observed in the laboratory where specific erosional conditions usually occurred (16).

**Depositional crust.** Crusts formed by deposition of the particles suspended in the overland flow were recognised by Evans and Buol (47). The term 'depositional crust' was later introduced by Chen et al. (53). Sedimentology provided the basic concepts which were transposed to the microenvironment of crust formation (67). Micromorphology was found a very useful tool for determining the main diagnostic characters, i.e. microbedding, particle sorting and orientation, which provide information on the hydrological conditions prevailing at the soil surface. Sorting of basic particles was studied by Mücher et al. (65). Deposits resulting from turbulent rainwash generally lead to laminae with 10-50 μm grains. Conversely, afterflow deposits show laminae with a greater percentage of particles smaller than 30 μm. Pure splash deposits do not show any lamination or particle sorting (65). The presence of aggregates within depositional crusts was also described (29). Mücher et al. (36) observed loose aggregates at the top of crusts, and suggested they were deposited by afterflow. Conversely, microbeds observed at the bottom of depositional crusts, filling in small pocket-like depressions in former structural crusts, contained small aggregates included within a densely packed material. This was related to a muddy flow process (31).

Various distribution patterns of microbeds have been described, e.g. 'rill' and 'finger-like' (36, 49) and deltaic (26). Superposition of different patterns has been used to assess the succession of different hydrodynamic conditions at the soil surface during crust development (31). Moreover, Bresson and Boiffin (31) also suggested that the size and duration of puddles played the main role in the characteristics of the depositional crust which, in turn, appeared to be partly controlled by the properties of the underlying structural crust. Some authors described as 'skin seals' (19, 68) or 'after rain deposits' (69) very thin and fine textured layers observed at the surface of some crusts as a result of deposition of clay particles dispersed in turbulent water flow when rain stops. Coarse textured surface microlayers occurring in slightly depressed areas, which showed that they were actually depositional features, have been described as 'washing-out' layers (70, 71).

**Silt-layer induced compaction.** Compaction by raindrop impact was invoked by McIntyre (24), but was not well documented in later micromorphological studies. Studying crust formation under simulated rainfall, Moss (38) observed after 1 min rain, a thin layer of tightly packed silt grains spread on the surface. Further experiments involving various kinetic energies as well as local shielding of the surface and telescopic observations, suggested that the silt layer played the major role in compaction of so-called 'rain impact' crusts (38, 46). Three stages could be distinguished: (1) 10-50 μm particles are concentrated at the surface by preferential removal of other sizes in the air-splashing environment; (2) the resulting silt grains are spread over the surface by lateral outflow sheets of the drops and deposit as tightly packed bed-load sediments; (3) this layer is dilatant, resists deformation by raindrop impact and prevents water penetration because its pores are <15 μm.
Therefore, the underlying layer may be compacted by stress waves (38, 46). Such a silt layer may be similar to washed-out layer described in the literature or to the sieving crusts observed on arid sandy soils by Valentin (26, 33) and Poss et al. (50). Besides, using a wider range of soil materials, Moss (46) also described plastic deformation of aggregates and washing-in of fine particles. The conditions which lead to silt layer induced compaction are yet to be established.

Cryptogamic crusts. Cryptogamic crusts have been recognised for many years in rangeland areas (72). However, the first microscopic characterisation of such crusts were carried out only recently in Australia (36, 37, 55, 73). Cryptogams develop preferentially on argillaceous materials containing carbonates and Ca-oxalate crystals exuded from plant roots during stable periods without deposition or erosion (36). Amorphous gel-like organic material has been observed near or associated with algal sheaths, and sometimes fungal hyphae extend a few millimetres below surface cryptogams (73). Individual algae, which often live in juxtaposition with lichens, contribute to aggregate stabilisation by secreting cementing gums (74), reinforcing the aggregation effect of associated fungal hyphae (72). The effect of cryptogamic crusts on the hydrological behaviour of the surface, however, is not well understood, and may be either beneficial or detrimental (75). Generally, such crusts are considered as a good protection against erosion due to their higher cohesion (72, 76). Destruction of the cryptogam cover by fire gives very clear evidence of its protective effect (37, 55, 73). However, Greene et al. (73) found that runoff could be greater from cryptogam mats than from bare surfaces and removal of the cryptogamic crust increased infiltration rate four times. This may be explained by the properties of the underlying layers which may control infiltration rate. Cryptogams have been observed on various types of crusts, erosion crusts and depositional crusts (18). Therefore, cryptogams should be considered as a micro vegetal-cover rather than a micro soil-layer, and thus should not be studied alone but in relation with the crust they colonise.

Micromorphological indicators of hardsetting. Hardsetting is a process that seems to operate most effectively in seasonally wet and dry environments in temperate and tropical environments. As yet it has not been adequately defined either physically or chemically, although it is characterised by the development of hard to very hard field consistence, poor aeration when moist and massive structure of soil A and E horizons, and is amplified by tillage (77, 78). Mullins et al. (78) have suggested that hardsetting develops partially as a consequence of effective stress processes. Whilst these processes are probably important, other physical factors including dense particle packing, appropriate particle size distributions and limited biological activity may also be significant in its development and may be recognised using micromorphology. In certain instances, ephemeral cementation by silica compounds may also play a part (79). Irrespective of the causes of hardsetting, soils which have this property are difficult to manage because of their propensity to change from too hard for cultivation to too soft as moisture content increases and thus have a very limited moisture range over which they can be worked without causing further structural degradation.

Micromorphologically, hardsetting horizons are characterised by low macropore space, a lack of microaggregation, porphyric fabrics with closely packed skeleton grains, little plasma and little or no evidence of soil faunal activity and organic matter. In many cases there are similarities in structure and fabric between hardsetting and fragipan horizons, although their processes of formation may be quite different and fragipans are natural as opposed to anthropogenically induced phenomena. In both cases several authors (79, 80, 81, 82) have proposed that amorphous silica compounds may account for the rigidity and strength of dry fragipan and hardsetting horizons. However, there is
little or no optical evidence to confirm the presence of these cementing agents. However, Chartres and Norton (81) have shown the occurrence of dirty, grainy zones consisting of very fine particles generally < 2 mm diameter is common to both hardsetting horizons and duripans, in which amorphous silica can be detected using optical methods. Observations using electron microscopy indicate that these materials consist of some very fine quartz grains and apparently amorphous particles and coatings of silica. EDXRA analyses indicate that Si/Al ratios are generally higher than found in layer silicate minerals and that Fe and Ti are commonly associated with these materials possibly suggesting strong weathering of clay minerals under seasonally wet and dry conditions (83)).

Micromorphological indicators of sodicity. Whilst crust development can occur as a response to sodic conditions, sodicity can also be responsible for a wide range of effects on soil properties below the soil surface. Sodicity, has in the past been defines as occurring when exchangeable sodium percentages are greater than 15 (84). In this paper we prefer to use the lower value of ESP (Equation 1) equal or greater than 6 (85). Whilst this equation 1 is commonly used, a more appropriate measure of soil sodicity is the sodium absorption ratio (Eq.2), which is thermodynamically more appropriate because it approximates to the activities of the various ions in solution.

\[
ESP = \frac{\text{Exchangeable Na}}{\text{CEC}} \times 100 \quad (\text{Eq.1})
\]

\[
\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{2+} + \text{Mg}^{2+}}{2}}} \quad (\text{Eq. 2})
\]

The use of the lower value of ESP is preferred for many soil types because several authors (86, 87) have demonstrated that soils can become potentially dispersive at very low ESP values if total cation concentrations are also low, which is often the case in leached environments. Micromorphologically, the characteristics of both the soil fabric and some pedological features may often provide evidence of past dispersive conditions. Redeposited dispersed clay has a tendency to pack in parallel oriented platelets, which when observed in thin section gives rise to relatively strong optical continuity and marked birefringence. In a thin section and SEM study of laboratory cores treated with sodium and calcium salts and then leached with distilled water Greene et al. (44) observed that in the sodium treated cores clay was dispersed and redeposited as void and fissure ferriargillans, with some clay being dispersed and redeposited as a strongly oriented surface seal. In other studies (e.g. 36) of crusted soils in which dispersion has taken place at some stage, such seals can be reburied and observed as zones of strongly oriented, sometimes disrupted clay within the matrix. Their greater width and parallel lamination can be used to differentiate them from stress induced cutans and similarly induced features in soils with ma and latti-sepic fabrics (88). Chartres et al. (89), Tessier et al (90) and Rengasamy et al. (91) found that clay mineralogy can have a strong influence on clay structures and orientation under sodic conditions with randomly interstratified minerals and smectites behaving differently from illititic and kaolinitic minerals under both floculating and dispersive conditions. In studies of two Australian red-brown earths (89) the soil with a higher proportion of illite/kaolinite had a higher proportion of void and grain ferriargillans.
and more sepic plasmic fabrics than the one with a higher proportion of randomly interstratified mineral/smectite. Similarly, clay content also influences dispersion/floculation processes as has been noted in many previous studies (86, 90, 91).

There is considerable evidence that crust formation is associated with clay dispersion and movement in the soil (93). However, on a sodic soil, Bresson and Boiffin (31) could not find any textural separation in structural crusts. Conversely, in a non-sodic environment, clear textural separation occurred, with silt grains illuviating just below the surface aggregates and clay particles depositing a few millimetres deeper. This was related to the remaining aggregate framework (43). El Morsy et al. (94) also suggested that conditions leading to dispersion provided a rapid crust formation which reduced the potential for illuviation. Therefore, textural separation should not be related to dispersive conditions. Moreover, other mechanisms often control the nature and the development rate of crusts. Even on sodic soils, swelling and deformation under plastic conditions could play the main role (31). Gypsum reduced crust formation more efficiently on soils with smectitic rather than kaolinitic clays (44, 89), which suggests that swelling occurred rather than real dispersion. As pointed out by Bresson and Valentin (16), physico-chemical dispersion, swelling and deformation under plastic conditions do not constitute different processes but different levels of the same process, i.e., hydration. Therefore, crust development in clayey and sodic environments should be related to global rheological properties rather than to the physico-chemical dispersibility sensu stricto.

Little et al. (95) also demonstrated that fabric and porosity varies between grey clays (Pellusterts) with differing structure and sodium contents. Argistriotubules (96) and papules associated with patches of adphorpyric fabric were found with increasing frequency below 30 mm depth and were considered indicative of clay dispersion and movement down the poorly structured, more sodic soil profiles. Fluorescent pore space images of the soil surface layers indicated a considerably greater area of macroporosity and continuous pore space in the better structure, less sodic soils and the authors hypothesised that these properties associated with widely spaced porphyric fabric may be important in the generation of self-mulching at the soil surface. The poorly structured profiles had close spaced porphyric, or adphorpyric fabric, which may prevent shrinking en masse and thus good aggregation is replaced by cracking.

Vesicular crusts or coarse pavement crusts may also develop under sodic conditions. In soils where they occur, the A horizons are frequently sodic with soluble salt concentrations variable, but often 0.5 mS/cm or less and no free calcium carbonate (97), thus suggesting that dispersion under sodic conditions may be a major cause of crust development in these soils with vesicles forming due to air being entrapped under a rapidly sealing surface. Limited data (63, 97) indicates that randomly interstratified and smectitic clays are common in the A horizons of desert loams. It is probable that the potential for these minerals to swell and disperse under sodic conditions further accentuates the probability of crust formation. Springer (56), Mabbutt (59) and Chartres (97) have all suggested that the swelling nature of soils with these vesicular crusts also may account for the development of desert pavements via the upward movement of stones through the unstable soil profile under swelling pressures on wetting. This contrasts with the origin of many stone pavements elsewhere whose formation is usually attributed to deflation of the finer particles leaving behind the larger stones as a residuum.

**Micromorphological indicators of land management practices.** In this section we review some of the literature which demonstrates how land management practices including cultivation and surface stubble management and traffic by machinery impacts on soil and how micromorphology can
be used to determine structural changes. Some attention is similarly given to the impact of ameliorative management practices.

Management practices and crusting. In a long-term experimental field which was established in 1929 to show the effects of various fertilizers on soil physical properties, Bresson and Boiffin (31) found dramatic differences of crusting rates between plots. Structural crusts developed much faster in the sodic treatment and much slower in the lime and the farmyard manure treatments compared to the reference plot. However, they were all coalescing crusts which mainly differed in thickness and porosity. Conversely, depositional crust microstructure markedly differed between plots, especially with regard to microbedding and particle sorting. Such differences, however, appeared to be more related to ponding duration than to dispersion. On the other hand, experimental treatments induced clear microfabric differences in the soil matrix: (1) fine particles were less abundant in the sodic plot, (2) association between fine and coarse particles was closer in the limed plot and looser in the farmyard manure plot and (3) a microaggregated (fluffy) microstructure was observed in the ammoniated plot. Such differences could be ascribed not only to direct effects of the fertilizers for over 50 years, but also to induced effects such as crusting (31).

Influence of fallowing on time-sequence crusting processes and interactions with termite activity and vegetation restoration and soil crusting have been studied over a 40-year fallow period in a wet savanna area in Africa (98). These authors showed that severe erosion crusts develop after field abandonment, which seemed partly associated to the occurrence of nests of foraging termites like Trinervitermes (99). Soil crusts are then permanent features which favour severe runoff generation. A ten-year span is necessary to allow the wood savanna to be restored and Trinervitermes to be replaced by more favourable termites like Macrotermes. Then, a litter cover attracts termites which perforate the crusts during the dry season. Soil crusting, mainly in the type of slaking, becomes a seasonal process, restricted to the early rainy season. Such a change is enhanced by the restoration of the soil structural stability to a level similar to that measured prior to cultivation.

In some studies of the effects of tillage practices on soils, different crusts were related to each treatment (100, 101). However, it seems that these crusts actually are different stages of the same crusting sequence, i.e. structural crusts, erosional crusts or depositional crusts. Similarly, the micromorphological differences carefully described by Falayi and Bouma (29) in different tillage practices and crop rotations cannot be clearly interpreted. This illustrates the difficulty in comparing different types of crusts without referring to the general pattern of crust formation. In general reliable data is limited.

According to the general pattern of soil surface crusting, erosional and depositional crust formation is mainly controlled by structural crust development and properties (31). Therefore, preventing or controlling structural crust formation is of major concern. Micromorphology provides some guidelines for selecting the most suitable control techniques, because diagnostic microscopic features have been found which allow recognition of the processes involved in surface crust formation (18). For instance, in arid sandy soils, crusts mainly forms due to raindrop impact (sieving crusts), so that mulching is especially effective (102). In temperate loamy soils, crusts which develop on dry seedbeds are slaking crusts so that hydrophobic conditioner which limits slaking by entrapped air compression may be successful (40, 103). On wet seedbeds, however, coalescing crusts can develop, which can be controlled using farmyard manure or lime application (31).

Since slaking results from the rapid wetting of dry aggregates whatever the kinetic energy of rainfall, mulching should not be invariably considered as a satisfactory control practice of crust formation. Yet, mulching reduces compaction which in turn may delay and reduce runoff (64). Moreover, it
favours faunal activity which tends to readily break the crust up. Therefore, Kooistra et al. (104) did not observe any crust under maize residues, contrary to a plot cultivated mechanically. Hydrophobic conditioners are effective in delaying slaking crust formation (40, 103): cracking is delayed, as well as sand stripping at the surface. Raindrop impact plays the main role in sieving crust formation, so that mulching is effective in limiting the development of such crusts (50, 104). In a semi-arid mulga woodland, Greene and Ringrose-Voase (51) also showed that surface cover reduces similar 'quartz crusts'. With no reference to sieving crusts, but in sandy soils, Radcliffe et al. (71) found more open framework and greater proportion of large voids under straw cover.

Trampling by continuous goat grazing induced sieving crust formation, due to the breaking-up of stable fine-textured microaggregates and sand grain coatings, to the further wind blowing of the resulting fine particles, and to the winnowing of the remaining material (52). Artificially pulverised sieving crusts quickly reformed (52). Similarly, the beneficial effect of weeding is thus rather limited in time since sieving crusts can form again after only 25 mm of rainfall (25).

**Effect of gypsum application.** Van der Watt and Claassens (75) observed a less dense crust on gypsum treated plots. Gypsum led to a stabilisation of macroporosity with fewer inter-aggregate contacts in red duplex soils (44, 89). Moreover, in gypsum treated soils, crusts were thinner and less continuous, vesicles were less apparent, and microbedded layers did not occur. In a sodic sandy soil, Gal et al. (66) observed that gypsum prevented dispersion of clay and the formation of a surface layer of bare sand grains. In a sodic clay soil, gypsum maintained the open structure due to clay aggregate packing.

**Effects of bush fires on cryptogamic crusts** In a semi-arid environment, Chartres and Miicher (37) found that the destruction of vegetative cover by fire induced partial removal of the cryptogam cover under rainfall. Subsequent erosion of the surface material resulted in sand grains protruding from more argillaceous material. In another experiment, Greene et al. (73) observed that fire could reduce the surface covered by cryptogams, which in turn enhanced crusting. For instance, many vesicles occurred on the burnt plots, as well as laminated void clay coatings below 20 mm depth. This could be due to the loss of gel-like organic cements associated with the cryptogams.

**Impacts of crop management practices on micromorphological properties.** Apart from crusting, land management practices impact considerably on soil structural properties including properties such as hardsetting and compaction (7, 75, 105, 106, 107, 108). A number of authors (109, 110, 111, 112, 113) have tried to link soil microstructural properties with processes causing soil compaction in a range of different environments. One area of major concern has been the effects of compaction on irrigated Vertisols. In Australia McGarry (109) was able to demonstrate that sowing a Vertisol under wet conditions resulted in the development of strongly striated orientation patterns in considerable areas (17 %) of the soil s-matrix. These zones never occurred deeper than approximately 0.5 m. and were not found in uncultivated control samples. They were also considerably larger than features reported by other authors as plasma separations. The fact that the zones were associated with increased massive structure, decreased bulk density, decreased porosity, decreased shrinkage and poor plant growth suggested that the zones developed due to compaction and shearing of the moist soil by metal cultivation instruments.

In France, Bresson and Zambaux (111) examined the effect of tillage traffic on silty Dystrochepctic Fragiudalfs. Their study showed that compaction caused the loss of compound packing voids in the
matrix and strongly reduced the "textural" porosity caused by the packing together of 50-75 µm soil aggregates. They also noted that compaction originates from shearing as well as normal stresses, and repeated compaction also reduces earthworm numbers, although physically did not destroy their channels. Also of note was that unlike in sodic soils, clay domain structure remained of the "card-house" type (ie. edge to face packing). Sweeney et al. (112) showed that Ap horizons under conventional cultivation developed structural properties similar to those of the deeper B and C horizons in contrast with never cultivated A horizons. Changes in the cultivated Ap horizon included a reduction in macroporosity from 50 % to 8 %, the dispersion of organic matter through the peds and the development of incipient gleying. Lhotski et al. (113) demonstrated that wheeled traffic not only caused structural degradation, but also the resulting compaction effected biochemical processes including nitrification.

Tillage and management systems have been studied on a midwestern USA mollisol continuously since 1876 at the Morrow Plots at the University of Illinois Champaign/Urbana (114). These plots were began to study the effect of agronomic inputs and crop rotations on corn yield. Over the past 117 years the plots have received additions of either no, medium or high fertiliser with rotations of continuous corn, corn-soybean, and corn-oats-alfalfa. The inputs and rotations have varied slightly over the years but have been the same since the 1960's. All of the plots have been tilled by conventional European techniques of mouldboard plowing and discing for seedbed preparation since there inception. With the present crop rotations, all of the plots are in corn every six years. In 1991 this was such a year and samples were collected to evaluate the degradation effects of the various crop rotations and inputs compared to the virgin soil kept in grass along the plot borders. In situ samples were collected for micromorphological analysis by excavation of large monoliths of the plow layer (114) and bulk samples were collected for physical and chemical measurements. Compared to the virgin plot border condition, all management systems have degraded the soil structure. The effect of crop rotation and fertiliser input on aggregate stability and organic matter was that the virgin soil had greater aggregate stability and organic carbon content followed by corn-oats-alfalfa, corn-soybean and continuous corn least. Only minor effects of fertiliser input was found for degradation of these two parameters. The most noticeable difference between treatments was that all crop rotations have produced smaller less well defined structure than the virgin site. Although the total porosity and bulk density was similar for all rotations the pores were smaller and less continuous in the cropped plots. Likewise, differences in pore size and continuity can be seen for the crop rotations. The corn-oat-alfalfa rotation had larger more well defined aggregates than the other two rotations with continuous corn having the smallest and least well defined aggregates. This is in accordance with the findings for aggregate stability and organic carbon content as reported by Darmody and Norton (114). Related to compaction, surface sealing and erosion, the continuous corn rotation has the greatest potential followed by corn-soybeans, corn-oats-alfalfa and virgin. Since all cropping systems regardless of fertility input with conventional cultivation have degraded the soil structure, the sustainability of this tradition European tillage system is questionable. Management systems that minimise disturbance such as no-till may allow cropping of these soils without the degradation of structure or organic matter.

Hall (106) demonstrated that long-tilled (>70 years) Rendolls in the UK developed more fine aggregates than land only tilled for 40 years. This may have been in part due to greater erosion in the long-tilled land and a greater percentage of calcium carbonate therefore occurring near the soil surface. It is important to note that this result is unlikely to be repeated in more Mediterranean and tropical environments, where frequent tillage may promote both crusting and hardsetting. Kooistra et al. (104) demonstrated the significant changes to soil microstructure and porosity that occurred in
Nigerian Paleustalfs under cultivation and mulching compared with forest cover. Their results showed that exposure of the soil surface without mulching caused serious crusting and reduced water infiltration. Mulching reduced the crusting and when combined with hand cultivation seemed to maintain active burrowing fauna and thus a good channel structure. Mechanical cultivation with and without mulching resulted in much less favourable conditions for water infiltration because of crusting and a reduction in biological activity. In US studies, Livingston et al. (115) demonstrated that long term cultivation of Udalfs and Udolls increased erosion potential as a result of decreasing organic matter contents and increasing bulk densities through the upper 50 cm of profile. Micromorphologically these changes were expressed in a reduction in interconnected pores, finer aggregate size, which was also associated with reduced aggregate stability. This study concluded that Udolls were more resistant to degradation due to cultivation than Udalfs.

**Future research directions.** A number of areas for potential research arise from the current review. In terms of crusting more attention is required to take into account the dynamic aspect of crust formation. This is of great practical importance because the impact of crusting on seedling emergence is closely related to the development rate of the crust compared to the emergence and establishment rate of the crop. Where weekly or seasonal monitoring are impossible an alternative may be to refer to the crusting stage if reliable comparisons of crusting in soils of different composition, climatic environment and land use and management are to be made (31). Also of concern is that there have been few attempts to predict crusting hazard taking into account not only sodicity (86), but all other factors relevant to crusting including vegetation cover and rainfall intensities.

Most of the reviewed studies dealt with the development of crust during the few weeks after sowing, which was pertinent to the impact of crusting on seedling emergence. However, the final state of the crust, after harvesting, greatly controls the ability of the soil to store water up till the next sowing as well as determining run off and to some extent erosion losses. Moreover, this final state may also control the tillage conditions and hence the properties of the next seedbed. In this respect, the evolution of crusts throughout the growing season and post-harvest should be considered, which requires taking account of the succession of climatic events.

In rangelands, crusting follows the same processes as in cultivated soils. However, the resulting crusts are not subsequently destroyed by tillage practices. Moreover, velocity of overland flow in rangelands is not limited by the surface roughness induced by tillage (18). As a result, rangeland crusts involve a complex succession of erosion, sedimentation and bioturbation periods (26, 35, 36, 52). Micromorphology should be used to identify such different phases and specific crust forming processes. Such a line of research should be particularly relevant in the arid regions submitted to recent (Sahel) or expected climatic changes (116). In particular, any textural modification of the top layer of crusts at a regional scale (as a result, for instance, of the transformation of prevailing sieving crusts into erosion crusts) may have a strong influence not only on runoff production but also on evaporation and albedo, hence in turn upon climate.

In the area of hardsetting attention should be focused on amelioration. Micromorphology may be a useful means of determining how ameliorants affect microstructure. In many respects the literature on the impact of cultivation on soil properties is extensive, much of it is purely descriptive indicating changes in pore space characteristics. The advent of colour image processing opens some interesting opportunities with respect to developing a better understanding of how fabric responds to cultivation and whether it can be used as a diagnostic factor with respect to potential soil behaviour.
Conclusions. The contribution of micromorphology to our present understanding of crust formation and to a lesser extent hardsetting, compaction and sodicity has been prominent. The general pattern of soil surface crust development was partly elaborated thanks to microscopic studies. Various crusting processes have been clearly identified or elucidated thanks to microscopic observations, and diagnostic features have been found which allow recognition of the processes involved in the formation of the various types of crusts. Similarly, micromorphology has helped to assess the role of initial moisture content and initial aggregate size distribution in controlling the nature and the kinetics of crusts and to predict infiltration rates. Therefore, micromorphology provides useful guidelines for selecting the most suitable control techniques. On the other hand, few micromorphological studies dealt with the micromorphological changes associated with ameliorative management practices, and some research opportunities can be suggested. In hardsetting soils micromorphology is at the stage where it has been used to determine the causes of hardsetting, but little work has been done with respect to amelioration of the condition. In studies of compaction, micromorphology has been used to elucidate soil behaviour following compaction, principally through its use to determine the nature of pore space changes and shearing effects. What is clear is that micromorphology must be used as a tool with which to capture and interpret the many dynamic changes that take place as soils are utilised by mankind.

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Hardened Volcanic Soils (Tepetate) in Mexico: Their Geological, Pedological or Anthropological Origin

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Abstract.

Fragipans unique morphology is the characteristic, other than brittleness, most commonly associated with fragipans by pedologists. Despite this, tepetates from Mexico, mainly classified as fragipans, show drastic micromorphological differences. Four types of substances known as cementing agents were detected in tepetates, often being present three or four of them in high concentration within the same sample. Each of them was observed in several microscopic forms inside tepetate groundmass, with its own distribution and orientation patterns. In the present work, the distribution and orientation patterns of each one of the cementing agents was united and named the cement morphological pattern and was related to geological, pedological or anthropological tepetate origin. Three clay morphological patterns were distinguished in tepetates. Only tepetates with P2-b, var.1 clay morphological pattern fulfil all the requirements of the Soil Taxonomy system for fragipan. We concluded that the classification of tepetates required some specific criteria to enable them to be compared with other cemented horizons accepted in the international classification.

Introduction.

In global assessment the cemented soil differentiation is based on the cementing agent origin that is dominantly responsible for soil fabric rearrangement during induration, which is typical of each one of the hardened horizons. Four types of chemically cemented soil horizons, each one with its own cement, are recognized by Soil Taxonomy: petrogypsic, gypsum; petrocalcic, calcium carbonate; placic, iron, aluminum, and organic matter; duripan, silica (Chadwick and Nettleton, 1990). It is well known that carbonates, gypsum and silica accumulations cover more than one third of the earth’s area (Miller, 1991), and represent one of the main causes of soil degradation and induration. Chemical bonding properties of the cementing material determine whether it coheres to itself or adheres to the s-matrix (Chadwick and Nettleton, 1990).

The other hardened horizon is fragipan. In the induration of this last horizon a variety of agents could be involved, including non-expanding silicate clays, oxides of iron, manganese and aluminum, also colloidal silica. All these substances are the weathering products originating largely in an overlying horizon (Rust, 1983).

Based on the results of macromorphological studies the main part of the tepetates analysed in the present study, cemented reversibly by clays and other substances, was classified as fragipans. Fragipans are defined by Soil Taxonomy as - a loamy or uncommonly a sandy natural subsurface horizon, low in organic matter, mottled, slowly or very slowly permeable, somewhat brittle when moist, and hard and appearing cemented when dry –(Soil Survey Staff, 1975). Fragipans are variable in their physical, chemical and mineralogical characteristics, but with a unique morphology (Miller, 1983). Morphological studies show that fragipans have clay coatings and sepic plasmic fabric in all or part of the horizon. Fragipans normally have bleached vertical streaks that form a roughly polygonal pattern in a horizontal plane (van Wambeke, 1992). It would seem fair to say that the majority of fragipans have developed nearly concurrent with the argillic horizon,
sometimes as part of it, in other cases, immediately below it (Miller, 1983). A fragipan is not uncommon in the horizon developments of the Alfisols, Ultisols, Inceptisols and Spodosols (Rust, Miller, 1983).

The origin of fragipans in temperate regions and at high elevations in the tropics has been explained by glacial or periglacial phenomena (van Wambeke, 1992). The mode of formation of lowland tropical fragipans needs further research. Fragipan genesis hypotheses fall into two general categories; those that rely largely on chemical processes and others that rely mainly on physical phenomena (Miller, 1983). The micromorphological observations are commonly considered as irreplaceable and of high utility in the process of cemented horizons differentiation and for tepetates classification according to international systems (Flach et al., 1992).

This presentation summarizes existing micromorphological studies of hardened horizons occurred in soils of volcanic origin in Mexico. It provides some micromorphological criteria, which seem useful to define (or suppose) the pedological, geological or anthropological origin of these cemented horizons. The micromorphological data were used to design the rehabilitation programme for different cemented soils.

The main purpose of this presentation is to show the importance of micromorphological studies as the first point of departure for cemented materials classification.

Materials and Methods

In Latin America, hardened soils of volcanic origin have often been referred to by using vernacular names (Zebrowski, 1992). In Mexico, they are called "tepetates" and included a lot of cementing materials of different origin. According to INEGI (the Mexican government agency for statistics and geography), the large areas of volcanic soils in Mexico present a hard horizon barred at different depths. The area of these formations, cover 30,700 km² or 27% of the Mexican neovolcanic region (Zebrowski et al., 1991). These lands are at high erosion risk. Several authors in Mexico emphasize the close relationship between climatic belts and the distribution of tepetates (Miehlich, 1984; Dubroeucq et al., 1989). Tepetates appear in the Mexican high plateau only under an average rainfall below 900 mm per year. The tepetates that are rich in calcium carbonate are located in areas of rainfall below 650-700 mm (Zebrowski, 1992).

In general, tepetates of the Mexican high plateau are natural, massive, compact and hard formations, cemented by different chemical agents.

The study's results of the reference profiles of the Project "Study of 'Tepetates', indurated volcanic soils of the Mexico and Tlaxcala Basins, in view of their agricultural rehabilitation", Agreement C.P. ORSTOM, contract TS2 * 0212 - C (EDB), ORSTOM-Commission of the European Community, are discussed here.

Materials.

During the macromorphological studies realized by the group of specialists, directed by Dr. Paul Quantin (1992), three main criteria were used to classify tepetates:

1. Deposits stratigraphy. According to this first criterion within a full stratum five different types of materials were described. H: sandy silt, aeolian colluvian deposit, with fragments of pottery and obsidians. This is a recent deposit which served as a parent material for present humified soil. T1: dark brown vertic soil; volcanic ashes deposit of Inferior Holocene. T2: set of 5 to 6 light grey or whitish horizons, similar to 2T tuff described by Miehlich (1984, 1991, 1992) and aged between 10,000 and 20,000 years B.C. T3: set of three to four reddish brown horizons, similar to 3T tuff of Miehlich, aged between 20,000 and 35,000 years B.C. T4: reddish brown paleosol and sequence of breach and thick tuff resulting from pumice stone. T2 and T3 sets present two series of deposits that consist alternatively of t2a and t3a paleosoils (of vertic origin) and of t2b and t3b tepetates. (Quantin, 1992; Quantin et al., 1992).

2. Tepetates consistence: two types of hardened horizons were distinguished: fragipan, brittle when moist and duripan, permanently hard.
3. Presence or not of hard calcitic accumulation, in laminar crust form (in the first case tepetate was described as petrocalcic horizon). Tuffs and tepetates were distinguished, considering the latter as horizons modified by pedogenesis. (Quantin, 1992).

As a final result of the project, most tepetates with or without brittle limestone, were classified as fragipans.

We will briefly mention the most outstanding results of chemical, mineralogical and physical analyses of tepetates obtained so far. (Quantin, 1992; Miehlich, 1991; Hessmann, 1992; Hidalgo, 1992; Werner, 1992).

A. Chemical and mineralogical composition of original materials. All the materials studied (soils, tuffs and tepetates) consist of pyroclastic volcanic products, of which more than half are phenocrysts and unaltered glasses. The chemical composition of unaltered materials of T2 and T3 series is similar to that of sodium alkali rhyolites, whereas that of surface deposits (H and T1) is more alkali and similar to dacites (alkali rhyolitic dacites). It has to do with magmatic series. A stable characteristic of these materials is high silica and sodium content, important for the genesis of tepetates.

B. Texture Four textural classes: Silty clay loam, sandy clay loam (prevailed), silty clay, and clay were identified in the hardened layers studied. According to the bimodal character of the elemental particles distribution in these materials, where a clear tendency to maximum fine sand and clay concentration was observed (according to Pye (1987), all aeolian materials characterize by high silt content), it was concluded that redeposited volcanic ashes prevailed in tepetates (Quantin et al., 1992).

C. Origin of alteration products Clays, silica, limestone and ferroxides were the most important alteration products for tepetates genesis.

One sequence was observed in clays composition within reference profiles:
- H and T1: uncrystallized clays and some halloysite;
- T2a: a stratified element with smectite and some halloysite;
- T2b: 80% well crystallized smectite and 20% halloysite;
- T3a: 80% halloysite and 20% poorly crystallized smectite;
- T3b: 90 to 100% halloysite and features of undetermined interstratified mineral.

D. Geomorphological position
Hardened horizons are inserted in piedmont and glacis soils.
This location coincides with subhumid and subarid regime (ustic), which suggests the climate and pedogenic effects on tepetates formation (Quantin, 1992).
Tepetates horizons located on piedmonts with fragipan character are associated with brown, clay soils, defined as Cambisols (Zebrowski, 1991).

On glacis, on the base of Faeozem, tepetate is defined as a petrocalcic horizon. (Quantin, 1992).

F. Tepetates Genesis
According to the study's final results, Quantin (1992) concludes, that tepetate origin continues to be controversial so far in relation to parental material formation and induration process. The question now is: The hardening of original material is prior or the consequence of pedogenesis?
In typical tepetates (t2 and t3) the abundance of pedological features, such as, for example, clay, ferroxides and silica accumulation, correlated to a ustic climatic regime, favors the
pedogenic origin of tepetates (Quantin, 1992).

However, Quantin concludes that these features are observed both in soil B horizon, as in tepetate. That is why they cannot clearly testify for the massive and hardened tepetate character.

G. Erosion

Surface soil is often removed by erosion, thus tepetate or tuff emerges.

Methods

The undisturbed samples of more than a hundred types of soils and tepetates of the Mexican basin were submitted to a detailed micromorphological study. According to Zebrowski (1991), the sampled area encompasses 1250 km² of the total basin surface.

The samples were directly obtained in the field, without previous impregnation. In the laboratory, the Brewer (1964) procedure was used for the soil impregnation with HU-543 epoxy resin under high vacuum conditions, and for the preparation of thin sections (of 30 μm thickness). The size of the thin section used was of 2 cm by 4 cm. Two sections per sample were prepared and observed with an optical microscope (OLYMPUS-BH-2). The description of thin sections was made using magnifications from 10 to 100, according to the -Handbook for Soil Thin Section Description-terminology (Bullock et al., 1985). In average, ten areas per thin section were analyzed.

An Image Analysis (ZIDAS, Carl Zeiss) was used for a quantification of the following physical parameters with magnification 10: total pores effective area in the field of vision; pores area without considering the pedofeatures; average area occupied by one pore; maximum (Dmax.) and minimum diameter of pores (Dmin.). The distribution of pore diameters was evaluated. Applying the Bouma (Kp) morphometrical model (Bouma et al., 1979), pore sizes data were used for the calculation of the hydraulic conductivity (m s⁻¹) due to plane slits and tubular voids of samples. Neck sizes are obtained by estimating the probability that voids of a given size class are continuous throughout the sample into voids equal to or larger than themselves.

\[
P_{\text{tot}} = (1 - \text{Dap.}) \cdot \text{Dr}
\]

where:
- \( p \) = density of water (kg/m³)
- \( d_n \) = width of the "necks" in the cracks (m)
- \( g \) = acceleration of gravity (m/s²)
- \( v \) = viscosity of the water (kgS m⁻¹)
- \( S \) = total cross-sectional area of soil (m²) containing a length of l(m) of plane slits with width d (m) and n pores with radius r (m).
- \( l \) = length of the stained cracks in thin section (m).

According to the value of sample effective porosity the bulk density (Dap.) was estimated, applying the equation:

\[
P_{\text{tot}} = (1 - \text{Dap.}) \cdot \text{Dr}
\]

These last values are artificially increased because the quantification made by the optical microscope (+10) did not take into account the microporosity. Using the values of the porosity without areas occupied by pedofeatures, bulk density before the cementation was estimated too.

Among the samples, 15 that belong to three profiles of a sequence described by Werner and Zebrowski (1990, notebook of the paper T.D. Tlaxcala, Mexico) have been studied in more detail (with electron microscope and microprobe, Oleschko et al., 1992). Most of the soil sequence has been developed from two volcanic deposits (tuff or projections) of different ages (Fig. 1).
One of the two thin sections prepared in each of the fifteen samples mentioned above, was submitted to micromorphological study with a scanning electron microscope (SEM, CAMBRIDGE model), equipped with an analyser of X rays (EDXRA - MICROPROBE).

Under vacuum conditions, the thin sections without a cover-glass were covered with a carbon homogeneous layer and were observed directly with the electron microscope. Each point of observation was previously chosen through the optical microscope.

In each point chosen, an analysis of the clay elemental composition was made with the microprobe. The molar ratio $\text{SiO}_2/\text{Al}_2\text{O}_3$ (C1) was calculated and was used as an indicator of clay mineralogy and of the silica accumulation degree. In the case of clay coatings and infillings, clay analyses in the pores and inside the matrix were made separately.

In the case of transmitted electron microscope studies, clay suspensions in water were prepared. Homogeneous drops of a suspension previously dispersed with ultrasound were deposited on a copper reticle. In order to have an adequate drying of the samples (later submitted for observations with TEM, STEM and microprobe), there was a 24-hour-wait. In this last test attention was paid to the nature of clay, and to the morphology and elemental composition of phytoliths, abundant in some tepetates.

Phytoliths were separated in heavy liquids (cadmium, with 2.3 specific density), with centrifuge (3000 revolutions per minute), for ten minutes, from different tepetate elemental particles fractions. Phytoliths were concentrated in the lightest fraction (method described by Golieva et al., 1987).

Afterwards thin sections were prepared for optic microscopic phytoliths observation in polarized light and with electron microscope (TEM).

In each one of the fractions, percentage content of phytoliths referring to 400 grains was calculated (2-3 times) (Shoba, 1993).

Results

The hardened layers studied were similar in their effective porosity (9 - 16%); pore size distribution and morphology (planes, vughs, chambers); coarse/fine related distribution (porphyric); microstructure (chamber, vughy). Four types of substances known as cementing agents were detected in tepetates, often being present three or four of them in high concentrations within the same sample. Among the cements, it was possible to distinguish: 1) clays (90% of thin sections); 2) carbonates (related to modern earth surface or distributed along the cracks at considerable depths); 3) iron and manganese oxides and hydroxides coatings within the crystalline clays reticle (according to SEM-EDXRA analyses) or in the form of nodules and mottles; 4) silica (according to SEM-EDXRA analyses). Each one of the first three cements was observed in several microscopic forms inside tepetate groundmass with its own distribution and orientation patterns. The distribution and orientation patterns of each one of the cementing agents in the present research were united and named the cement (micro) morphological pattern.

During the micromorphological description, three special criteria were applied to differentiate tepetates based on their more common cement morphological pattern: 1) The nature, mobility (based on cement relationship with tepetate pore space), degree of accumulation and kind of transformation of the substances known as cementing agents (based on the present pedofeatures); 2) The type of cementing agent distribution inside the tepetate groundmass, used to define: whether it coheres to itself or adheres to the groundmass; the stages of groundmass reorganization during tepetate induration, and to suppose the possible mechanism of this process; 3) The decrease of "tepetate" effective pore space in view of pedofeatures presence: assuming that tepetate porosity without taking into account the areas occupied by pedofeatures corresponds to porosity of the samples prior to hardening.

Clay morphological patterns.

Three very different clay morphological patterns were distinguished in tepetates. Each of them has its own micromorphological features, including abundance and degree of clay orientation,
thickness of microlaminated clay coatings and degree of clay integration to the groundmass and type of groundmass reorganization.

A. Clay pseudomorphic pattern (P1).

The first pattern (P1) was called clay pseudomorphic pattern. Its micromorphological indicators are: pseudomorphs of mineral crystals (mainly feldspars). These minerals undergo a generalized and homogeneous alteration, i.e. the transformation of the mineral starts and proceeds quite homogeneously throughout the whole volume of the grain, with a degree of pseudomorphosis, from moderate to strong (Fig. 2). The morphology of the fresh feldspar crystals is exactly the same than that of their pseudomorphs. The halloysite and uncrystallined clays are the final products of this process (EDXRA-MICROPROBE, SEM data, Fig. 1). The first P1 pattern did not show any relation to the material pore space (which averages 9.1%), and did not affect the general organization of the groundmass, yielding low K values (4.4 cm/hr) (Table I).

The estimated bulk density of P1 tepetates is 2.4 g/m$^3$ with a sandy clay (or loam) texture. Through optical microscopical observation, the estimated bulk density (without considering the pore areas occupied by clay) is 2.0 g/m$^3$. These tepetates show a medium hardness (48 kg/cm$^2$). Among the P1 samples, carbonate concentration was not observed. Ci relation in clay inside the pseudomorphosis is 3.5 and increases to 4.6 inside the matrix. Iron oxide content in P1 clay is 7.8, whereas inside the matrix is 8.1% (Fig. 1). All iron appeared within the clay reticle. Amorphous or cryptocrystalline pedofeatures were not observed in P1 tepetates.

B. Clay coatings and infillings pattern (P2).

The second clay morphological pattern (P2) indicators, independent of the origin of the cemented layer, are the dense, complete and incomplete macropores infillings and the typical microlaminated clay coatings, pure or alternated with silty layers. The thickness of the coatings reached 0.3 to 0.4 mm. The clay of infillings and coatings have from low to moderate and strong orientation. The laminated morphology of these pedofeatures testified the periodical clay depositions in the pore space during P2 pattern development.

P2 clay pattern has a close relationship with the type and magnitude of the layer pore space where it develops mostly in the macropores. This may suggest its direct relationship with water preferential flows which exist in the material before cementation. Their development produces a reduction of horizon effective porosity, from 24 to 9 - 13% and a corresponding decrease of estimated hydraulic conductivity, from 11 cm/hr up to 3 cm/hr. Estimated bulk density of material prior to P2 formation is 1.9 - 2 g/cm$^3$ and it rises up to 2.2 - 2.4 g/cm$^3$ after its development (Table I). P2 appeared in horizons with different texture, from sandy clay loam, silty clay up to sandy, and showed a hardness between 30 and 130 kg/cm$^2$.

The halloysitic clay of infillings and coatings was characterized by a high content of iron oxide that fluctuated between 7.2 and 11.5%, as compared with 7.3 inside the matrix.

Three P2 subpatterns were distinguished in tepetates according to: 1) the origin of the cemented material; 2) its texture; 3) total and effective porosity and; 4) Ci in the clay of textural pedological features and inside the matrix.

a. P2-a subpattern.

The first subpattern appears in pyroclastic materials little weathered or unweathered, sandy, and similar in their mineralogy to parent materials of all profiles studied. In them, the predominance of volcanic glasses (40%), feldspars (30%) and pyroxenes can be observed. The clay infillings and coatings in P2-a are associated with simple packing voids, and produced a reduction of the soil average porosity from 24.4% to 9.1%. Iron content in clay under this pattern varies between 7.5 - 9.8%, and determines the yellow to yellowish brown clay color. As a result of the infillings and coatings complete pattern development inside the groundmass, the interconnected porous space was replaced by -chambers- (40%) and -vughs- pores. It is clear that these last voids have a different genesis compared with vughs, produced as a result of biological activity. But the morphological features of both voids are the same. The planar voids occupy only 10% of the whole.
pore space volume, which obstructs the flow circulation within the horizon. The $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio in the clay of coatings inside the P2-a samples is very low and reaches only 3.3 (Fig. 1).

In the reference profiles, the P2-a subpattern observed in the sandy layers (TP3-3, TP1-3) are bordered in their lower part by silty clay loam texture horizons (TP1-4, TP3-4). The estimated bulk density of these materials was changed from 2.0 kg/m$^2$ to 2.4 Mg/m$^3$ with a P2-a pattern development and its corresponding effective K value was 3.5 cm/hr.

b. P2-b subpattern.

The second clay subpattern (P2-b) has the same indicators and morphological features as P2-a, but it develops in the more clayey horizons, with a clearly pedological origin (vertic features). One part of tepetates with P2-b clay pattern coincided with t3b (dominance of halloysite clay), and the other part corresponded to t2b materials (smectite is dominant) (Quantin, 1992).

P2-b clay pattern development produces from partial to total soil groundmass reorganization in different sizes subangular blocks. Block surfaces are partially or totally covered by microlaminar clayey coatings which partly form complete and dense macropore infillings. P2-b has two varieties within "tepetates" that are differentiated according to: 1. the degree of clay orientation in the textural pedostructures; 2. the coatings thickness; and 3. the size of subangular blocks which were formed as the result of groundmass reorganization. The first variety is characterized by a low clay orientation in coatings. These last pedological features are very thick (up to 0.5 mm) and divide the soil groundmass in subangular blocks of homogeneous macro size (1.4 – to 3.2 mm).

Subangular blocks have a high mechanical resistance and are stable in water. Results of the detailed study of specific physical and mechanical properties of the blocks will be described separately (Martinez, Oleschko, 1994). Thirty four of the evaluated samples have a P2-b, var.1 pattern. Depending on the degree of development of this pattern in soils, some of them are described as "tepetates", and others are not hardened. According to Fedoroff’s classification (1990), P2-b var.1 corresponds to argillic fragic and argillic silty textural fabrics. The development of the P2-b var.1 pattern produces a reduction from 26% to 13% of the tepetate total porosity, and it comes with a reduction of the layers estimated hydraulic conductivity from 3.8 cm/hr to 2.7 cm/hr. The second variety of P2-b clay morphological pattern is characterized by coatings with clay orientation from moderate to perfect. These features are much finer (up to 0.025 mm), and separate the groundmass in the heterogeneous subangular blocks (with size from 0.09 mm up to 6.00 mm). In the case of P2-b clay pattern, one part of tepetate's small aggregates, covered with perfectly oriented clay, formed the complete orthogonal striations which can be observed under the crossed polarizers (Fig. 5). Clay in this P2-b variety has filled not only macropores, but also mesopores and corresponds to Fedoroff's (1990) textural nitic argillic fabric. No substantial change was detected in the value of effective porosity of the P2-b, var.2 layers which reached a 16.2% average porosity, a 3.3 cm/hr hydraulic conductivity and a 2.1 g/cm$^3$ estimated bulk density.

The second P2-b variety (P2b, var.2) was the most representative in the studied toposequence and it appeared in the TP1-2, TP1-4, TP3-4, TP2-2 layers, with a $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio in the clay of the coatings which varied between 4.1 and 5.2. The Cl ratio in the matrix of tepetate layer was similar to that of coatings, fluctuating between 4.7 - 5.2 (Fig. 1). P2-b, var.2 was described in 23 layers with hardness fluctuating from 30 to 33 kg/cm$^2$.

c. P2-c subpattern.

P2-c clay morphological subpattern appeared in the cemented layers of old volcanic ashes. Its development is related to the compound packing voids and produced a reduction of horizon effective pore space, from 43.1% to 15.3%. The estimated layers hydraulic conductivity decreased from 16.8 cm/hr to 4.6 cm/hr, and bulk density changed from 1.67 to 2.24 g/cm$^3$. In the TP toposequence, layer 5 with P2-c clay morphological pattern shows a maximum concentration of Si inside the coatings with a $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio which reaches 7.5. The Cl relation in the matrix clay is 5.4%.

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Tepetates with P2-c pattern are characterized by a maximum hardness similar to tepetates cemented with carbonates: up to 130 kg/cm².

All P2-c samples have a high concentration of bioliths among which phytoliths prevailed. In some cases, the concentration of the latter reaches a 5-7% of all fine material (Shoba, 1993). This fact shows the importance of pedological processes in its formation (Gerasimova et al., 1992).

The separation of phytoliths from the different fractions of elemental particles of tepetates showed its maximum concentration in the 0.05 mm fraction. Phytoliths of different morphology were observed. The stick shape prevailed in the silt fraction (of a length exceeding 5-10 times the diameter). Most bioliths were well conserved. However, several bioliths showed a strong corrosion. Phytoliths of irregular morphology are scarce among tepetates, and correspond to 20-25% of all bioliths studied.

C. Paleosoil clay morphological pattern (P3).

The third clay morphological pattern (P3) appeared in the paleosoil clayey layers, with a predominance of smectite clay within the soil matrix (Fig. 4). P3 micromorphological indicators are the pedofeatures related to the alternate clay expansion and contraction, and to the illuviation process.

Carbonates morphological patterns.

There are three calcium carbonate morphological patterns in the tepetates studied, including micrite (which impregnated all groundmass), microsparite (precipitated in different pores) and sparite (occupied vughs). Only the first calcitic pedofeature was related to the very hard tepetates. The development of the first carbonate morphological pattern (K-fabric) related to micrite and microsparite forms produced a considerable reduction of soil porosity, up to 11.8%. This corresponded to 3.2 cm/hr hydraulic conductivity values, to 2.3 g/cm³ bulk density, and the utmost hardness of the material (up to 625 kg/cm²) (Table I). The distribution of micro and macrosparite crystals through the macropores (the second pattern) produced a reduction of porosity, from 24.7% to 11.0% and of hydraulic conductivity, from 9.0 cm/hr to 3.3 cm/hr. The development of these carbonate morphological patterns produced an increase in the tepetate bulk density, from 1.99 up to 2.33 g/cm³.

According to their external morphology, internal fabric and stages of interaction with groundmass, different iron pedofeatures and morphological patterns were described in the tepetates studied. More details about carbonate and iron morphological patterns in "tepetates" will be discussed separately.

Discussion

The micromorphological data confirm the geological origin of "tepetates" with P1 clay pattern which belong to an area of advanced weathering of redeposited materials (paleo or recent, depending on the relationship between the sample studied and the modern soil surface), with a very low degree of development of pedological processes. Tepetates with P1 clay morphological pattern totally coincided with H materials (aeolian-colluvial origin) in Quantin (1992) classification and do not have the fragipan features.

The second clay morphological pattern (P2) was the most common in tepetates and it appeared both alone and together with P1 and P3. P2 is the pattern of clay coatings and infillings (Fig. 3) and coincides in its features with classic fragipan (Soil Survey Staff, 1975). The very clear limit between the unchanged groundmass and coatings and infillings observed in all cases proves its formation by illuviation (Parfenova, Yarilova, 1977). Nevertheless, the differences observed and discussed above on the morphology of P2 clay patterns tepetates poses a doubt about whether it is possible or not to include them in one single fragipan group.

We related three P2 morphological subpatterns distinguished in tepetates to different degrees of original materials pedogenesis. On the whole, six studied tepetates have the P2-a pattern. According to Fedoroff's classification of textural fabrics, P2-a corresponds to argillic fragic fabric (Fedoroff, 1990). The formation of
a P2-a subpattern was related to the presence of textural screens (duplex solum) within the studied profiles (van Wambeke, 1992). This textural change, related to materials lithologic or chronologic discontinuities, was the main factor that defined the periodical flows velocity reduction on the boundary between the layers, and the sedimentation of clay and silt suspensions. These suspensions were rich in silica and iron, which favored the adsorption of the mentioned elements on the clay surfaces and their irreversible induration during the drying process (Quantin, 1992). We think that their formation has a close relationship with the areas of high hydro-erosion rate, responsible for the clay suspensions enrichment, rather than with active illuviation process. The question is, Can we consider all these materials as geological formations (tuffs), with insignificant advance of pedogenic processes, or are they fragipans of pedological origin?

All materials with P2-a subpattern are very similar in their micromorphology to Loess Remarks, described by Kubiena (1970). The micromorphology of these wet raw soils is characterized by conspicuous mud coatings on mineral grains and small aggregates. They are produced because the sedimentation of the sand has taken place in muddy water (Kubiena, 1970). The same origin is possible for P2-a pattern tepetate.

The thirty four layers with P2-b var.1 clayey pattern fulfill all the requirements of the Soil Taxonomy classification for fragipans. However, there are two facts not very common in the fragipans that are noteworthy:

1. The total low porosity of the samples (26%), prior to the formation of clayey infillings and coatings, does not correspond to a crumb structure that prevails in these materials and to their clear pedological origin; and
2. A high silica concentration inside the matrix with clay of a halloysitic composition (SEM data; Ci equals 4.7) (Fig. 1).

These considerations make us believe that in the case of "tepetates" with P2-b var.1 and 2 clay patterns, there were two different phases of soil cementation. In the first phase, the cementing substances were accumulated in the soil capillary porous space. This accumulation could have been related to the continuous fluctuations of the phreatic level, or of the water capillary border inside the soil profiles in the area under study. While these fluctuations have occurred, cements precipitated from solutions, rich in silica and iron in the areas of major aeration. In this case, the silicification or hydrogenic accumulation of silica and iron in the soil fine pore space could be identified as the first step of material reorganization. This last reorganization was related to the change of the tensions of adhesion and cohesion forces fields inside the soil groundmass (Chadwick and Nettleton, 1990). As a result of silica and iron accumulation soil hardening was produced as well as a change in soil effective porosity, porous continuity and morphology.

During the second phase of cementation, clay begins to play the role of a cementing agent. The transition from phase one to phase two may be considered an indicator of important changes in the external conditions (climatic or anthropogenic?) occurred in the area under study where, at the moment of consolidation, there were abundant fluxes of clay rich suspensions. Clay sedimentation from these suspensions produced the soil macroporous infilling. The hardening was favoured by the presence of textural screens within the profiles of polymorphic origin. These screens are related to numerous intercalations of fresh volcanic material layers (result of continuous volcanic eruptions) inside the pedogenic horizons.

The change of clay orientation observed in tepetates with P2-b var.2 compared with P2-b, var.1 clay pattern and related to the dominance of smectite clays inside the coatings in these tepetates, confirm our hypothesis. Active illuviation process more than pure suspension sedimentation possibly occurred in the more humid paleo conditions in the case of P2-b var.2 tepetates.

Despite all the facts discussed, we classified tepetates with P2-b var.1 clay pattern as fragipans, instead of duripans or other known hardened horizons.
P2-b, var.2 tepetates do not fulfill the common criteria so as to have them classified as fragipans. Firstly, the clay coatings thickness was not enough, and secondly, no substantial pore space and bulk density changes were detected in tepetates with P2-b, var.2 clay morphological pattern.

We concluded the same about P2-c clay pattern tepetates. In these, a major participation of silica in cementation was observed. One part of amorphous silica immobilizes in the materials studied, forming inert components of the system (bioliths) and another part directly participates in the hardening of tepetates, concentrating inside the fine, dispersed material (Shoba, 1993). Bioliths have great importance in pointing out pedogenic processes that actively develop within P2-c tepetate system.

We considered that hardened soils with P2-c clay pattern require a special classification as they are not typically fragipans nor duripans.

P-3 was described in 12 hardened layers, which were not defined as "tepetates" in the field, but as "paleosols", after detailed analysis.

**Conclusions**

1) In the broad tepetates group that fulfills the requirements to classify them as fragipans and which was analysed with micromorphological methods, a clear morphological difference was observed. We concluded that the classification of tepetates required some specific criteria to enable them to be compared with other cemented horizons accepted in the international classifications. Maybe, it is convenient to propose some new criteria for tepetates systematization.

2) We speculate, that in spite of a relatively constant and similar SiO2/Al2O3 ratio in the clay of coatings and inside the matrix (except P2-c case), the silica enrichment is one of the principal reasons for tepetate induration. The few silica accumulations inside the tepetate groundmass favored its rearrangement in the first phase of tepetate formations. All physical data obtained show that tepetate hardening developed with clay participation, which can take place in the second phase of the process and can be inactive (suspensions rich in clay, sedimentation presented on textural screens, possibly as a result of high erosion intensity, P2-a y P2-b, var.1 cases) or active (result of illuviation developed inside the profile, P2-b, var.2 example). In the analyzed samples, Si microforms were not clearly distinguished by optic or electron microscopy. However, the high SiO2/Al2O3 ratio inside tepetates matrix with halloysitic clay proves the presence of silica.

3) In the area studied, four factors were identified as requirements for tepetate formation: 1) the periodical volcanic deposition (material needed for clay and other cementing agents accelerated synthesis); 2) the free circulation of Fe, Si, clay highly concentrated solutions - defined by climatic conditions; 3) drastic textural changes between the profile horizons, related to lithologic or chronologic discontinuities of the origin materials and 4) the strong erosion that exposes the consolidated layer to the surface where its final irreversible induration is produced. This last factor can be related directly to anthropological activities in the studied areas.

4) All steps of tepetates' hardening can be identified based on micromorphological features analysis.

5) Only a small part of tepetates can be classified applying present classification systems. Inside these systems only tepetates with P2-b, var 1 clay morphological pattern can be recognized as fragipans.

6) We propose the name Argipans for tepetates where silica and clay play a decisive role in its consolidation and in the rearrangement of its groundmass, but where the fragipan requirements do not fulfill.
References


32. Fedoroff, N.
33. Fedoroff, N.
FIG. 1. Studied soil sequence: TP₁, TP₂, TP₃

TP₂ (2530)

TP₃ (2610)

TP₁ (2675)

- Colluvium
- Aluvium
- Recent soil
- Sand
- Paleosol

- X 1
- X 2
- X 3
- X 4
- X 5

Effective porosity

Pores area without considering the pedological features

Fe in the coatings
Fe in the matrix
Matrix Si/Al ratio
Coatings Si/Al ratio

Exc. - excremental

ex. - excremental
Table 1. Tepetates physical parameters (by the Image Analysis).

<table>
<thead>
<tr>
<th></th>
<th>PI</th>
<th>PII (a)</th>
<th>PII (b) var. 1.</th>
<th>PII (b) var. 2.</th>
<th>PII (c)</th>
<th>PIII</th>
<th>K-fabric</th>
<th>carbonates in the macropores</th>
</tr>
</thead>
<tbody>
<tr>
<td>clays patterns physical parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total pores area: effective without pedological features</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg. area occupied by one pore: ef./w.p.f.</td>
<td>0,19</td>
<td>0,03</td>
<td>0,12</td>
<td>0,36</td>
<td>0,03</td>
<td>1,20</td>
<td>0,03</td>
<td>0,12</td>
</tr>
<tr>
<td>S:c.v.:n**</td>
<td></td>
<td>1,9 ( \times ) 10^{-3}</td>
<td>3 ( \times ) 10^{-3}</td>
<td>1,4 ( \times ) 10^{-3}</td>
<td>4,1 ( \times ) 10^{-3}</td>
<td>2,3 ( \times ) 10^{-3}</td>
<td>5 ( \times ) 10^{-2}</td>
<td>4,3 ( \times ) 10^{-3}</td>
</tr>
<tr>
<td>Maximum diameter of the pore: Dmax (mm) ef./w.p.f.</td>
<td></td>
<td>0,34</td>
<td>0,41</td>
<td>0,41</td>
<td>0,45</td>
<td>0,61</td>
<td>0,45</td>
<td>0,61</td>
</tr>
<tr>
<td>Minimum diameter of the pore: Dmin (mm) ef./w.p.f.</td>
<td></td>
<td>0,17</td>
<td>0,13</td>
<td>0,13</td>
<td>0,13</td>
<td>0,13</td>
<td>0,13</td>
<td>0,13</td>
</tr>
<tr>
<td>Hydraulic conductivity K (cm/hr) ef./w.p.f.</td>
<td>4,42</td>
<td>3,47</td>
<td>3,76</td>
<td>3,34</td>
<td>4,64</td>
<td>16,80</td>
<td>3,93</td>
<td>3,17</td>
</tr>
<tr>
<td>Total porosity: ef./w.p.f. (%)</td>
<td></td>
<td>9,1</td>
<td>9,1</td>
<td>13,2</td>
<td>16,2</td>
<td>15,3</td>
<td>43,1</td>
<td>15,1</td>
</tr>
<tr>
<td>Bulk density ef./w.p.f. (Mg/m³)</td>
<td>2,41</td>
<td>2,40</td>
<td>2,40</td>
<td>2,26</td>
<td>2,12</td>
<td>2,24</td>
<td>2,20</td>
<td>2,30</td>
</tr>
</tbody>
</table>

*ef./w.p.f. - effective/without considering the pedological features.

**S:c.v.:n** - Std. Dev.: variation coefficient : mean pore number.
Fig. 2. P1 pattern, P-13k

Fig. 3. P1 pattern, P-13k
Fig. 4. P2-a pattern, TPl-3

Fig. 5. P2-a pattern, TPl-3
Fig. 6. P2-b, v.1 pattern, P(20-7),11

Fig. 7. P2-b, v.1 pattern, P(20-7),+
Fig. 10. P2c. pattern, P10

Fig. 11. P2c pattern, P38-7.
Fig. 12. P3 pattern, P27-3

Fig. 13. P3 pattern, P27-3
Fig. 14. Micrite and Sparite in the tepetate

Fig. 15. Micrite and Sparite in the tepetate
Ancient People - Lifestyles and Cultural Patterns

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Abstract

The aim of this paper is to illustrate the recent efforts of soil micromorphology in providing more relevant data in archaeology for understanding the relationships between environment and human behavior. Progress have been primarily achieved in two convergent research trends in archaeology that encompass the organization of activity systems in human settlements in space and in time, and the dynamics of the cultural landscape controlled by the interaction of human and environmental factors. The need to demonstrate how archaeological sediments may reflect site anatomy and subsistence economy has stimulated investigations of the micromorphological signatures related to use of space. In addition to study of ethnoarchaeological analogues and experimental situations, the study of a wide diversity of cultural and geographical contexts has resulted in the formation of a substantial data base of anthropogenic microfabrics characteristic of discrete functionally specific activities (i.e. food preparation and consumption, stabling).

This paper attempts to show that 1) observations at the microscopic level transcend all scales of observations in the study of the organization of activity systems in space and time, and 2) that such observations are strongly needed in order to understand how the archaeological record was formed.

Introduction.

One of the principal goals of archaeological research is to reconstruct past human activity systems and overall behavioral patterns\textsuperscript{1} as inferred from the study of artefacts, structural materials and environmental context, which in this paper refers to the soil-sedimentary matrix. In an archaeological perspective, the soil-sedimentary matrix has been shaped by cultural and natural processes that interact at the interface between the atmosphere and the lithosphere\textsuperscript{2}. It is thus conceptually defined to offer a record of past environment-human behavioral relationships that require integration of a large variety of spatial and temporal scales of analysis to be thoroughly investigated\textsuperscript{2,3}.

It was shown long ago that investigation at microscopic scales is strongly needed to decipher the complexity of geosystems. Such investigation is accomplished by the identification of basic processes and related diagnostic signatures that are controlled by the interaction of human and natural agents\textsuperscript{4}. The choice of this level of observation is directly related to the refinement of archaeological research that now aims to reconstruct ancient lifestyles and how these may have changed through space and time\textsuperscript{2,3}.

Application of soil micromorphology to the characterization of depositional and post-depositional alteration of archaeological contexts by natural factors has largely benefited from research in sedimentology and in soil science. These disciplines provide comprehensive principles of the general
laws that describe sedimentary processes associated with depositional environments and pedological processes that take place in the formation and functioning of soils. Our knowledge on the microscopic expression of human-induced mechanisms on formation and modification of the soil-sedimentary matrix is only in its infancy. Specific types of anthropogenic accumulations, such as the ones related to firing activities, have been more extensively documented by using soil micromorphology. Diagnostic micromorphological signatures of ancient cultivation practices have also been thoroughly investigated, especially from Holocene buried soils of North-Western European regions. Micromorphological characterization of structural transformations induced by human compaction has recently revealed to be an important research trend for an accurate identification of activity surfaces in habitation areas. Microstratigraphic studies of multiple occupation sites now demonstrate how soil micromorphology can throw new light on the archaeological understanding on areal and temporal variability in the use of space. Diagnostic micromorphological signatures of ancient cultivation practices have also been thoroughly investigated, especially from Holocene buried soils of North-Western European regions. Micromorphological characterization of structural transformations induced by human compaction has recently revealed to be an important research trend for an accurate identification of activity surfaces in habitation areas. Microstratigraphic studies of multiple occupation sites now demonstrate how soil micromorphology can throw new light on the archaeological understanding on areal and temporal variability in the use of space. In a recent review of the progress of soil micromorphology in archaeology, Macphail and Goldberg have stressed how complementary data from earth science and soil science are essential to support soil micromorphological interpretation. These authors have also emphasized how an increased collaboration of soil micromorphology with all other environmental disciplines, has specifically improved the understanding of taphonomic processes. They have thoroughly illustrated how comparison with modern and experimental situations helps to understand better the dynamics of anthropic processes on soil-sedimentary systems and the controlling parameters responsible for cultural and environmental variability. The aim of this paper is to illustrate how soil micromorphology has been adapted to be accordant with archaeological objectives. The first part of the paper explains how sampling strategies and methodologies of micromorphological research have been adjusted to the novel field of archaeological contexts. We then review some of the most important results that have been recently obtained for characterizing interactive dynamics of past anthropogenic and natural processes in intra-site and off-site contexts. Discussion of these findings stresses how palaeoenvironmental and past behavioral information provided by soil micromorphology help to refine archaeological reconstruction of ancient lifestyles and past cultural patterns and to assist evaluation of the archaeological record.

Materials and Methods.

Investigated sites and sampling strategies

Here we consider at a wider regional scale the results from a number of archaeological contexts that represent different lifestyles in individual sites and exploitation strategies. They include Palaeolithic Old and New World hunter/gatherer camp-sites, early Neolithic semi-sedentarist villages, Neolithic pastoralist-farming communities, and complex urban societies. These sites represent various climatic and depositional settings that allow us to account for localized, environment-specific phenomena and post-depositional changes. The scale of investigation is however not limited to the area of habitation but ranges from the scale of the area of site catchment to that of the regional landscape. We also refer to micromorphological research that has been simultaneously conducted on various experimental and ethnographic sites. The sampling strategy of a micromorphological study has to suit the geo-archaeological questions that are specific to each situation. Timing, location and number of undisturbed samples collected for thin section preparation are not only directly linked to the spatial and temporal level that is expected for the final reconstruction, but are also strongly constrained by the availability of exposed surfaces and stratigraphic sections. In some cases, field investigations for micromorphological study take
place at the time of excavation, which generally occurs at regular intervals during a few consecutive years. This sampling choice efficiently stimulates the use of soil micromorphological data to better monitor the excavation, especially to solve stratigraphic problems that remain unclear even after careful field examination. Such time investment in the field also greatly helps the micromorphological study because it allows the observer to become familiar with minor changes in cohesion, color, micro-lamination.

Analysis of spatial patternings of human activities in thin section requires closely spaced sampling in largely exposed occupation surfaces and from various stratigraphic sections. Sampling is greatly facilitated by evident features exposed during excavation, such as boundaries and structures (hearths, storage pits, etc.) or the architectural framework in proto-urban and urban contexts. Recognition in the field of minor variations in sedimentary characteristics are however the only features that can guide sampling in unbounded spaces. A careful examination of field characteristics greatly facilitates sample selection that is strongly guided by the fundamental objectives of archaeology. In most cases, excavation is aimed at carefully excavating human refuses from their embedding soil-sedimentary matrix and then studying integrity of the archaeological association in order to identify the degree of preservation of occupation surfaces.

Undisturbed samples have to be collected before occupation surfaces are excavated, but with minimum disturbance of the spatial distribution of human refuses that is essential to all archaeologists to evaluate integrity of archaeological association. These constraints, in addition to financial limitations, makes difficult to achieve a comprehensive micromorphological study of occupation surfaces.

The number of undisturbed samples that have to be collected to thoroughly investigate spatial patterning of human activities must be adjusted to each specific situation. Collection of a great number of samples, not only from evidently different areas but also from those that share similar field characteristics, is a prerequisite to successfully address the question of use of space by micromorphological study. Collection of undisturbed samples from off-site contexts on the other hand, is not limited by archaeological constraints. Buried soils sealed by occupation layers have long been proved to offer a unique record of ancient landscape conditions that can be precisely correlated with archaeological data. Therefore, they are preferentially sampled simultaneously to sampling from all other type of stratigraphic materials. In conclusion, success of a micromorphological study of intra-site and off-site contexts not only relies on the quality of stratigraphic materials but also on the definition of clear archaeological objectives.

**Methodology**

Most of the progress achieved in soil micromorphology applied to archaeology is based on study of thin sections with the polarizing microscope. Fluorescence microscopy is occasionally used, although it is not helpful in precisely characterizing organic rich microfabrics because appropriate staining techniques have not yet been investigated. Basic microscopic observation seems to be the most appropriated level to give a preliminary overview of the complex relationships between soil-sedimentary formation processes and human-environment factors in archaeological contexts. In most cases, micromorphological observations provide a sufficient level of interpretation to illuminate questions raised by excavation that initiated the study. Investigations at sub-microscopic level have not been largely developed although they have been proved to be essential for a better characterization of the fine mass, especially for micro-cristallized calcitic fabrics of ashy materials.

The system of soil thin section description proposed by Bullock et al. has been slightly modified in order to make this standard terminology better suited to the specificity of archaeological materials.
The methodology generally followed to interpret thin sections from archaeological contexts is adapted from methods commonly used in sedimentary petrography and in soil science. Analysis of individual signatures in thin sections allows to decouple the complexity of soil-sedimentary phenomena into three groups of elementary mechanisms:
- sedimentary mechanisms controlled by natural agencies,
- pedogenic or post-depositional mechanisms also controlled by natural agencies,
- sedimentary and post-depositional mechanisms controlled by human-related effects that correspond to anthropogenic processes as previously defined.

The great advancement of research on these naturally induced processes allows for the interpretation and recognition of the natural effects of sedimentary and pedogenic agents on formation of the soil-sedimentary matrix. At the present stage of micromorphological research in archaeology, the interpretation and recognition of human-induced signatures rely on the tentative empirically derived relationships of effects induced by humans on the formation of archaeological soil-sediments. These effects are expressed in the thin section by a hierarchy of spatial and temporal patterning of features that can be used to reconstruct a sequence of sedimentary, pedogenic and anthropogenic events.

The basic principle of stratigraphy is used to recognize in each thin section a sequence of individual microstratigraphic units that are defined by their boundaries and their internal micro-fabrics. These units are correlated with the stratigraphic ones observed in the field. Comparison of all the microstratigraphic units identified in each context enables the establishment of an interpretative classification of sedimentary facies. The basic principle of sequential analysis of sedimentary petrography is used to study the vertical and spatial variability of sedimentary facies. The integration of all micromorphological data thus produces two types of sequences:
- chronosequences, which describe the temporal succession of phases that are comprised of interactive anthropogenic and natural events, and
- spatial sequences, which describe the lateral variability of human activities and environmental conditions for each phase of the chronosequence.

In sum, the study of thin sections made from archaeological contexts is the logic continuation of intra-site excavation and detailed off-site archaeological survey. Soil micromorphological data are then integrated with archaeological and environmental data that relate to other components of the geosystem, such as vegetation, or higher, levels of spatial organization. The relative chronology of occupational and natural events provided by micromorphological data is examined through absolute radiometric dating to estimate the length of time that each phase may represent.

Results and discussion

The effects of anthropogenic modifications of soil-sedimentary systems relevant to archaeological interpretation and understanding are manifested at a wide variety of scales: the regional landscape, the area of site catchment, the area of habitation, and the stratigraphic unit or horizon. Two types of effects induced by human agencies can be distinguished:
- Direct effects are controlled only by human agents, and correspond to anthropogenic accumulation, redistribution and structural modification of the soil substrate. These activities have played a major role in the formation of the soil-sedimentary matrix in habitation areas, and are thus an important concern to intra-site analysis. To a lesser extent, these actions may have also affected off-site contexts, especially in the case of landscape modifications induced by past cultivation.
- Undirect effects correspond to anthropogenic modifications of natural processes and environmental conditions that may have been operative both at the scale of habitation areas or, more commonly, at larger regional scale.

Intra-site analysis

**Anthropogenic structural transformations.** The common occurrence in anthropic units of finely crushed aggregates down to a few hundred microns in diameter has permitted to establish a correlation between human trampling and aggregate crushing\textsuperscript{22,23}. This hypothesis has been supported by the observation of aggregated fabrics within activity surfaces of ethnographic and experimental locales\textsuperscript{26,29} and of occupation floors from Middle East Protohistoric tells\textsuperscript{25}. An interpretative model that relates the mechanical effects of human activities on the soil-substrate to the formation of three superimposed microstructural units has been formulated\textsuperscript{23}(table 1).

<table>
<thead>
<tr>
<th>Microstructural unit</th>
<th>Characteristics</th>
<th>Processes involved and forming conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Active unit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sub-type 1</td>
<td>loose packing</td>
<td>trampled in dry conditions</td>
</tr>
<tr>
<td>sub-type 2</td>
<td>dense packing</td>
<td>trampled in dry/wet conditions</td>
</tr>
<tr>
<td>sub-type 3</td>
<td>dense packing, slaking crust fragments</td>
<td>trampled in dry/wet conditions, watered</td>
</tr>
<tr>
<td>sub-type 4</td>
<td>dense packing, micro-layering, interconnected plant remains, or decayed wood remains</td>
<td>regularly maintained, covered by a plant floor covering</td>
</tr>
<tr>
<td>sub-type 5</td>
<td>a few aggregates, dense packing, iron rich organic staining</td>
<td>regularly maintained, impervious covering material</td>
</tr>
<tr>
<td><strong>Reactive unit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>subtype 1 (loamy to sandy)</td>
<td>elongated, densely compacted microaggregates, subhorizontal fissures</td>
<td>highly trampled in dry conditions</td>
</tr>
<tr>
<td>subtype 2 (loamy to sandy)</td>
<td>densely compacted subrounded micro-aggregates; channels and subhorizontal fissures</td>
<td>highly trampled in wet/dry conditions</td>
</tr>
<tr>
<td>subtype 3 (clay rich)</td>
<td>densely compacted fine mass, subvertical/subhorizontal fissures</td>
<td>highly trampled in wet/dry conditions</td>
</tr>
<tr>
<td>subtype 4</td>
<td>weakly aggregated, dense microfabric, vugly porosity</td>
<td>trampled in water saturated conditions</td>
</tr>
<tr>
<td><strong>Passive unit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sedimentary layer surface soil horizon dumped wastes prepared floor</td>
<td>variable</td>
<td>no mechanical deformation or incorporation of human residues related to formation of the activity surface; all features inherited from previous activities</td>
</tr>
</tbody>
</table>

Table 1 - General characteristics and basic interpretation of the three distinct units identified in activity surfaces (modified from Gé et al., 1993\textsuperscript{23}).
Interpretation of microfabrics observed in thin sections made from a large variety of archaeological activity surfaces has greatly benefited from soil science research carried out on the structural transformations of soil systems under well defined hydric and physical conditions. The degree of compaction of the microaggregated fabric reflects the hydric conditions of the active unit when it was trampled. Spatial variability of microstructure of the active unit and of occurrence of features induced by natural processes, such as slaking crusts, calcitic hypocoatings or biological transformations, points to local changes in hydric conditions. Such changes help to discriminate roofed areas that were protected from raindrop effects from open spaces more exposed to natural agencies during the period of occupation. Boundaries between the active and the reactive units reflect the sensitivity of the underlying soil-substrate to mechanical disturbances that are dependant upon physical characteristics of the soil materials and existence of a covering material (table 1). In addition to nature, size and abundance of anthropogenic microaggregates in the active zone, specific plant remains, organic stainings and other features characteristic of local specific conditions provide information on human activities and maintenance of the surface during occupation and on the type of covering material (table 1 and photo 1 & 2).

Photo 1: View of a densely packed, aggregated active unit lying on a reactive unit of a constructed mud floor with large and subhorizontal fine vughs. Plane polarized light

Photo 2: Detailed view of the active unit showing subrounded silty clay, aggregates derived from soils and bricks, rich in fine charred particles; their formation relates to alternated phases of intentional washing and intensive trampling on a surface by an impervious material. PPL.

Pre-ceramic Neolithic site of Netiv Hadgud, Jordan Valley (excavated by O. Bar-Yosef).
The internal components and microfabric of the passive unit are related to anthropogenic and natural events which occurred before formation of the activity surface. Their study thus helps to determine the initial conditions of a natural surfical soil-substrate before it was trampled. Alternatively, they can be used to identify the source of construction materials and in the case of an intentionally prepared floor, the technonology associated with its preparation\textsuperscript{24,25}. A clay rich mud floor, for example, characterized by an homogeneous, dense, flow microfabric with vesicular porosity probably results from a careful preparation and packing of the material under saturated conditions, with drying under circumstances of mechanical stress\textsuperscript{24}.

Study of microfabrics induced by anthropogenic structural modifications also helps to identify preparation of other kinds of archaeological materials, such as bricks or ceramics. In the case of finely prepared ceramics that display a very dense internal microfabric, systematic study of experimental materials with high resolution microscopic techniques has proved necessary to complement macroscopic observation and traditional X-ray characterization\textsuperscript{36}. Observation at this high level of organization thus permits recognition of different microstructural patterns of clay domains, coarse inclusions and voids which are specific to wheel thrown ceramics or to coiled and modeled ceramics shaped on a wheel\textsuperscript{36}.

**Animal effects.** The need to precisely define micromorphological features characteristics of anthropogenic or animal effects has been more specifically addressed in two types of archaeological situations. This includes archaeological sites, especially caves and shelters, which may have been occupied by wild animals simultaneously with human occupation, and archaeological sites in which domestic animals, such as herbivores or winged creatures, have been living. Based on experiments the effects of animals have been characterized by both the specific types of excrements they produce and by the original structural transformations they may have induced\textsuperscript{4-37-38-39} (table 2). These diagnostic criteria were helpful in recognizing wild bird activity, represented by thick, layered accumulations of phosphatic rich ashy deposits found in Mesolithic caves of Southern France, where the only detectable human influence may have been their intentional burning\textsuperscript{38}.

In Arene Candide cave in Northern Italy, vertical and spatial variability of the types of herbivore accumulation permitted differentiation of continuous stabling episodes during the Early Neolithic occupation from temporary stabling episodes during the Middle Neolithic occupation\textsuperscript{39}. In the later case, minor signs of biological degradation and compaction of each ashy stabling deposit provided good evidence that intentional burning occurred soon after use of the cave for keeping sheep/goat and cattle.

Important diagenetic transformations of thick, phosphatic accumulations, such as bat guano in caves, hampers determination of the original source of phosphate, as well as recognition of the environmental conditions under which it formed. Phosphate concentrations often appear in the form of well crystallized phosphatic minerals of various types which can be derived not only from animal activity, but also from alteration by cryptogamic vegetation\textsuperscript{40} or from bone weathering\textsuperscript{4}. Complementary analytical data, such as isotopic composition or infrared spectroscopy, is therefore necessary to trace the origin of the phosphate\textsuperscript{41}. 

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<table>
<thead>
<tr>
<th>Animal type</th>
<th>excremental microfabric</th>
<th>structural modifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carnivores</td>
<td>dense, bright yellow, well crystallized phosphatic dung; bone fragments and coarse mineral inclusions</td>
<td>sub-rounded large-sized aggregates; compaction</td>
</tr>
<tr>
<td>Omnivores</td>
<td>spongy, pale yellow, phosphatic dung and diffuse impregnations; fine phytoliths and silt-sized mineral inclusions</td>
<td>sub-rounded large to fine-sized aggregates; compaction</td>
</tr>
<tr>
<td>- vegetarian diet</td>
<td>bright to pale yellow, weakly crystallized phosphatic dung; fine bone fragments and mineral inclusions</td>
<td>sub-rounded large to fine-sized aggregates; compaction</td>
</tr>
<tr>
<td>- meat diet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Herbivores</td>
<td>convolute</td>
<td>sub-rounded fine-sized aggregates; intense mixing</td>
</tr>
<tr>
<td>sheep/goat</td>
<td>abundant disarticulated phytoliths and transparent calcium oxalates mixed with a rare calcitic fine mass when burnt</td>
<td></td>
</tr>
<tr>
<td>- green grass fodder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- leaf hay</td>
<td>abundant brown calcium oxalates embedded in a calcitic fine mass when burnt</td>
<td></td>
</tr>
<tr>
<td>- tree shedding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cattle</td>
<td>layered; dense brown stained aggregated crusts, semi-articulated phytoliths embedded in a calcitic fine mass when burnt</td>
<td>elongated large sized-aggregates; dense compaction</td>
</tr>
<tr>
<td>Winged animals</td>
<td></td>
<td>not observed</td>
</tr>
<tr>
<td>wild birds</td>
<td>bright yellow, amorphous to weakly cristallized phosphatic laminated dung and impregnation</td>
<td></td>
</tr>
<tr>
<td>domestic birds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bats</td>
<td>pale/bright yellow, amorphous to cristallized phosphatic layers, impregnation, nodules</td>
<td>not observed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 - Main characteristics of excremental microfabrics and structural modifications induced by various animals that can be encountered in archaeological contexts.

**Anthropogenic deposits.** Besides structural transformations, human intervention has long been recognized to play a direct role in the formation of the soil-sedimentary matrix of human refuses through four basic mechanisms: accumulation, redistribution, transformation and loss. Geoarchaeological study has simultaneously stressed the importance of post-depositional processes on site modifications and alteration of the original archaeological association. In order to elucidate the formation of archaeological units and the sedimentary significance of site configuration, micromorphological research has been conducted in three integrated directions: - characterization of the nature of soil-sediments that produce anthropogenic deposits,
- reconstruction of the historical sequence of human activities and their interaction with natural processes which are synchronous with individual occupational events; this is accomplished by studying the geometrical arrangements of all organic and mineral components of each stratigraphic unit (i.e. the fabric);
- identification of the impact of post-depositional processes (i.e. natural processes subsequent to human occupation) on alteration of the archaeological record.

Some anthropogenic deposits, such as ashy deposits or construction materials, have been widely recognized and thoroughly interpreted, especially because of their common occurrence and good degree of preservation\textsuperscript{4-32,33}. The identification of the original, predominantly type of deposit or of organic materials seems more delicate because of the important biological transformation and mineralization they may have suffered at different stages of their history\textsuperscript{19}. In the latter case, their interpretation requires taking into consideration undirect soil-sedimentary signatures, such as biological fabrics, that permit tracing the origin of the anthropogenic deposits. The occurrence of original constituents that are obviously not natural helps to distinguish the anthropogenic nature of deposits and to relate them to a specific type of activity. For example, recognition of finely layered, silty clay salt pan, in one area and abundance of fired aggregates of soluble salts mixed with ashes in another area has allowed the tracing of anthropogenic deposits that are characteristic of salt preparation\textsuperscript{44}. Progress in soil micromorphology will certainly help to enrich our knowledge of anthropogenic deposits and understand better crosscultural resemblances that seem to reflect universality of some human activities. The classification of the main types of anthropogenic materials presented in table 3 is therefore tentative and should be refined by further investigations.

<table>
<thead>
<tr>
<th>Anthropogenic deposits</th>
<th>Main features characteristic of the mode of formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashy deposits</td>
<td></td>
</tr>
<tr>
<td>- primary ashy deposits</td>
<td>homogeneous to layered; dense to open fabric; articulated woody pseudomorphs; semi-articulated phytoliths; gradual transition with charred plant remains</td>
</tr>
<tr>
<td>- secondary ashy deposits</td>
<td>heterogeneous, discontinuous layering; dense fabric; disarticulated charred and ashy plant remains; abundant non fired mineral and organic inclusions</td>
</tr>
<tr>
<td>- ashy wastes</td>
<td>heterogeneous, loose, chaotic fabric; disarticulated charred and ashy plant remains; abundant sub-rounded mineral aggregates</td>
</tr>
<tr>
<td>Organic rich wastes</td>
<td>spongy micro-aggregated fabric; abundant phytoliths and calcium oxalates; amorphous to weakly crystallized yellowish calcium phosphate</td>
</tr>
<tr>
<td>Compound wastes</td>
<td>heterogeneous, dense to open, chaotic fabric; disarticulated charred, ashy and humified plant remains; bone fragments; micro-flints; abundant aggregates from natural deposits and construction materials</td>
</tr>
<tr>
<td>Construction materials</td>
<td>vesicular, fissural or elongated chambers; common articulated phytoliths; dense, homogeneous or dense micro-aggregated fine mass</td>
</tr>
<tr>
<td>Destruction deposits</td>
<td>dense to loose packing; aggregates of various forms and compositions</td>
</tr>
</tbody>
</table>

Table 3 - Tentative classification of the main types of anthropogenic deposits in habitation contexts.
Comparison of similar types of anthropogenic deposits formed in a great diversity of environmental conditions has allowed the tracing of specific pedo-sedimentary signatures that help to evaluate the degree of preservation of human related information within the soil-sedimentary matrix. All intermediate stages of preservation can be encountered between two extreme poles:

- Unaltered anthropogenic deposits: are those that have not suffered modifications of the original composition and arrangement of organic and mineral components of human origin; they are more typically observed in archaeological sites where (1) anthropogenic accumulation was largely dominant on natural sedimentation and (2) post-depositional disturbances were limited because of weakly aggressive environmental conditions. Occupational sequences from tells in semi-arid and arid regions or from closed systems, such as some exceptional caves, provide the best examples of excellent degree of preservation of anthropogenic materials.

- Totally altered anthropogenic deposits: the soil-sedimentary matrix of archaeological materials display no morphological signs of human presence.

In the latter case, micromorphological study of all sedimentary and pedogenic signatures of natural origin helps to identify two types of situations:

- Anthropogenic deposits and features that may have been originally present but have suffered complete in situ alteration through post-depositional processes, such as biological degradation or carbonate dissolution. The critical issue is to find sufficient information to estimate how much anthropogenic and natural soil-sediments were lost and how these may have modified the original distribution of archaeological materials. Often loss of original constituents is so important, that it may have produced concentration of archaeological materials. In this case, study of specific archaeological patterns, such as refitting flints or interconnected bones, provide the only reliable data for relating these concentrations to genuine events of human occupation.

- Anthropogenic deposits and features have been totally altered and the soil-sedimentary matrix has been displaced from its original context. This situation is more commonly encountered in flood plain and in depositional environments which were exposed to colluviation. Interpretation of pedo-sedimentary signatures helps to evaluate the importance of transportation and its effect on archaeological materials.

Disturbances induced by bioturbation appear to be the most common process responsible for moderate degree of preservation of anthropogenic deposits. They can be tentatively evaluated though semi-quantitative estimation of the volume change induced by biological mixing. Study of the relative distribution of micro-artefacts and larger sized archaeological materials also helps to evaluate intensity of perturbation. For example, a 10 cm thick archaeological unit at the late Palaeolithic, flood plain, site of Verberie (France) was found to result from a 40% volume increase through earthworm mixing, low energy alluvial deposition and moderate carbonate dissolution. Occurrence of scattered millimetric bone fragments and charred particles in the fine mass suggest that these disturbances did not significantly modify the spatial distribution of archaeological materials. Recognition of these disturbances however, helps to explain why boundaries between archaeological units could not be clearly identified during excavation.

**Spatial and temporal variability of use of space.** Archaeological exploitation of micromorphological data requires the elucidation of the relationships between the spatio-temporal patterns of human activities and the physical expression of human intervention (i.e. anthropogenic deposits and human-induced structural changes). When integrated with all other archaeological data, this high level of interpretation can be used to underscore the significance of the soil-sedimentary matrix properties with respect to use of space. The main types of functionally discrete activities...
that can be presently identified based on the interpretation of anthropogenic fabrics are the following:
- activities related to processing, cooking or consumption of food,
- passage activity either of human beings, or of animals or both (photo 3),
- resting activity,
- stabling activity and maintenance of stabling area,
- surface maintenance by using covering materials or by sweeping,
- use of water,
- processing of objects that produce mineral or organic residues,
- management of refuse: type of wastes and periodicity of dumping (photo 4).

Lateral changes in anthropogenic microfabrics are interpreted to reflect spatial variability of past uses of space during a single occupation event only when the soil-sedimentary expression of each occupation phase can be defined at a high level of resolution. The prerequisite condition is first to establish that the different samples do relate to the same occupation phase. This is generally deduced from field observations, especially when excavation permits clear identification of upper and lower boundaries of each anthropogenic unit. A reliable field control is, however, more delicate when individual occupation phases are represented in some areas by an ultra-thin layer (less than 1 mm), especially in the case of well defined activity surfaces with limited sedimentary addition of human origin. Even the finest tools, such as dentist scrapers, may not be sufficient to enable accurate peeling off the successive microstratigraphic layers.

The microstratigraphic framework that has been identified in the field thus requires testing and refinement by comparing a great number of thin sections from the same occupation unit exposed over a large surface. When microstratigraphic correlations are clearly established, lateral variations of anthropogenic fabrics and of their degree of alteration by natural agents can be interpreted to reflect the spatial patterning of human activities.

Marked changes in some significant micromorphological characteristics help to delineate boundaries between specific activity areas. For example, a fabric characterized by a continuous accretion of incorporated human refuse and evidence of water percolation would point to intensive trampling in an open passage area. Close juxtaposition of with a fabric typical of a well maintained activity surface with absence of features induced by percolation can be interpreted as a covered activity surface protected by a superstructure, such as a roof or a tent.

Reconstruction of spatial patterning of human activities is often more hypothetical when post-depositional disturbances, such as erosion or biological mixing, have altered the lateral continuity of each occupation unit. Reconstruction of the evolution of a specific area is based on the interpretation of vertical variations of anthropogenic fabrics and environmental conditions. A large diversity of situations has been observed:
- perennial use of space is reflected in a few centimetre thick, homogeneous anthropogenic deposit in which microstructure and composition relates to a single activity or to synchronous activities,
- a sequence formed of several millimetric units that clearly differ by their specific anthropogenic fabric characterizes a continuous polyphased occupation marked by rapid variability of human activities; these sequences common in proto-urban and urban occupation layers23,24,25,
- an alternation of millimetric to centimetric anthropogenic units of different fabrics and microstratigraphic units formed by natural processes characterizes a polycyclic sequence; this succession reflects discontinuous occupation and changes in use of space through time.
Site of Haloula (Euphrate, Syria): Late pre-ceramic Neolithic units (excavated by M. Molist)

Photo 3: Microfabric interpreted as a passage area, trampled by herbivores. Dense packing of rounded, poorly sorted, phosphatic rich, aggregates, mixed with finely layered charred plant remains and embedded in an ashy fine mass with abundant fragments of herbivore excrements. PPL.

Photo 4: Dumped area. Loose packing of poorly sorted, subangular to subrounded aggregates, derived from construction materials, mixed with an ashy fine fraction rich in bone fragments. PPL.
Micromorphological interpretation of natural induced transformations of each anthropogenic unit and interlayered natural deposits helps to reconstruct the evolution of environmental conditions and assist in estimating the relative duration of each occupation phase. For example, in the pre-ceramic Neolithic site of Dja'dé (Syria) we could observe an alternation of well structured, constructed mud floors with microstratigraphic units formed of loosely packed rounded aggregates of human and natural origin; these were crushed by secondary crystallization of gypsum and slightly reworked by wind. This sequence was interpreted to reflect a temporary occupation with an increase in aridity during a phase of abandonment which may possibly represent seasonal events. This tentative interpretation illustrates how soil micromorphological research in archaeology is stimulated to extend its limits for deciphering changes of environmental conditions that are significant at a human time scale.

**Off-site analysis**

**Landuse practises and human-induced soil alteration.** Microscopic traces of modifications of natural soils that were induced by past human exploitation have been mostly recognized from buried soils from various environmental contexts. In these conditions, rapid burial by anthropogenic deposits is suggested to have more or less preserved the diagnostic microfabrics of anthropogenized soils. Their exact original nature may have been transformed by burial effects, such as loss of organic matter by biological decomposition, percolation of solutes, biological mixing or compression by weight of overburden. Experimental investigations show that earthworm and other fauna may survive burial to induce these transformations, in spite of localised anaeorobic conditions developing along the old ground surface. As a result of these modifications, the typical horizonation of a soil is often weakly expressed in the field when studying buried profiles. Careful micromorphological examination permits us to determine if the original surface horizons were preserved by burial or if the soil profile was truncated before sealing.

Anthropogenic soils that derive from human-induced accumulation of finely mixed natural soils and occupation deposits for agricultural purposes have been rarely observed. Plaggen soils that were formed during the late Medieval times in the Netherlands are certainly the most typical anthropogenic soils that offer a unique record for reconstructing their agricultural history with the help of other environmental data, especially those provided by pollen analysis. In this case, the exact nature of organic manure that was brought up to the soils could not be precisely characterized in thin section because of strong effects of biological decomposition. In less aggressive conditions, features and microfabrics of anthropogenic origin are recognized and thus provide direct information for understanding conditions of past land exploitation.

Comparison with experimental situations and modern farmed soils have been essential to understand how the physical effects induced by farming practises can be recorded in ancient soils. Based on this reference data base, various attributes, such as specific structural fabrics, slaking crusts or coarse textural features, have been more systematically investigated in buried soils because they can be considered as excellent indicators of anthropogenic alteration of natural soils. Recent progress of micromorphological research of buried soils thus permits to broad characterization of several types of landuse practises by specific micromorphological features and fabrics (table 4; photo 5 and 6).
<table>
<thead>
<tr>
<th>Landuse practises</th>
<th>Micromorphological features and fabrics</th>
</tr>
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<tbody>
<tr>
<td>Slash and burnt</td>
<td>burnt soil fragments; abundant fine charred particles and coarse charcoal</td>
</tr>
<tr>
<td>Up-rooting</td>
<td>mixing of soil horizons; fragments of trees and soils burnt in situ</td>
</tr>
<tr>
<td>Ploughing</td>
<td>incorporated fragments of slaking crusts; dusty silty clay intercalations and coatings; mixing of soil horizons; loss of fine fraction; decrease in biological activity and changes in biological fabrics</td>
</tr>
<tr>
<td>Manuring</td>
<td>abundant organic fragments and charred organic wastes; change in biological fabric</td>
</tr>
<tr>
<td>Irrigation</td>
<td>increase in clayey silt fine fraction; abundant clayey silt intercalations and coatings, incorporated fragments of slaking crusts, collapsed vugly microstructure</td>
</tr>
<tr>
<td>Horticultural practises</td>
<td>abundant highly humified organic matter; mixing of anthropogenic fabrics and natural soil fragments; totally excremental fabric</td>
</tr>
<tr>
<td>Pasturing-herding</td>
<td>phosphate impregnation and weakly crystallized phosphate minerals; fragments of humified herbivore excrements; dark, dusty, silty clay coatings and infillings; dense compacted, heterogeneous fabric</td>
</tr>
</tbody>
</table>

Table 4: Main micromorphological features and fabrics characteristic of ancient landuse practices

Photo 5: Buried Neolithic soil at Carn Brea, Cornwall. A shallow humo-ferric podzol (Typic Haplothord) formed during the Neolithic from a acid brown earth (Cambisol) on granitic head, because of clearance and occupation; secondary clearance of shallow rooting vegetation ahead of rampart construction caused mixing of the pale depleted A2 horizon and dark Bh horizon. closed vughs formed as dusty clay was translocated locally due to this disturbance. PPL.
Micromorphological data from buried soils are not however sufficient for reconstructing the dynamics of ancient human landscapes at micro-regional or regional scales. Data have also to be obtained from the non-buried soil contexts of an entire catchment area in order to understand how and for how long it was exploited. This raises two main difficulties:

- how to individualize effects of early phases of human exploitation in ancient soils that have been exposed for a few millennia to a continuous pedological development;
- how these early episodes of soil development affected by human activities can be precisely dated in order to obtain a reliable temporal record of the successive phases of land exploitation.

Complex stratigraphic deposits that consist of well-defined soil-sedimentary units are the most informative sequences for analysis of ancient cultural landscape. They can be more or less precisely dated by using various types of chronological data:

- direct absolute radiometric dating when reliable materials such as charcoal or shells are present,
- cultural dating provided by archaeological objects found in each unit,
- relative chronology based on stratigraphical correlations with well-dated, buried soils below occupation deposits.

Recognition of ancient phases of human exploitation is more delicate in relict soil-sedimentary deposits of the Holocene that have been considerably transformed by recent pedological development. Features inherited from earlier episodes of soil development can be discriminated in thin sections from the recent ones. The lack of a reliable chronostratigraphical framework does not permit precise correlation of the hierarchy of features observed with successive phases of human occupation.

Photo 6: Raunds Area Project, Northamptonshire, England. A Bronze Age barrow containing some 100 cattle skulls buried a Typic Hapludalf developed on loamy alluvium; the thin (30-40 cm) buried soil is characterized throughout (here at 25 cm) by very abundant, dark, clay coatings and infillings; the enhanced phosphate content (800-1300 ppm) may indicate that these dark stained (humic?) coatings arise from animal herding and trampling. PPL.
When working on complex stratigraphic sequences, an accurate micromorphological interpretation of all sedimentary and pedogenic features identified in each unit permits refinement of stratigraphical correlations that have been initially established in the field. Each palaeogeography is thus characterized by its spatial association of different physiographic units that comprise various depositional environments and related soil cover. When comparing these different physiographic units, micromorphological data are essential to understand how spatial variability observed in depositional and pedogenic dynamics relate to local conditions or to conditions that are controlled by factors acting at larger regional scale. For example spatial and temporal variability in the type of features and microfabrics that are characteristics of farming practises (table 4) should help to delineate extent of areas devoted to cultivation from the ones devoted to animal husbandry or to exploitation of natural resources and evolution of exploitative strategy through time.

Interactive effects of human and natural factors on ancient landscape dynamics. Detailed palaeogeographical reconstruction that can be supported by micromorphological data are not only essential to studying conditions of ancient exploitation but are also necessary to investigate the complex relationships between human factors and natural agents on the changes of ancient cultural landscapes. This concern is directly linked to archaeological objectives because conclusions will provide important information to better understand how patterns of cultural deposition were shifting across the occupied area though time. In addition, it can help to better evaluate the significance of site distributions within the modern landscape, with respect to the original one. These archaeological objectives requires a high level of temporal and spatial resolution that can be matched in various aspects by micromorphological data.

Similarly to the study of ancient farming practises, the most reliable record for studying ancient landscape dynamics is provided by complex stratigraphic sequences which can be directly linked with successive phases of human occupation. Micromorphological investigations of soil-sedimentary features and fabrics that characterize the various depositional and pedogenic components of each palaeogeography is aimed at determining the five basic factors that interactively control landscape dynamics:

- structural stability of the soil surface,
- soil physical properties,
- farming practises,
- morphology of elementary catchment basins and patterns of field systems,
- climatic parameters.

As previously stated, this research objective is strongly constrained by the quality of the spatial and temporal record, because we need to consider that the respective weight of each of these five factors is thoroughly understood (i.e. field systems). Consequently, the formulated conclusions are highly speculative although they help to highlight simplistic relationships previously established between human impact and landscape response or climatic impact and human response. For example, manifestations of Holocene soil erosion that has been commonly observed from various geographical regions, are often explained as a direct response to human effects because they broadly coincide with an increase in population density or with human degradation of the natural vegetation, as shown by pollen data. In this case, micromorphological investigations are imperative in order to precisely characterize the sedimentary and pedogenic mechanisms that resulted in soil erosion and to determine causality of the observed changes.

When combined to a detailed record of socio-economic events and a precise chronological framework, micromorphological data have been shown to efficiently match the high level of temporal and spatial resolution that one should achieve to demonstrate the causal links between an
abrupt environmental change and a synchronous modification of ancient activity system, such as a sudden decline of an ancient civilization\textsuperscript{52}.

Recent research from numerous Holocene contexts has now amply demonstrated how various pedo-sedimentary mechanisms, such as biological activity, wind deflation, surface, runoff, carbonate redistribution are expressed by a high sensitive morphological signal that reflect upon past hydric or wind regimes, rainfall intensity or seasonal climatic patterns\textsuperscript{48,53,54,55}. The temporal and spatial precision that is achieved is fully compatible with a human time scale and can hardly be obtained from proxy-climatic indicators.

Conclusions

Integration of micromorphological data with archaeological, chronological and other environmental data now illustrates the considerable precision that can be achieved in defining spatial patterns of past human activities in term of environmental influence and temporal patterns of past cultural changes in terms of environmental influence. Soil micromorphology in archaeology thus provides access to a different pool of information which does not violate basic archaeological assumptions, compromise other archaeological data, or simplify a theoretical assumption\textsuperscript{56}.

This approach has no pretention to be innovative. Earth scientists, especially the ones studying pre-Quaternary periods, have long been familiar with integrated system models to study, at different spatial and temporal scales, terrestrial environments from thin sections to, field exposures, regional basin and the earth planetary system. Stimulated by the critical problem of global environmental change, soil scientists have more recently stressed the considerable variability in time and space of factors of soil formation. Proper study of this variability requires the integration of various sources of data from microsamples to pedons, landforms and the pedosphere to be properly understood\textsuperscript{56}. Surprisingly, one of the continuing challenge for soil micromorphology in archaeology is to demonstrate to archaeologists how study of human settlement systems from site to regional level cannot ignore investigations at microscopic scales. The necessity to decompose past soil-sedimentary systems from their high level of organization to lower scales is fully justified by the need to completely understand the complex interaction between human behavior and natural processes.

Efficiency of soil micromorphology in assisting archaeological interpretation of lifestyles and cultural patterns is closely linked to the level of accuracy of field investigations, especially excavation. Refinement and progress of our present knowledge would certainly benefit from systematic investigations of extensively exposed surfaces and from comparative study of different occupational areas in sites of great socio-political complexity.

In line with the study of experimental and ethnographic situations, simulations in laboratory and in natural conditions have also to be developed to better characterize and quantify the dynamics of the soil-sedimentary systems under the interactive effects of human and natural agents. This field of research should also be of interest to students of earth history (geologists, geographers, pedologists) who wish to monitor or document the effects of past human activities as a means to evaluate the effects of modern human practices, such as land-use: compaction associated with vehicular traffic in agriculture and recreational areas; forest clearing and soil erosion in tropical utreas. This emphasizes that research in soil micromorphology carried on for archaeological purposes transcend archaeological achievements and should thus be conducted in close association with all allied fields of environmental research.


Micromorphological Assessment of Degraded Soil-Landscapes

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Abstract. The extent of severe soil degradation is globally small, but locally or regionally can be quite devastating. This presentation summarizes existing uses and provides suggestions for future use of micromorphology for investigating processes of soil degradation and its rehabilitation. A review of micromorphological studies of degraded soils is provided, together with a specific illustration of in situ microanalytical techniques. Most micromorphological studies of degraded soil focus on heavy metal contamination or neoformed inorganic precipitates. Studies of other contaminants (e.g., pesticides, petroleum products) are not reported, presumably because suitable techniques are not available for in situ analysis, and studies of biological or physical aspects of degraded soil are sparse. Future use of micromorphology will benefit from (i) adopting a broader and more sophisticated array of microanalytical techniques, (ii) closer links with studies operating along a continuum of scales (micro to landscape and beyond, and (iii) more emphasis on its use for developing and evaluating rehabilitation strategies.

Introduction. In their global assessment of human-induced soil degradation, Oldeman et al. (22) have described strongly-degraded soils as those that require major engineering for rehabilitation and extremely-degraded as those considered unreclaimable and beyond rehabilitation. These strongly- or extremely-degraded soils occupy about 300 million hectares of a total land surface of about 13,000 million hectares, and characteristically are extensively physically-degraded. Most of the land affected by chemical pollution occurs in Europe (19 of 22 million hectares) and the bulk of it is categorized as moderately-degraded, which implies greatly reduced productivity. Globally, a broad distinction can be made between physically-degraded land, characterized by extensive terrain deformation and soil loss, and polluted land in which deleterious anthropogenically-derived chemicals have accumulated.

The magnitude of chemical and severe physical soil degradation appears small globally, but local consequences can be devastating and present major challenges for designing and implementing sustained rehabilitation. Relatively few micromorphological studies have focused on degraded soil landscapes. The purpose of this presentation is to summarize existing knowledge and provide a framework for future use of micromorphology for investigating and interpreting degraded land and its rehabilitation.

Methods. A review of the micromorphological literature that addresses physically- and chemically-degraded soils forms the primary data base for this presentation. In addition, previously
unpublished work by J.M. Arocena on microanalytical techniques for in situ investigation of trace element distribution in organic matter and Fe oxides is presented. The methods used by Arocena included use of x-ray microdiffraction (XRMD) and infrared microscopy (IRM), together with conventional light, electron and fluorescence microscopy for in situ investigation of Fe and organic-matter bearing nodules. Both IRM and XRMD provide point analyses in areas as small as 50 μm in diameter in thin section peel or a few micrograms in weight. The use of XRMD involved use of a transmission type of x-ray camera with exposure from about 8 to 24 hours. The diffraction pattern is recorded in photographic film. Infrared microscopy was conducted using a Nicolet Magna 700 IR microscope. More detailed discussion of these procedures will be provided in forthcoming papers by Arocena and co-workers.

Literature Review. In this section, we provide a selective review of micromorphological research on degraded land. The literature is sparse and focuses largely on describing various types of degradation. There are even fewer studies that use micromorphology to help define processes of degradation or that focus specifically on rehabilitation of degraded land.

One of the earliest applications was by Bisdom et al. (4, 5) in an international cooperative project in which they demonstrated the utility of micromorphology in combination with other analytical techniques for investigating heavy metal contamination in experiments simulating soil conditions beneath a landfill. More recently, Sivolobova et al. (28) demonstrated a technique for laser spectral microanalysis of thin sections and polished blocks that includes data on reproducibility of measurements and limits of detection for elements occurring in small quantities.

Following an initial study by Drodz and Kowalinski (9), Weber and co-workers have reported on the interaction between soil and heavy metal-bearing dust particles derived from Polish copper smelters (15, 34-36). These studies provide a detailed account of the chemical and morphological attributes of the types of heavy metal-bearing dust particles found in soils near the smelters and a basis for interpreting modification of dust particles in response to soil processes. Preliminary submicroscopic studies indicate that dust particles have not undergone major transformation, but regular spherules found in snow samples have not been isolated from mineral soil samples.

Strzyszcz (29) observed an increase in the ferromagnetism of soils forming under spruce (Picea) and pine (Pinus) in some Polish National Parks. The increase in ferromagnetism was attributed to addition of fly ash derived from coal-burning power plants. Iron-rich sphaerules were identified by scanning electron microscopy (SEM) in the litter layer (O horizon). Dudas and Warren (10) developed a submicroscopic model of fly-ash particles, based on SEM and studies of trace element distribution. Studies of this type are particularly useful for providing baseline data for identifying anthropogenic additions to the soil and for developing models for simulating their behavior in soil environments.

McQuattie and Crang (20) and Brogowski et al. (7) have studied the influence of heavy metal contamination and soil conditions on structural components of plants.

In a study of sewage sludge and sewage sludge-amended soil, Essington and Mattigod (11) used a physicochemical particle size fractionation scheme (particle size, density and magnetic susceptibility separations) to obtain isolates for analysis of trace element bearing particles. Heavy density
particles (2.96 t/mZ) were shown by SEM and energy dispersive x-ray analysis to contain trace element bearing particles of industrial origin. The concentration of trace elements was insufficient to be determined by x-ray diffraction analysis. A SEM and x-ray analysis of root nodules of *Trifolium repens* L. grown in sewage sludge-treated soils was conducted by Leung and Young (16). They found that the bacteroides of *Rhizobium tropici* appeared pleomorphic in nodules from plants grown in both test and control soils. The heavy metals present in the sewage sludge included Cu, Zn, and Ni; only Cu was found in the nodules associated with the sewage-sludge treated soil.

Studies by Hiller and Brummer (12, 13) have provided valuable insight about the migration and retention of heavy metals in soils (8). They have shown that Zn and Pb in wetland soils can migrate into clay coatings. They have also shown, under a range of soil conditions (pH 3.9 to 7.4), Fe, Cu, Cd, Ni, Si, Mn, Pb, Zn, and Co are bound by organic matter and pedogenic oxides and to a lesser extent by clay minerals and, that with time, Fe, Si, and Mn diffuse into the inner zones of oxidic concentrations. Tiessen et al. (31) have shown that in semi-arid soils of the tropics, ferruginous nodules have a larger sorption capacity for P than unaggregated fine material. Microprobe and x-ray analysis showed high concentrations of Al and Fe in pores and nodule surfaces and micromorphology showed that the seemingly inert nodules were quite porous. This study and that of Brummer indicate that oxidic concentrations in soils merit further investigation as possible sinks for contaminants.

Using column experiments, Thompson et al. (30) found that calcium carbonate formed very rapidly as a secondary precipitate in pH 11.8 bauxite processing waste. Micromorphology showed infillings, coatings, and hypocrocoatings of calcium carbonate replacing gypsum. Wiggering (38) and McSweeney and Madison (21) have reported on weathering and secondary formation of minerals in mine waste. McSweeney and Madison (21) used a combination of SEM, microprobe, and image analysis of porosity from thin sections to interpret formation of a cemented horizon from initially unconsolidated waste after only 70 years of weathering.

McCurdy and McSweeney (19) investigated the origin of macropores in artificially compacted earthen liners designed to prevent leakage of dairy manure from outdoor storage basins. Thin sections of the macropores indicated that both physical (shrink-swell, freeze-thaw) and biological (root and earthworm burrowing) were responsible for their formation. They also concluded that the viability of the liners will decrease with time because they are subject to pedogenic processes.

**Discussion.** The preceding literature review indicates that the utility of micromorphological approaches for investigating chemically-degraded soils is somewhat limited by the availability of techniques suitable for *in situ* detection of contaminants in undisturbed soil. Studies of heavy metal contamination, and secondary solid phase precipitates dominate, and provide useful information about gross chemical composition. However, methods suitable for *in situ* determination of more specific chemical information such as redox status, nature of bonding between heavy metals and organic molecules have yet to be developed as routine techniques. It should be noted that studies of organic contaminants (e.g., pesticides, hydrocarbons) are absent in the micromorphological literature. The small atomic numbers associated with the dominant elements in organic molecules precludes their detection by *in situ* microanalytical techniques commonly used by micromorphologists (3). There are also few micromorphological studies of physical and biological attributes of degraded soils.
The array of information that can be obtained using the spatial context provided by thin sections, polished blocks or other forms of undisturbed soil material needs to be expanded in order to improve our understanding of processes that either drive degradation or foster recuperation of degraded land. Two general approaches involving (i) isolation of features and (ii) enhancement of features for specific analyses are outlined below and both are designed to take advantage of the high spatial resolution provided by micromorphology. Improving micromorphological approaches for defining the roles of the various colloidal organic, organo-mineral, and mineral components in soil is crucial for refining our understanding of processes that influence fate of contaminants. Colloidal components also play a crucial role in aggregation and thus influence pore geometry and hydrological processes such as those affecting contaminant transport.

The first approach involves removal of specifically targeted features or zones of an undisturbed sample for further analysis. Arocena et al. (2) provide an example of extraction of Fe and Mn from targeted features identified in thin section. This basic approach could be extended to deal with a variety of contaminants, provided that suitable extractants are available to remove the contaminants and that they occur in sufficient quantities to be detected. Alternatively, targeted areas of the undisturbed sample can be physically isolated and then used for subsequent more detailed analysis, once their micropedological context has been defined.

The second approach involves some form of treatment of the undisturbed sample to enhance or highlight particular attributes. Atemuller (1) describes a technique for rendering organic soil components in thin section suitable for fluorescence chromatography. Further work in the area selective staining and isotopic or radioactive labeling will be most useful for identifying the fate of contaminants.

Figures 1 through 4 illustrate various techniques of in situ analysis pertinent for investigating contaminant fate in soils. Figure 1 is based on analysis of Fe-oxide nodules from a Bs horizon of a Cryorthod. The XRMD indicates that the nodule includes goethite and quartz. The goethite crystals are small (10 μm) and randomly oriented, as indicated by the small and continuous Debye-Scherrer rings. The identification of goethite, its size and distribution provide important information for predicting its role in adsorption reactions that could not have been obtained from the energy dispersive spectra alone. Goethite possesses type A-OH (23), which are much more reactive than the type B and C-OH hydroxyls found in other Fe oxides. The nature of organic matter can strongly influence contaminant fate. Figure 2 shows the presence of esters and proteins in organic matter, both of which play roles in adsorption of organic contaminants.

Figures 3a and 3b illustrate various properties of glaebules or zones of accumulation of (i) organic matter and quartz and (ii) organic matter, quartz, Mn oxides, phyllosilicates. Preliminary isotherm studies indicate greater adsorption of anthracene in the darker zones compared to the matrix and greyer zones. The darker Mn-rich zones are preferentially distributed along cracks, which is an important consideration for any attempt at an integrated assessment of adsorption and transport of contaminants in the fractured Lethbridge shale.

The distribution of Cr and Pb in phosphagypsum (Figure 4) is likewise not random but centered on surfaces of goethite and ilmenite. This provides valuable information that can be used to design removal of Cr and Pb from phosphogypsum by density and magnetic separation techniques.
Figure 1. Composite illustration of combined microanalytical techniques for investigating soil nodules: (A) partially cross-polarized view of soil nodule; (B) energy dispersive spectrum showing major elemental composition of nodule; (C) x-ray microdiffraction pattern revealing presence of quartz and goethite.

Figure 2. Comparison of the infrared spectra from (A) organic matter nodule in thin section and (B) humic acid extracted from a similar soil horizon. Note absence of absorption bands at 1735, 1785, and 1870 cm$^{-1}$ in the humic acid. The bands are correlated to esters and proteins. The inset shows the presence of quartz (Qtz), organic matter (OM) and phyllosilicates (phyllo) in the nodules (adapted from Arocena et al., in preparation).
Figure 3a. Micrograph showing accumulations of organic matter (OM) (gray zones in micrograph; red under fluorescence) and accumulations of OM, Mn oxides and phyllosilicates (black zones and black under fluorescence) in Lethbridge shale.

Figure 3b. Reconstructed x-ray microdiffractionograms of glaebules (accumulations) from Lethbridge shales: A) red zones; B) black zones. Organic matter is indicated by the G-band around 0.447 nm (adapted from Arocena et al., in preparation).
Micromorphometry provides the tools for developing models of pore geometry. Such models may provide the parameters (e.g., tortuosity, connectivity) for refining hydrological models (18). The operational significance of particular pore networks is crucial for assessing the hydrological conditions that are likely to result in accelerated transport of soil-borne pollutants.

Wang et al. (33) used micromorphological techniques to evaluate and interpret a hydrological model developed from an infiltration study made on burrows created by ants. It had been postulated that the burrows, which occur in sandy agricultural soils of Wisconsin, may serve as conduits for accelerated movement of agricultural chemicals to groundwater. Thin sections were especially useful for interpreting the hydraulic conductivities of saturated soil matrix (Ks) measured by a macropore infiltrometer. The matrix Ks of ant burrow walls was about eight times smaller than matrix Ks of adjoining (unburrowed) sandy soil. Thin sections provided evidence of extensive infilling by fine material between sand grains in the burrow walls, which was interpreted as the likely cause of the large decrease in Ks.
Summary and Conclusions. The challenge when employing enhancement or isolation techniques or other types of microchemical analysis is to first have a sound description and understanding of the micromorphology of the sample under investigation so that the subsequent more sophisticated analysis can be interpreted in an appropriate micro- and macro-pedological context. Creative strategies need to be developed so that the interpretative framework provided through investigation of undisturbed soil can be linked with analytical advances such as nuclear magnetic resonance spectroscopy (6), synchotron x-ray analysis (26), or electron spin resonance spectroscopy (27) to advance understanding of processes operating from microscales and beyond (17).

The discussion to date has focused on approaches for identification and interpretation of degradation processes. Inquiries of this type will continue to be important in the future, but there is also a need to develop micromorphological techniques that aid in development of strategies for rehabilitation of degraded land. Although laboratory simulation experiments (e.g., 4, 5, 30) have been under-utilized for defining degradation processes, they should be considered for evaluating rehabilitation strategies. A variety of strategies that are used for rehabilitation, such as addition of organic amendments (24) and addition of beneficial soil animals (14, 37) have been evaluated in terms of micromorphological changes. Micromorphology may be particularly useful as a means of detecting incipient changes following application of a rehabilitation treatment, especially if combined with measurements of other attributes (e.g., soil strength, aggregate stability, rooting behavior).

Sampling designs for collecting micromorphological samples (32) and then the scaling of interpretations made at the microscale to the horizon, profile and the soil-landscape remains a challenge (25). Functional relationships between sorption of a contaminant and a specific micromorphological feature can be reasonably generalized to horizon attributes such as nodules, clay coatings, and so forth. However, scaling of hydrological interpretations related to contaminant transport, especially those involving preferential flow remains largely enigmatic.

Literature Cited.


Wetland Habitats -- Qualities, Processes, and Attributes

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ABSTRACT

Human influences on wet soils worldwide have been both extensive and diverse, including such direct effects as the drainage of wetlands for agriculture, flooding for paddy rice culture, or the construction of wetlands for more intensive purposes. Human impacts on wetlands might also be broadened to encompass less direct aspects, such as accelerated submergence of coastal areas by rising sea level associated with anthropogenically induced global warming. Micromorphological studies of these soils yield significant insights into important processes associated with the soils both before and after human intervention. Where microfabrics or pedofeatures had formed in the soils prior to human impact they may be well preserved and provide important insights into the original geomorphic and pedogenic processes associated with the formation of these soils. When the soils become affected dramatically by human activity, whether intentionally or otherwise, there is a concomitant shift or perturbation in soil processes. These disturbances lead, of course, to the development of new fabrics or features which may either be superimposed upon, or replace, the previous features or fabrics. If the old features are not in equilibrium with the present processes, but nevertheless preserved, they would be considered relict. Thus, careful micromorphologic observations of anthropogenically affected soils will yield useful perspectives on the nature of current or former soil processes.

INTRODUCTION

In the past, most wetland areas have been thought to possess little inherent value, and until recently they have been considered by many to be essentially wastelands. At present there is a growing recognition of the value of natural wetlands. Their usefulness as fish and wildlife habitat has been traditionally acknowledged, but more recently additional values of natural wetlands have been identified, including their role in water purification and storage for many uses, and as areas which possess a rich biodiversity. Over the years, valuable wetland products have been harvested or mined including timber, fin and shellfish, wild waterfowl, and peat. Nevertheless, apart from paddy agriculture, wetlands have been viewed as having low potential for human use. Thus, because a large portion of the earth's population lives in or near lowland areas, there has been significant anthropogenic alteration of wetland areas through the centuries.

DRAINAGE OF WET SOILS

In order to transform wetlands into more productive agricultural resources, extensive efforts have been made worldwide to close off and drain wetlands, marshes and lakes. In each of the cases
below, soils had formed initially in a saturated and reducing environment and were subsequently altered through drainage. Drainage has caused changes in physical, chemical, and biological soil characteristics which have led to the development of macro and micromorphological features that reflect both the initial aquatic conditions and the ensuing pedogenic processes associated with drainage (11, 27, 36).

**Drainage of Coastal Marshes and Mangroves**

During the Pleistocene maximum, sea level was about 100 m below the present level. Sea level rose continuously throughout the Holocene and several transgressive phases have been recognized. Around 5000 YBP the rate of sea-level rise decreased and an enclosed system of nearly continuous coastal barrier islands formed, behind which there developed extensive peat deposits. A number of local transgressions occurred when the sea breached the weakest points of the barrier islands or entered via river estuaries. These transgressions caused local erosion, and new tidal sediments were deposited (22). The discussion below focuses on polders of the Netherlands (Fig. 1), but should be illustrative of Northwestern Europe in general. [A polder is an area in which drainage systems (open drains, ditches, canals) are cut off from outside water by dams and sluices, and where the water level is controlled (44).]

Around 4300 YBP, people began to settle on the barrier islands behind the dunes and on high natural levees along the creeks in the salt marshes (32). To protect settlements from the continually rising sea, low dams were built and dwelling mounds were raised. These low dams built for artificial water-level control formed the first type of polders. The areas had only a simple drainage system following the dendritic creek pattern, which functioned at low outside water levels. This settlement continued into the Middle Ages. These older defensive polders have an irregular topography due to differential shrinkage, and now cover approximately 300,000 ha. These areas have non-calcareous, fine-textured soils, often

![Figure 1. Distribution of the four types of marine polders in The Netherlands.](image-url)
overlying peat. From about 1200 AD onwards the first offensively embanked coastal polders were reclaimed from tidal foreland, mostly adjacent to the older defensively embanked polders, or new islands silted up to the level of mean high tide. Human influence upon the patterns of these areas is greater than in the old-land polders. The main creek courses were kept open as primary drainage channels; smaller creeks were filled and the land was levelled. Most ditches are arranged in a rectangular pattern and the fields are larger than in the older lands. Generally, the soils are calcareous and medium-textured, and they are tile-drained with pumping levels 1-2 m below the surface. These lands cover approximately 400,000 ha.

A third group of polders were drained from shallow fresh water lakes, formed by peat erosion or peat cutting for fuel, and cover approximately 100,000 ha. The lake bottoms were level before drainage and the patterns of ditches, roads and fields very regular. The soils are mainly non-calcareous, fine-textured and locally acid. The Zuyderzee polders, also known as Usselmeerpolders are the last group and come from the non-drained remnant of the Zuyderzee, a shallow marine inlet from the North Sea and cover approximately 165,000 ha. The Zuyderzee also originated by peat erosion, and the history of the Zuyderzee polders resembles that of the drained lakes. The Zuyderzee, however, have more recent sediment overlying the eroded peat layer, which is rather uniform in composition, has a high organic matter content, and is calcareous (11). Taken as a whole, the marine polders of the Netherlands have a total area of about 965,000 ha (Table 1) (11). Many of the soils of the polders are used for either cultivation of potatoes, sugar beet and cereals, or for pasture and hay crops. The micromorphological features related to these marine polders can be split in two groups viz., those occurring in former salt marshes and intertidal flats, and those occurring in former underwater deposits.

<table>
<thead>
<tr>
<th>Origin</th>
<th>Old land</th>
<th>Coastal polders</th>
<th>Drained lakes</th>
<th>Zuyderzee polders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age of the upper part of the parent material</td>
<td>natural forelands, bordering peat, and Pleistocene</td>
<td>coastal marshes outside dikes</td>
<td>shallow mostly man-made lakes</td>
<td>shallow, wide marine inlet</td>
</tr>
<tr>
<td>Period of enclosure</td>
<td>before 1200 AD</td>
<td>1200 AD - present</td>
<td>1500 - 1942 AD</td>
<td>1930 - present</td>
</tr>
<tr>
<td>Elevation</td>
<td>-1 to +5 m</td>
<td>-0.5 to +1.5 m</td>
<td>4 to 6 m below sea level</td>
<td>3 to 5 m below sea level</td>
</tr>
<tr>
<td>Soils carbonates and acidity</td>
<td>non-calcareous and shallow non-calcareous, non-acid</td>
<td>calcareous</td>
<td>calcareous and non-calcareous, non-acid to strongly acid</td>
<td>calcareous</td>
</tr>
<tr>
<td>Areal Extent</td>
<td>300,000 Ha</td>
<td>400,000 Ha</td>
<td>100,000 Ha</td>
<td>165,000 Ha</td>
</tr>
</tbody>
</table>

**Former Salt Marshes and Intertidal Flats**

There are a number of micromorphological features visible within these polder soils which formed prior to reclamation. The specific features are related to the particular zone of sedimentation in relation to elevation and the tidal range. Bare, slightly undulating flats constitute the lowest parts of the intertidal zone and are only dissected by a few gullies. Salt
marshes form at elevations above the flats, and are covered with vegetation. There may be an elevational range of 3 to 4 m between the low intertidal flat deposits and the high salt marsh. An accretionary sequence can often be seen within the deep profiles beneath the tidal marsh. During accretion from the low intertidal flat to the high salt marsh, different soil-forming processes are involved. In figure 2 the main processes and their related micromorphological phenomena are given.

Faunal induced features are formed by normal living and feeding activities of Mollusca, Vermes and Crustacea. Channels, for example, are mainly produced by Vermes and Crustacea species, and persist because they were in use for longer periods. Pedotubules are channel-like features that are infilled with excrements or striated laminae, mainly produced by Mollusca and Vermes. Passage features are also channel-like features, but they lack a distinct external boundary. They are the result of a passage of an animal through unconsolidated soil material and are produced by all faunal species. Often excrements are present and sedimentary laminations usually are disturbed. Features related to the physical processes are mainly due to water losses from the sediment. Shrinkage cracks as well as biological voids can be in-filled with sedimentary material from the surface. The most important chemical processes include: pyrite neo-formation (framboidal pyrite) in clay-rich sediments containing organic matter under reducing conditions; carbonate neo-formation due to local evaporation from supersaturated solutions; decalcification due to the cyclic oxidation of iron, and iron and manganese accumulation where aeration is possible in otherwise reduced sediment (27, 28, 29).
While the micromorphological features present in these polders are mainly formed by processes occurring in the pre-reclamation phase, there are significant changes which occurred following reclamation, which are reflected in the micromorphology (27). The soils in the embanked old land have become decalcified, not only by the cyclic oxidation of iron, but also by the oxidation of sulfides, including pyrite. In the coastal polders, which were reclaimed sooner following sedimentation, the decalcification is restricted to some local top soils. In these polders illuviation of clay-sized material has occurred, due to the change in cations in the clay-complex and the improved drainage. The microscopic pyrite is completely oxidized or has ferruginous margins, and the iron accumulations have a crystalline structure (goethite).

**Former Underwater Deposits**

In the polders formed from the formerly underwater deposits, (from shallow lakes and the Zuyderzee polders) the micromorphological features observed are strongly related to the presence of peat and other organic material and the components of the mineral sediment. Where quantities of organic material and clay-sized sediment were high, an abundance of pyrite often accumulated. In addition, passage features can be found on a large scale. Following reclamation, physical ripening of the sediment (including structural development and aeration) caused the pyrite to oxidize. In a calcareous environment the oxidation products were initially non-crystalline iron hydroxides and gypsum associated with the pyrite. Afterwards, a redistribution of iron forms can take place, whereby hypocoatings and coatings of crystalline iron oxyhydroxides (goethite) are formed around voids.

In environments with less carbonates or large quantities of pyrite, pseudomorphic alteration of pyrite framoids into jarosite \([\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6]\) framoids occurred first, which later could be redistributed forming hypocoatings of jarosite. These are the yellow mottles of the acid-sulfate soils, which in thin sections under plane light, appear dark grey to black, but which show a characteristic yellow or white color under incident light. In the zones which initially contained pyrite, and also deeper within the profiles, amorphous and crystalline coatings of iron oxyhydroxides form as iron is released through the oxidation of pyrite (36, 5). When the sediment becomes oxidized, soluble ferrous iron within the sediment (in addition to Fe released during the oxidation of pyrite) also oxidizes forming coatings and hypocoatings along large voids, such as cracks and large root channels. Manganese accumulations also occur, often in combination with hypocoatings of amorphous iron oxides or in association with organic matter remnants.

In the Zuyderzee polders the underwater sediment contained less pyrite and the mineral material was strongly calcareous. Here the most striking features after reclamation are the iron and manganese accumulations that formed following the oxidation of soluble reduced species of iron and manganese. Manganese accumulations are also observed in and around organic matter remains such as peat grains. Thus the micromorphological features present in these polders mainly formed by processes occurring after reclamation, but the sedimentary processes (such as pyrite formation) largely determine the features and related properties of the soils following reclamation. Micromorphological analyses of polder soils provide insight into which features formed through pre- or post-reclamation processes.
The information gained through micromorphological studies can be useful in making decisions in tide level management as part of coastal protection projects, and in decisions concerning whether or not to reclaim new areas. The information can also be used in historical geography and archeology, e.g., by tracing the environmental conditions at the time of the first settlers and their land use practices.

**Drainage of Mangroves**

Mangroves are the tropical counterparts of temperate salt marshes. Well developed mangroves are found only where the coldest monthly temperatures exceed 20°C and the seasonal range does not exceed 5°C. Like salt marshes, mangroves develop in sheltered areas where fine-grained sediment is available, that is within estuaries or low energy coasts. Where rainfall is low, salt pans occur instead of mangroves. Because population pressure in tropical lowlands is high, a number of mangrove swamps have been diked and drained. The intended use for these newly drained lands has been for agriculture. However, attempts at draining mangroves have met with mixed success and have occasionally resulted in environmental disasters.

Similar to salt marshes, pyrite neo-formations occur in mangrove soils. Organic matter contents in mangroves can be high and the sediments can contain large quantities of sulfides. Diking and drainage can therefore lead to sulfide oxidation resulting in strong acidification and jarosite formation, as sometimes occurs in the drainage of salt marsh soils (51, 43). Where the soils are calcareous, neo-formed gypsum may occur as a byproduct of sulfide oxidation (35). Only under more humid climatic conditions and in freely drained soils can the oxidation products of pyrite be removed by leaching. For example, in the West African country of Guinea Bissau diking and a pronounced dry season resulted in the accumulation of sulfate salts in the upper soil horizons. This combination of extremely acid and saline soil conditions was particularly detrimental for plant growth (12). A similar situation was also reported in Gambia where dams were placed along tidal rivers in an attempt to increase the production of rice on coastal lowlands (38). In areas where the rainfall is high, but soil conditions are strongly acid, as in Indonesia, local farmers try to grow crops on small ridges formed from the less acid surface soil materials. Reclamation and subsequent cultivation of Malaysian mangroves can sometimes proceed more quickly in areas of slightly higher elevation which were flooded less frequently. These higher areas were more oxidized, in part due to faunal pedoturbation, and had a lower pyrite content in the surface horizons (0.1 to 0.5% pyrite-S), than the lower lying areas which had a higher pyrite content (1-2% pyrite-S) (8). Micromorphology can be very useful in studying mangrove sediments and soils as the occurrence and distribution of pyrite can be examined. Pyrite accumulation in former root (Rhizophora sp.) channels gives strong acidification upon reclamation, while pyrite embedded in the muddy sediments oxidizes much more slowly, and sometimes with less acid conditions developing.

**Drainage of Interior Wetlands**

*Eastern and Midwestern North America*

Significant areas in eastern and Midwestern North America were comprised of poorly drained soils. Extensive engineering efforts during the last century, utilizing tile and open ditch drainage,
have been effective in lowering seasonally high water tables in many of these poorly drained soils such that they were converted to some of the most highly productive agricultural land on the continent. Similar efforts have succeeded in many places around the world. The most striking and distinctive morphological features of poorly drained soils are related to the development of microbially mediated reducing conditions during periods of saturation. Under these conditions ferric and manganic oxyhydroxides are reduced to ferrous and manganous forms making them highly soluble and mobile, which during subsequent periods of aeration become re-oxidized and precipitated as brown, red, or black colored features. Repeated fluctuations in soil redox potentials cause segregation of the sesquioxides both as lower chroma depletions and higher chroma (or black in the case of Mn) concentrations (53). These features can be observed microscopically in association with such features as channels, ped surfaces and roots. Depending on the hydrological conditions (flow direction, permeability, etc.) and soil properties (such as texture, pedality, etc.), either the depletions or the concentrations can be associated with the voids or roots. Where pedality and macropores are absent, segregations may appear to be more randomly distributed. Where the voids or surfaces are more reducing than ped interiors, low chroma depletions may be observed at these surfaces (7, 5, 53). These have been termed Type II mottles by Fanning and Fanning (13). On the other hand, ped interiors may be more reducing with voids or ped surfaces being locally oxidized, leading to the formation of sesquioxidic hypocoatings (type I mottles)(13, 7, 5, 53).

When soils are drained they no longer experience such extended periods of reducing conditions. In the absence of easily weathered Fe-bearing minerals (such as pyrite) the weathering rates of other Fe-bearing silicate minerals are slow. Thus, the grey zones of Fe oxide depletions tend to persist as low chroma or grey zones. Similarly, the zones of Fe oxide concentrations (hypocoatings and nodules) are also stable under the more oxidizing drained conditions, and are only slowly redistributed or homogenized by pedoturbation. Thus they remain as "relict" features in the sense that they may not reflect the current hydrologic or redox status of the soil. Thus, although the seasonally high water tables in these soils have been effectively lowered, the macro and micromorphological features associated with undrained conditions persist.

Mexico

Within the Mexican Basin of Central Mexico, soils have formed in lake floor sediments exposed following drainage of lakes. Two types of wet soils occur in these lake deposits, depending on whether the lake water was saline (eg. Lago de Texcoco) or fresh (eg. Lago de Chalco). Drainage of the saline lake Texcoco began initially in pre-Hispanic times due to natural processes and then continued with additional influence by humans, who were trying to prevent the mixing of saline water with the fresh waters of surrounding lakes. The main phase of drainage occurred during the beginning of this century, partially in response to the inundation problems of Mexico City.

Drainage of the lake resulted in the exposure of saline sodic sediments upon which few plant species could flourish. Therefore, these poorly-vegetated soils became susceptible to wind erosion, causing problems of dust and pollution in Mexico City (20). To address this problem, the government transformed the area into an agricultural zone by dividing it into small plots which were reclaimed by farmers using successive leachings with fresh water and continual
applications of organic manure. This approach was somewhat successful, resulting in a decrease of the electrical conductivity in the surface soil horizons from 80 to 3 ds/m.

Because of their low geomorphic position in the basin, these soils still remain subject to seasonally high, saline water tables. During the wet season water tables reach to within 30 cm of the surface, completely saturating the profile, but during the dry season they drop to depths of >1 m. These soils contain primary carbonate as micrite distributed in bands and associated with microorganisms (ostracods), and also as concretionary micritic and sparitic nodules. Both the drainage of the soils and the seasonal fluctuations in the water tables have caused the dissolution of carbonates and the formation of carbonate pedofeatures such as hypo-coatings, diffuse nodules, and crystallitic b-fabrics near the surface (21).

Strial b-fabrics are commonly observed in the majority of the soils, but they are, however, completely fragmented. The strial b-fabrics are forming due to the nature of the clays, which are prone to shrinking and swelling, thus inducing fabric changes in the clayey soils. Initially the soils were lacking structure (apedal) because of the high sodium content, but due to the application of organic matter and the removal of the salts, aggregates have formed. In the soils dominated by clays or amorphous materials, the structure is sometimes strongly expressed as granules or subangular blocks. The continual inundation and drainage in these soils has caused the formation of illuvial silty-clay coatings which are frequently observed.

Because these soils have a seasonally high water table and are periodically saturated, hydromorphic features are present, their intensity being related to proximity to the central lacustrine zone. Soils near the periphery of the former lake and presently under human influence, show characteristics of low to moderate hydromorphic conditions. These features include Mn hypo-coatings along fissures and channels, concentric, impregnative, calcium carbonate nodules, and iron nodules. In the lowest, central portions of the basin, where conditions of permanent saturation exist, amorphous materials with a high sodium content occur. These soils, which are permanently reduced, are characterized by an olive green color. In the intermediate zone (between the center and the periphery) the reduced (olive) horizon is found at some depth and is overlain by horizons showing characteristics of moderate to strong hydromorphism, with Fe and Mn accumulating at the boundary between these two zones. Many soils in the intermediate zone, and all of those in the lower central zone show evidence of sulfidization, where newly formed rhombohedral pyrite is associated with plant residues.

In contrast to the saline Lake Texcoco, Lake Chalco was a productive, eutrophic, freshwater lake which was gradually drained while extracting water for human consumption in Mexico City. The soils have formed in the exposed lake sediments but remain permanently saturated with stagnant water. The lakebed sediments are composed largely of moderately to strongly decomposed organic matter, forming soils with a moderate agricultural potential (19). The principal micromorphological characteristics of these soils are: spongy to massive microstructure typical for the organic nature and biological activity of the material; an open porphyric c/f related distribution (RD), monomorphic and polymorphic organic matter; varying degrees of decomposition of the plant residues; intense accumulations of diatoms (up to 40 cm thick), sweet water algae, rotifers, protozoa and ostracoda; primarily undifferentiated b-fabric, although stratified b-fabrics are clearly developing, and loose continuous infillings of excrements composing up to
50% of some soils. The drainage of these soils caused the mineralization of organic matter especially in the surface horizons, but to a lesser degree in the deeper horizons, where anaerobic conditions prevail and residues of microorganisms remain intact.

**Organic Soils**

Many organic soils (peats and mucks) have a high potential for use in agriculture, horticulture, or silviculture. Where organic soils have been converted for higher intensity land uses, they are almost always drained to lower the water table. Such drainage results in shrinkage and consolidation due to desiccation, the loss of the buoyant force of groundwater, and compaction. Ongoing consolidation and fabric alteration are caused by the enhanced decomposition of the organic materials following the shift from an anaerobic to an oxidizing regime (48). Reported rates of long-term peat consolidation range from 1-4 cm yr$^{-1}$ for temperate regions to 5-12 cm yr$^{-1}$ in the tropics (3, 33). This consolidation is accompanied by changes in the physical properties of the peat, including higher bulk densities and lower moisture content.

The degree of decomposition in organic soil materials presently is based on such macro scale criteria as rubbed and unrubbed fiber content and color of pyrophosphate extracts (47). A similar but more detailed (10 class) classification scheme has been named for its originator (Von Post scale) and has been used quite broadly (33). Micromorphological observations provide more direct examination of the structural integrity of plant fragments and components. In general, micromorphological studies confirm macroscopic observations.

In a review article, Fox (17) summarized the micromorphological characteristics of organic soil materials at various stages of decomposition (fibric, hemic and sapric materials.) The microfabrics of fibric materials mainly show unaltered or slightly altered plant tissues without appreciable darkening, and with little organic fine material. The slightly decomposed plant fragments appear to be loosely arranged with a high porosity and open structure. Hemic materials, which are partially decomposed, still possess a fibrous appearance, but most fragments show incomplete degradation. Distinct browning or blackening of the plant tissues is typical. Some quantity of fine organic material is present, intermixed with or adhering to the coarser fragments of plant tissue (Fig. 3). Evidence of faunal activity (fecal pellets) is also common. In sapric materials, which are most highly decomposed, organic fragments are sufficiently darkened and decomposed so that identification of botanical origin is no longer possible. The fine organic material is generally the dominant component although faunal excrements are also quite common.

The effects of draining organic soils also become evident during microfabric examination. When an undrained sphagnum peat profile in Ireland was compared with those

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**Figure 3.** Thin section of organic material from hemic Oe horizon of a Sulfihemist in Maryland; frame length = 5mm; PPL.
which had been drained for 100 years with low intensity management or for 10 years with high intensity management, substantial microfabric alteration had occurred (23). The undrained peats contained relatively undecomposed plant tissues (humiskel) and showed an open, highly porous fabric with no browning nor the formation of organic fine materials. The drained (reclaimed) profiles had undergone substantial "moulding," meaning that little of the original tissue structures were evident, the fine organic material (humicol) was dominant, with biological granulation also present (42, 30). While this was accentuated by liming and cultivation in the surface horizons, differences persisted well below the surface horizons. The change from a dominantly humiskel microfabric to humicol fabric directly corresponded to an increase in density of the material.

In examining a Medisaprist which had been drained and cultivated for over 50 years, Lee and Manoch (31) concluded that much of the decomposition had occurred subsequent to drainage, as did the development of pedogenic structure in the subsoil. In the lower portion of the profile where the soil remained saturated, sedimentary structure persisted and the peat was more highly fibrous and less decomposed. The activity of soil fauna in the drained portions of the soil contribute to biological granulation and moulding forming distinct surface horizons. Two main types of surface horizons which were strongly affected by soil fauna were the moder, which mostly consists of faunal excrement and usually forming in oligotrophic peats, and the mull, which is formed by an intense mixing and binding of organic with mineral particles by larger organisms such as earthworms, and usually forming in mesotrophic or eutrophic peats.

Sometimes following drainage and cultivation, illuvial humus accumulates in the lower parts of acid organic soils. The translocated humus has been termed humilluvic material (47). While not reported in the USA, the micromorphological observation of illuvial humus in peat soils has been identified in the Netherlands (52). Both the lower pH of the oligotrophic peat and the disturbance by cultivation contribute to the dispersion of the organic fraction which can then be translocated within the soil. These illuvial materials apparently can accumulate within the lower horizons of the peat, at the peat mineral contact, or within the underlying mineral soil material.

FLOODING OF UPLAND SOILS

Flooding in Paddy Rice Culture

In tropical and subtropical regions, especially in SE Asia, wetland rice is an extensive agricultural crop. After leveling or terracing and the construction of dikes, soils in these systems are puddled and flooded during the early part of the growing season, mainly to control weeds. The ponded conditions in association with fresh organic materials lead quickly to the development of anaerobic conditions in the upper portion of the soil. A number of micromorphological characteristics of the artificially flooded paddy soils are very similar to those of the natural strongly hydromorphic soils (37).

Of particular significance to many upland paddy soils is that they are not continuously in subaquatic conditions; they are only flooded during part of the growing season, and frequently the paddy is rotated with other crops, so that relatively long periods of more aerated conditions occur. The "paddy soil" is then only an ephemeral feature. No systematic study of the
morphological aspects of these changes yet exists. It is clear that a distinction should be made between paddy soils which were originally poorly drained and those which were relatively well drained under natural conditions. In the latter case, soil characteristics may be markedly different from more typical hydromorphic soils, as a reduced layer commonly overlies an aerobic one (antheraquic conditions according to Soil Taxonomy (47)).

In most paddy soils the surface layers are generally massive, the structure having been destroyed as a result of puddling (39). Channel and weakly developed spongy micro-structures, described by some authors, may have formed as a result of root growth. Fragments of stratified surface crusts are commonly observed. Very little information exists on the structure of these horizons in a wet condition. The puddled layer is generally less porous (in particular, macropores are lacking), but in some cases a vesicular microstructure has been observed. Pagliai et al. (40) quantified the influence of puddling on porosity using micromorphometric methods. They demonstrated that puddling of the surface horizon caused a decrease in porosity in the 0-15 cm layer. Just before harvest the porosity in the surface layer increased, whereas the porosity in the underlying layer decreased. The most striking difference they noted was the shape of the pores. In puddled soils 19% of the elongated-pore area consisted of pores longer than 16 mm, while in non-puddled soils this proportion was 29% (39, 41). Within the subsoil a channel microstructure commonly is found, but pedal (micro)structures may be present, possibly inherited as pre-paddy characteristics.

The composition of the coarse material of the groundmass reflects the nature of the parent material and its degree of maturity (weathering). Characteristics of former soil forming processes may be preserved (in situ or transported), such as hematite inclusions in quartz grains (runiquartz) as mentioned by Brinkman et al. (6). The fine material usually has a grayish to yellowish-gray color, and a strongly striated b-fabric throughout the pedon. This b-fabric has been observed even in some soils formed in volcanic materials, although in such cases, an undifferentiated b-fabric is more common (50). Only porphyric c/f RDs have been observed, their type depending upon the c/f-ratio.

Although pedofeatures of paddy soils are essentially related to the present day hydromorphic conditions, some of them may be inherited from former or alternating soil-forming processes. The most striking feature is the segregation of Fe and Mn oxyhydroxides in the groundmass. In the surface horizons they are essentially (in many cases exclusively) represented by channel hypocoatings. This has been shown to be related to the oxidation of ferrous ions around rice roots following O₂ transport, which may itself be a physiological adaptation of the plant to prevent Fe-toxicity (9). These coatings and hypocoatings of Fe oxyhydroxides which surround living roots in saturated soils have been termed oxidized rhizospheres, and are thought to be diagnostic for wetland soils (16).

In many surface layers only brownish hypocoatings associated with present day channels have been observed, but no nodules nor fragments of hypocoatings. This would suggest that each season following puddling and inundation of the fields, previously formed ferric segregations are reduced and new hypocoatings are formed in association with new root growth. Within subsurface horizons (mainly below the puddled layer) iron-oxyhydroxide hypocoatings on channels remain the dominant pedofeature observed. Also within this zone different types of
nodules may be observed. Most of them are impregnative nodules, quite often with a dendritic shape and composed of an agglomeration of Fe or Fe-Mn micronodules (50).

In several cases more pure (non-impregnative) Fe-features have been observed. The most common are coatings of isotropic brownish limpid Fe-oxyhydroxides or fibrous goethite within channels or vughs. In a few cases infillings of siderite surrounded by brownish hypocoatings were also observed, indicating alternately reducing and oxidizing conditions. In some cases, both pyrite, and goethite pseudomorphs after pyrite, have been reported (2). Mitsuchi (37) also mentions the presence of iron-depletion hypocoatings on ped surfaces and channels in "greyized" subsurface horizons.

Another characteristic feature commonly observed in most rice soils and frequently mentioned in the literature, is the presence of textural pedofeatures, mainly clay coatings. Two origins may be considered. Brinkman et al. (6) submit that the weakly birefringent clay coatings with a dotted limpidity and grainy appearance are the result of the alteration of older clay coatings by ferrolysis induced by reducing and leaching conditions. Apart from chemical arguments, their conclusion is strengthened by the observation that the transition between the more and less grainy zones is gradual. It is clear that ferrolysis is an active process in the alteration of pre-paddy materials. Indeed, coatings of limpid, strongly oriented, birefringent fine clay are quite often found in the deeper, undisturbed layers, and even inside iron mottles. They were thus clearly formed during a former pedogenic stage, probably under a drier environment.

Another textural pedofeature observed in paddy soils is a dusty coating, sometimes containing silty lamellae. This is thought to be due to the infiltration of clay suspended during puddling and flooding (flood coatings). Both the internal stratification and high content of organic matter, (especially decomposable organic nitrogenous compounds and sugars, as discussed by Kondo and Takai (26)), are evidence that these materials have been moved via mass-transport of suspended coarse clay and silt during flooding. These authors also mention a high concentration of gram-negative bacteria. Pagliai and Painuli (39) observed a downward migration of clay to a depth of 20-30 cm between the time of transplanting and harvesting. This illuviation appears to be related to the large quantity of water percolating through the soil during this period.

Although frequently present, textural features cannot be considered as characteristic of paddy soils. Recently a few paddy soils from Iran were studied in which no clay coatings were observed. Either the differences in climate or a less acid soil environment may be one of the causes of this difference. A striking feature observed in the same soils was the high concentration of decaying organic matter in the puddled layer, not observed in paddy soils from Southeast Asia. This may be related to variations in cultural practices, but on this topic additional research is needed.

**Submergence of Coastal Areas**

In areas of transgressive coastlines, upland soils have become inundated through gradually rising sea level joined with coastal submergence (together termed *apparent* sea level rise). Global warming has been the focus of extensive worldwide dialogue and it appears that this phenomenon may be human-induced. Possible ramifications of global warming projections include increased
rates of worldwide sea level rise which could dramatically impact land areas marginal to the coastline. Micromorphological studies of submerged and submerging upland soils, indicate striking changes in soil chemical properties and in the nature of pedogenic processes.

Prior to submergence of soils, illuvial processes caused the formation of well oriented clay coatings on ped surfaces and in pores. Subsequent submergence with brackish or saline waters has led to the disruption and disorientation of illuvial clay zones (Fig. 4). This suggests that there has been a deterioration of soil structure, presumably caused by increased levels of exchangeable sodium, which has been confirmed by macromorphological observations.

The presence of neo-formed pyritic infillings of root channels within argillic horizons in submerged soils has also been observed (Fig. 5). This demonstrates that progressive inundation with brackish or saline water leads to the development of such strongly reducing conditions, that sulfate reduction occurs. The persistence of the pyrite also demonstrates the continual nature of the water tables and the presence of peraquic conditions (49). The localized distribution of the pyrite within root channels of the submerged mineral soils is in contrast with the more dispersed arrangement of pyrite framboids in the overlying peat horizons. These basic distribution patterns are informative regarding the components which might be limiting the formation and accumulation of pyrite in these systems (45).

**SOILS OF CONSTRUCTED WETLANDS**

While extensive areas of natural wetlands have been drained, some wetland areas have been formed by either the indirect or the intentional activities of man. Construction and earthmoving operations sometimes cause modifications to drainage and hydrology resulting in impoundments of water and the development of wetlands. Also, water management efforts and the construction of reservoirs have often resulted in the formation of wetlands at the periphery of the water bodies. In some cases, wetlands have been engineered with particular purposes in mind.
As appreciation has grown for the functions and values of wetlands, there has been a growing number of wetlands constructed for particular water treatment strategies. Constructed wetlands have been shown to lower suspended solids and BOD in wastewaters. Operators of municipal and domestic waste treatment facilities have built experimental emergent wetlands as a part of their tertiary treatment strategy (24). Primary interest has been in the use of wetlands for the removal of nitrate through denitrification. In addition, peat wetlands have been utilized for the removal of phosphorous. The principal mechanism for P removal has been postulated to be the sorption or complexation of P by metals such as Ca, Fe, or Al, depending on pH of the system. Because most peat is not naturally high in reactive Fe and Al and thus has a low potential for P sorption, Fe-rich materials have been added to the peat in an attempt to increase the P sorption capacity (25). A combination of light microscopy and electron microprobe analysis could be used to identify phases associated with P and would likely yield useful insight into sorption mechanisms, in a manner similar to the way it has been used to located microsite concentrations of trace metals in contaminated soils (4).

Wetlands have also been constructed for the purpose of treating acid mine drainage (AMD) from coal and ore mining activities. Numerous processes have been cited as being effective in removing metals and in some cases (sulfidization) have been shown to lower acidity. Iron "oxides" (oxyhydroxides) are commonly observed precipitating on the surface of constructed wetlands, where the redox potential (Eh) is higher. The iron precipitate commonly occurs as a coating or encrustation of plant components. Figure 6 shows the accumulations of Fe oxyhydroxides
which have precipitated and "fossilized" the organic tissues near the surface sediment.

Beneath the upper few cm (or mm) of wetland sediment, however, the chemical conditions do not usually favor the formation of oxidized forms of Fe. When AMD moves into more reducing portions of the wetland sediment, the AMD may be ameliorated both by lowering the soluble iron levels through precipitation of iron monosulfides and disulfides, and by neutralizing acidity through the generation of bicarbonate. Microbially mediated sulfate reduction appears particularly promising in the treatment of acid mine drainage (46). Chemical extractions of sediments in experimental wetlands have provided indirect evidence that metal sulfides are forming. Micromorphological observations, however, provides direct evidence that authigenic pyrite is forming in the sediments of wetlands constructed to treat AMD (34) (Fig. 7).

**Pre-Hispanic Constructed Wetlands**

Within the Mexican Basin near Lake Xochimilco, anthropogenic soils were intentionally constructed for pre-Hispanic agriculture. These soils, called "chinampas," were formed as "islands" built from seams of aquatic plants and sediments dredged from the bottom of the bog, and which presently extend up to 1 meter above the water surface. Each of these "islands" is approximately 100 m² in area and is surrounded by fresh water. Because of their design, the construction of chinampas made it possible for agriculture to be practiced on soils which otherwise had severe limitations due to excessive wetness. One distinctive characteristic of these soils is that they were naturally watered by subsurface irrigation (1, 18), and the immediate abundance of water permitted agricultural activity regardless of precipitation. Therefore, these constructed soils played an important role in the rural economy of pre-Hispanic Latin Americans by permitting agricultural production with a minimum of environmental deterioration, and became part of an integrated system of agriculture, cattle-breeding and forest production.

The important micromorphological characteristics of these chinampa soils include: a moderately developed granular structure, an open or single spaced c/f RD; undifferentiated b-fabrics caused by the high amount of strongly humified organic matter, and moderately altered plant residues. The organic materials occur alternately with silty-clayey deposits with a parallel distribution. These soils demonstrate characteristics generally indicative of strong hydromorphism. The dominant color is dark gray and the soils are acid with evidence of moderate biological activity. At the present time, many of the chinampas have become subject to degradation processes caused by a lowering of the water level and by salt contamination. Together, these have begun to cause a drastic decline in the growth of plants and other organisms on the chinampas.

**Wetlands Constructed from Dredged Materials**

Dredging operations are needed worldwide, principally for the purposes of keeping channels open in major rivers as well as in ports and harbors. In the disposal of dredged materials, new lands are often created, many of which would be considered wetlands. Not surprisingly, soils formed in dredged materials share many characteristics with soils of the polders. Micromorphological studies of soils derived from sediments dredged from Baltimore harbor, illustrate the processes of physical or chemical ripening (14). Initial drainage and physical ripening formed strong
blocky structure with the development of Fe oxide hypocoatings (type I mottles) reflecting the diffusion and redox gradients between the ped surfaces and interiors. In some cases, the subsequent formation of jarosite coatings and hypocoatings demonstrates that acid-sulfate weathering processes are involved in the pedogenesis of sulfide-bearing dredged sediments. Also of concern is that sediments dredged in proximity to industrial centers may be contaminated with heavy metals (15).

Within the ped interiors, the soils invariably show a porphyric RD with c/f ratios largely defined by the particle size of the original dredged materials. The soils commonly show stippled-speckled b-fabrics, and biological features such as siliceous algal tests are also abundant displaying the estuarine nature of the original sediments (Fig. 8).

CONCLUSIONS

The impact of humankind on wetland habitats has been both striking and varied, intentional and inadvertent. The primary motivation for human disturbance has been to expand agriculture and other land uses. The conversion of wetlands to agricultural land has resulted in extensive drainage of wetlands, but also the seasonal creation of wetlands in otherwise better drained soils. The desire to use wetlands for water and waste treatment has also led to the construction of wetlands specifically for these purposes. Whether through the drainage of former wetlands or through the flooding and formation of new wetlands, affected soils experience drastic changes in hydrological, chemical, physical and biological conditions. Micromorphological studies have provided distinctive insights into the nature of the pedological processes associated with dramatically altered soil conditions. In those parts of the world today where heightened attention is given to the interpretation of hydromorphological features, micromorphological studies have contributed significantly to an expanded knowledge base, which will hopefully lead to wise and accurate applications.

LITERATURE CITED


Figure 8. Thin section showing jarosite hypocoating along channel in silty dredged material; note abundant siliceous algal tests, frame length = 1.2mm. PPL.


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Micromorphology for Diagnostics, Control and Forecasting the Anthropogenic Effects on Soils

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INTRODUCTION. Genetic micromorphology deals with internal organization of soil material and real spatial distribution of all the soil components as coarse material (mineral grains, fragments of different rocks, plant residues, pedofeatures and newformations) and as fine material (organic, clay, salt and ferrogenous plasma, plasma separation and concentration).

Micromorphology as a branch of soil science appeared to be of great importance and the most perspective because it enables to fix the first change in fabric and structural organization, to monitor the reorganization process and to forecast them in future. Our experience shows that the macrofeature and/or property can change only after changing a number of microfeatures or definite microfeatures have changed remarkably. It needs much time to observe and register these changes by means of routine methods.

Micromorphology has another advantages in comparison with the other trends in soil science and permits:
- to study undisturbed, unmixed (non-averaged) soil samples and
- to determine simultaneously the organization, composition and structure of material in the wide range of magnification and in a definite point of interest.

MATERIALS AND METHODS. Our experience, gained to use the micromorphology for studying arid soils under irrigation, leaching of salt affected soils, drainage of the soil waterlogging, chemical and biological amelioration, fertilization of soils and etc., yielded good results both in the theory and in practice. In any case, micromorphology aims to improve the definite component of microstructure (fabric), to recognize and identify the reasons for bad situation inferior properties of soils and to find the best way for improving them.

Irrigated soils were studied in a wide range of climatic, geomorphological and parent material conditions as well as in different soil types such as chernozem, chestnut soils, solonetzes, salt-affected soils. Micromorphological studies have been carried out in detail. For instance, irrigated chernozems in Ukraine, in the Volga and Trans-Volga regions, chestnut soils in Precaspian plain and the Crimea, solonetzes soils in Kazakhstan and Altai region, the salt-affected soils in Precaspian plain, Central Asia and Mongolia.

Amelioration of solonetzes soils was conducted in different ways and namely under and without irrigation, by using own soil accumulations of carbonate and gypsum (newformations) as ameliorants in addition with some chemicals; amendments were applied in the surface horizon or/and digged at the definite depth. The improvement of solonetzes soils was examined in wide range of soil conditions from Ukraine to Siberia and from Central Russia to the Crimea.

One of the most difficult problem for Central Russia is improving textural-differentiated soils (podzolic, sod-podzolic, gray forest soils, etc.). The problem is to study the reason of low struc
tural organization and the low soil fertility. If textural differentiation is resulted from pedogenesis, we need to choose one way for improving, if it is consequence of lithological heterogeneity, one may use quite another approach for amelioration of podzolic soils. This approach is based on new data of micromorphological investigations for Central Russia.

Waterlogging soils are widespread in Central Russia and in Siberia. Their amelioration is connected with problems concerning the humus preservation, improving the structural organization and impermeability of the soil profile. Micromorphological forecasting of these soils plays the most important role, because in this case all the microproperties will be able to determine macrofeatures in future. Control and prediction of new features can be guaranteed only by micromorphology.

RESULTS AND DISCUSSION. In irrigated soils the micromorphology makes it possible to diagnose and control the structural organization of soil mass from ped level to level of primary structural units and the changes in micro-, meso- and macroporosity, to predict crust formation and impacking, to estimate the carbonate and gypsum movement and changing the initial fabric as well as the correlation between microporosity and salt accumulation.

The most debatable problem as related to chernozems irrigation appeared to be solved by means of micromorphological data. It was shown that the most stable and perfect structural organized soils such as chernozems are greatly changed as affected by irrigation in terms of the structure deterioration, when the irrigation water is poor in calcium or enriched with sodium. But in all these cases it is feasible to observe the loss of primary cloddy clay-humus aggregates. The specific clay-humus microstructure is destroyed by humus release and even when the irrigated chernozems improved their structural organization and were biologically reworked, they suffer from humus leaching. This is testified by appearance of humus concentration on the ped surface, humus bridges between micro-peds, humus films on mineral grains and in pores. Simultaneously one can observe bleaching of ploughed horizon in chernozems and decreasing the humus content. In case when the irrigation water is poor in Ca (Odessa region in Ukraine), the chernozems suffer significantly from micro- and mezoporosity decrease, structural destruction, humus plasma illuviation; cloddy humus microforms are disappeared, thus showing an increase of dispersed (pointed) humus microforms. If the irrigation waters contain sodium salts and are highly alkaline (water of Sasyk Lake in Ukraine), chernozems loose their perfect structural organization after 2-3 waterings and reveal a hard impermeable crust.

The surface crust has laminar structure, it is light-grey in colour, but in microdepression this crust is black coloured due to active lateral humus illuviation. The clearly expressed change is associated with destroying the clay-humus primary microaggregates and disappearance of perfect vughs and tracery porosity. In the crust we can identify only isolated vesicles and laminar pores. Besides, the mineral grains lose their films and all the cloddy aggregates are decomposed. At the depth of 10-15 cm illuviated humus is concentrated and the clay material becomes enriched with exchangeable sodium. It is the first stage of solonetz formation.
under influence of sodium-containing irrigation waters. The main micro-morphological features of this process are as follows: leaching of humus-clay plasma (lateral and vertical); crust formation; dispergation of fine-dispersed material and the formation of plasma separation; appearance of optical oriented clay cutans; changes in structural organization and pore space. Every effort to improve chernozems proves a failure. Only high rates of gypsum can result in destroying the surface crust, but internal structure is changed little.

The change in microstructure of calcareous chernozems, induced by irrigation (terraces of the Kanych river) is related to carbonate movement within the soil profile. As a result the cementation of fine dispersed material with carbonates and full reorganization of aggregates are observed, macro- and micro-aggregates are disappeared. The plasma fabric is changed from isotic to microcrystalline. As a consequence the pore space is reorganized; sharply decreased micro- and mesoporosity (from 24-23% to 14-15%), whereas macro-porosity is increased from 4-5% to 15-16% (Fig.1).

The most significant reorganization of the structure in chernozems is developed under irrigation in case of rice cultivation. Our observations in the Crimea, Odessa and Stavropol regions show that in chernozems with high humus content the processes of gleification and iron segregation as well as transformation of fine-dispersed material from aggregated into peptized state are developed more active and rapidly as compared with southern arid soils. Micromorphological features of chernozems reveal changes in plasma fabric, structural organization, pores, new formations. In some cases slickensides and optical orientation of cutans are observed. Primary internal microaggregation is completely lost, showing a decrease of porosity from 25-30% to 5-10%.

Summarizing the changes in chernozems under irrigation it is possible to indicate the most significant new micromorphological features:

1. reorganization (compaction) of primary structural elements and at the same time the decrease of interaggregate micro- and mesoporosity and total aggregation;
2. regrouping of microforms of humus with loss of cloddy microforms;
3. illuviation of humus plasma and formation of dark-coloured clods, bridges, microzones, subcutans on ped surfaces under ploughed horizon;
4. solution of carbonate nodules and replacement of carbonates in ploughed horizons and changing its plasma fabric;
5. iron segregation and appearance of optically oriented clay in zones of Fe-leaching under influence of waterlogging;
6. crust formation and peptization of aggregated humus-clay plasma under influence of alkaline irrigation waters;
7. appearance of the first stages of vertilization in case of high content of Mg-montmorillonite clay.

Studies of chestnut soils irrigation show that the same problems as to chernozems are important to solve. But solonetzic properties need to register the possibility of illuviation of fine dispersed material in profile. Micromorphology helps judging about the increase of humification and biological activity as positive result
Fig. 1. Changing the porosity (>100 mkm) of chernozems under irrigation
of irrigation. At the same time the carbonates redistribution throughout the profile causes the change in plasma fabric, in the structure and pore space. The appearance of clay and carbonate neoformation in chestnut soils under irrigation is found to be a very typical phenomenon.

The main problem for salt-affected soils under irrigation (chestnut and the other arid soils) is origin and behaviour of water-soluble salts. The morpho-mineralogical characteristics allows to describe real salt accumulation (Stoops, 1980), to sub-divide the salt newformations into two groups, inherited from parent rocks and formed due to soil evolution (Tursina, Oboba, 1981) as well as to predict the process of reorganization of salt accumulations in the course of irrigation.

We succeeded in understanding the salt accumulation structure by means of SBK together with using microanalyzers. For example, in chestnut soils the sulphur salts are represented by crystals of tenaridite, glauberite and gypsum-glauberite, formed a very specific structure, which is named as pseudo-sand one. In this case the salts are situated in the centre of aggregates and clay particles, covering salts as thick coatings. Such salt accumulations are spread at the depth of 3-5 cm in some soils and after leaching of salts the soils assume very good structural properties in comparison with the other soils.

Micromorphological studies of salt accumulations make it possible to characterize the pore space and to determine physical properties of irrigated soils after salt leaching. Thus, white salts (halite) form thick channel-like voids, gypsum fills pores with very hard and dense accumulations and after leaching these voids become impermeable for water solutions. Halites act very actively in the soil mass, when their crystals grow resulting in appearance of clay optical orientation in adjacent zone.

With the help of direct morpho-mineralogical-chemical investigations of the salt composition (Uzbekistan, Armenia, Mongolia) it is feasible to determine the type of soil salinity in detail, and to describe intermediate forms of salts (mirabilite-tenaridite) and double salts (tenaridite-glauberite, gypsum-glauberite, etc.). Gypsum is cited as an example to show the difference between forms, inherited from parent material and pedogenic gypsum. The latter is derived in the form of single crystals within the ground mass and in the form of gypsans around the voids. Lithological gypsum is presented by large rosettes and druses of crystals and elongated crystal-bruches, infilling the rock cracks. The behaviour of pedological and lithological gypsum under irrigation is quite different. Knowing the salt genesis one can predict and improve the properties of salt-affected soils after the salt leaching. For arid and salt-affected soils micromorphology permits to forecast successful amelioration and irrigation through characteristics of pore space and salt accumulations. It is very important to know:

- real mineralogical composition of salts instead of chemical composition of water-soluble salts
- morphological form and size peculiarities of salt crystals and their accumulations
- character of pore space and with what salt they are infilled
Solonetzic and solonetz-like soils amelioration is aimed to transform the peptized optically oriented plasma into coagulated state and thus to perfect its structure and consistence and to increase the porosity as well. Micromorphology enables to answer the questions as follows:

- which of amendments has the best coagulating effect,
- whether the complete interrelation of amendment with soil peptized plasma occurs,
- if the total reorganization of fine-dispersed material is reached,
- what's the fate of clay and salt newformations,
- what's the type of transformation of total and plasma microstructure, porosity and other components of microstructure.

In general form the answer is very simple: all depends on the hydrology, salinity, presence of horizons of carbonate and gypsum accumulation, thickness of humus horizon, etc. In reality only loosening of the solonetzic horizon without any amendments application increases considerably the mobility of pepitazed clay plasma and formation of argillans as well as colmantage of natural and newly formed porosity.

Comparative effect of 40 t/ha gypsum application and the adequate rate of sulphuric acid at the background of loosening speaks to benefit of the latter method as soon as more complete reorganization of the plasma optical orientation, destruction of cutan coatings and solonetzic material aggregation are noted in this case. Gypsum application under the rainfed conditions even at the background of soil loosening does not result in complete interaction between the solonetzic material and the amendments. It diminishes the ameliorative effect and limits plasma reorganization within the ped, promotes considerable macrostructural perfection and results in active aggregative effect in places of gypsum application. In these microzones the better rooting system development and perfection of infiltration capacity is observed. Only partial reorganization of plasma microstructure is found to be more easily subject to aggregation that of the low humus content.

Ameliorative reclamation of solonetzic soils in Stavropol region by means of phosphogypsum as well as lime application together with nitric acid revealed less efficiency of the former method. High initial optical orientation of the iron-free clay plasma changes considerably: it becomes fibrous or scaly instead of masepic plasmic ones. Phosphogypsum effects locally only at zones of its application, the principal background is represented by plasma with high optical orientation, as the same time it possible recognized unreacted particles of phosphogypsum.

Experiments on soil carbonates inclusion into the active ploughed layer were effective at the first stages when considerable decompaction of solonetzic horizons and increasing of macroporosity were achieved. However, at the next stages active carbonate redistribution and porosity decrease are noted due to the clay material reorganization. The solonetzic fragments are saturated with carbonates, but this process developed very slowly and for ten years of plantation only one tenth of solonetzic horizons fragments changed its optical properties. Besides ameliorative effects are less due to subsoil compaction and carbonate illuviation.
Our experiments on gypsum application in solonetzic soils of Trans-Volga region showed that more or less even re-aggregation of solonetzic material was achieved at 15 t/ha and higher rates of gypsum. However, complete reconstruction of initial microstructure and total elimination of the clay plasma high orientation have not been achieved in any case.

Amendments application at the background of irrigation gives similar results with those under rainfed conditions. However, interrelation of amendments with solonetzic material is much more effective under the rainfed conditions: the amendments residues amount not included into this process is considerably lower.

Comparison of different amendments effect revealed that sulphuric acid application (40-50 t/ha) produced the highest effect on peptizated plasma reorganization. However, this type of amelioration does not affect the soil aggregation. The highest aggregation effect was obtained at application of FeCl₃ even at sodic solonetz.

Rotary cultivation at high rates of phosphogypsum (30 t/ha) gives positive results. However, low phosphogypsum rates under irrigation do not effect positively due to three negative after-effects as follows: 1 - formation of the surface crust of peptizated optically oriented clay; 2 - soil compaction due to the local movement of peptizated clay within different horizons; 3 - appearance of new illuvial-carbonate horizon.

To forecast the situation it is necessary to understand the solonetzic soils nature and genesis, specific features of their profile construction as well as the quality of irrigation water. If solonetzic soils are characterized by the thick structural humus horizon and high humus content of clay cutans, reclamation of such solonetz soils is not difficult. High level of the carbonate horizon enables their involvement into amelioration.

Sub-solonetzic horizons salinization produces certain problems. Knowledge on the saline horizons composition and microstructure enables to forecast the solonetz salt-affected soils reclamation depending on the saline horizons microstructure. Removal of solonetzic horizon at soil surface levelling is a way to solonetz amelioration due to quick and effective salts leaching that follows this method.

Amelioration of solonetzes and solonetze-like soils is accompanied by certain changes in microstructure of separate components and general microstructure.

Humus microforms do not change greatly but the clotty microforms ratio increases distinctly. Besides, the share of water-soluble humus substances also decreases.

Clay plasma changes considerably: fibrous or fibrous mosaic fabric with great amount of ped separation comes into flakes or isotic. When carbonates are used as amendments the clay plasma transformation into fine-crystalline and considerable reconstruction of the pore space structure, in particular micro- and mesoporosity, are noted.

The newformation fabric as affected by amelioration changes much less than plasma fabric. Argillans and cutans become deformed, cracked and loose some optical properties but are not completely reorganized. Carbonate newformations are changed considerab-
ly only as a result of irrigation, nodules grow, become swollen and fused. Changes of salt-soluble neoformations are more evident.

Drainage of water-logged soils causes great changes in macro- and microorganization of the soil mass. Our observations in Moscow region and in Preamur plain on drained textural soils show that the most significant properties appear at the first two years and these properties can be determined and fixed only with the help of micromorphological methods. The main properties are follows:

- active illuviation of humus and iron;
- increasing optical orientation of fine-dispersed material (clay plasma) due to the loss of iron and the development of clay neoformations (cutans, bridges, films, microcrusts, etc.);
- decomposed cloddy humus microforms and decreasing all the humus microforms;
- appearance of specific neoformations of humus and iron;
- destructural reorganization and compaction of soil mass at all levels of organization;
- loss of micro-, meso- and macroporosity.

The amelioration of water-logged soils needs accuracy and application of organic and mineral amendments as well as improving structural organization of drained soils.

CONCLUSION. All cultivated soils need micromorphological control especially the soils under intensive human activities (drainage, irrigation, chemical amelioration, fertilization). Micromorphology helps to reveal and to explain the mechanism of changes in soil fabric and microstructure, humus content and microforms of humus, in pedo features and neoformations, fine and coarse material, caused by anthropogenic effects upon soils. Micromorphology is one of the most important methods for monitoring soil evolution under anthropogenic pressure and forecasting of potential unfavourable changes in soils under reclamation.

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Effect of Different Long-Term Soil Management Practices on Strength and Swell-shrink Characteristics, Voids and Microstructure

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Abstract. Changes in soil structure due to shallow and deep tillage practices on an Alfisol were investigated, relative to no-tillage area (grassland) adjacent to the experimental site. Friability, specific volume dynamics derived from clod shrinkage data, physical, distribution and orientation fabrics on soil thin sections, and pore size and shape distribution patterns measured on thin sections by means of electro-optical image analysis were studied.

Friability decreased in sub-soil of deep tillage plots. Compared to tilled plots, in no-tillage area, the slope of normal shrinkage line and the value of $\theta$, where residual shrinkage starts was higher, whereas, the specific volume of air-filled pores at start of residual shrinkage was lower. Packing pores were more in no-tillage, whereas, vughs were better expressed in tilled plots. Because of dominance of f-members, differences in distribution and orientation fabrics did not find proper expression. Total porosity formed by pores greater than $50 \mu m$ was higher in top soil of shallow and deep tillage plots, whereas, it was lower in sub-soil of deep tillage plots. Elongated pores represented a high percentage of total porosity in top soil of deep tillage plot, and a low percentage in top soil of no-tillage area. Transmission pores (50-500 $\mu m$), when expressed as percentage of total porosity, were lowest in top soil of deep tillage plot. The methodologies brought out differences in soil structure between tilled plots and their no-tillage counterpart, however, no assertions could be made with respect to differences between tillage treatments. Nevertheless, examination of pore size and shape distribution patterns seems to be useful in differentiating tillage treatments for their structure.

Introduction. Soil structure is the size, shape and arrangement of solid particles and voids (4). Because pores determine various physical properties important to plants, soil structure was defined in terms of porosity and pore size distribution (11, 16, 18). It might be considered to be the architectural arrangement of primary particles (17), or as the spatial heterogeneity of different components or properties of soil (8).

Soil structure is highly sensitive to human activity, and in many parts of the world, there is evidence that soil structure and its stability are becoming less favourable for agriculture (8). It remains difficult to predict or even interpret changes in soil structure under different management practices, since it does not lend itself to quantification. Numerical values of soil structure indices almost always depend on the measurement procedure, and there is no general agreement on the appropriate criteria by which we may judge soil structural decline (17).

Soil structure can be characterized in terms of form, stability and resiliency (14). A number of methods for measuring soil structure have been described (8). Micromorphological observations can provide useful insights into soil structure and aid interpretation of soil behavior (26). Image analysis has been used to study the effects on soil structure of a variety of soil treatments (10, 15, 22, 24).

In the present investigation, changes in soil structure due to tillage practices on an Alfisol on the farm of the Central Research Institute for Dryland Agriculture, Hyderabad (India), were investigated. These were assessed relative to the no-tillage (grassland) area adjacent
to the experimental site. The methodologies chosen for structural characterization were fiability (8), specific volume dynamics derived from clod shrinkage data (19), comparison of physical, distribution and orientation fabrics on soil thin sections (26), and analysis of thin sections by image analysis (Quantimet 570) to measure the porosity and to characterize pores according to their shape and size (23).

Materials and Methods. On the experimental plots of CRIDA, representing Alfisol, shallow tillage and deep tillage has been practiced continuously for 5 years, and castor was followed by sorghum. Shallow tillage was given with a traditional wooden plough, working to a depth of 12 cm, and deep tillage was given with a tractor-drawn reversible mouldboard plough, with an average working depth of 22 cm. The cultivated plots received 120 N and 40 P per hectare.

Soil samples from 0-10 cm as well as 12-22 cm depth were collected after withdrawal of monsoon, when the soil was moist. Undisturbed block samples were collected in closed containers (plastic boxes) and transported to the laboratory. For the preparation of soil thin sections, samples with natural fabric were collected in 7 cm x 10 cm plastic boxes.

Some characteristics of the soils of the experimental plots are given in table 1.

TABLE 1

<table>
<thead>
<tr>
<th>General characteristics of soil</th>
<th>Shallow tillage</th>
<th>Deep tillage</th>
<th>No-tillage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-10 cm 12-22 cm</td>
<td>0-10 cm 12-22 cm</td>
<td>0-10 cm 12-22 cm</td>
</tr>
<tr>
<td>Clay (%, w/w)</td>
<td>26.5 31.0</td>
<td>22.5 26.0</td>
<td>31.0 28.0</td>
</tr>
<tr>
<td>Silt (%, w/w)</td>
<td>7.5 8.0</td>
<td>10.0 6.0</td>
<td>12.0 12.0</td>
</tr>
<tr>
<td>Sand (%, w/w)</td>
<td>66.0 61.0</td>
<td>67.5 68.0</td>
<td>57.0 60.0</td>
</tr>
<tr>
<td>Organic matter (%, w/w)</td>
<td>0.69 0.62</td>
<td>0.55 0.73</td>
<td>1.46 1.09</td>
</tr>
<tr>
<td>pH (H₂O)</td>
<td>5.9 5.5</td>
<td>5.9 5.7</td>
<td>7.2 6.3</td>
</tr>
<tr>
<td>Pore volume (%, volume)</td>
<td>34.3 29.4</td>
<td>30.9 30.1</td>
<td>36.6 33.6</td>
</tr>
<tr>
<td>Moisture retained at suction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.033 MPA (%, volume)</td>
<td>24.0 20.7</td>
<td>20.0 20.6</td>
<td>27.5 30.4</td>
</tr>
<tr>
<td>1.50 MPA (%, volume)</td>
<td>10.4 12.5</td>
<td>9.7 10.2</td>
<td>12.8 12.8</td>
</tr>
</tbody>
</table>

Friability. Soil friability, which is the tendency of a mass of unconfined soil to breakdown and crumble under applied stress into a particular size range of smaller fragments (27), was measured with a simple equipment fabricated in the laboratory (13). The aggregates subjected to the crushing were taken from the block samples after air-drying. Seven different size classes were chosen, namely, 3.5-4.0 cm, 3.0-3.5 cm, 2.5-3.0 cm, 2.0-2.5 cm, 1.5-2.0 cm, 1.0-1.5 cm, and 0.5-1.0 cm. The diameter of each of the aggregates in each size class was measured in three different axes with a vernier calipers, and the average diameter of each of the aggregate was obtained.

The tensile strength (Y) is given by:

\[ Y = \frac{C.f}{d^2} \]  

\[ \text{(1)} \]
where,  
\[ C = \text{the coefficient of proportionality, the value taken being 0.576 (9)} \]
\[ f = \text{the crushing force, and} \]
\[ d = \text{the aggregate diameter (in cm)} \]

The friability of the soil is obtained from the regression equation:

\[ \log_e Y = -k \cdot \log_e V + \text{constant} \]  ..........(2)

where,
\[ Y = \text{tensile strength}, \]
\[ V = \text{volume of aggregate}, \]
\[ k \text{ is identified with friability} \]

**Swelling and shrinking and specific volume dynamics derived from clod shrinkage.**

Clods of 2-3 cm diameter from block samples were saturated and coated with rubber solution (No. 758, DUNLOP Co.). The weights of coated clods were recorded both in air and water. They were then allowed to lose moisture by air drying, and at different stages of drying, weights were recorded in air and water (3). Bulk densities were obtained from the oven-dry weight of the coated clod and its volume at different soil water contents and at oven-dryness, after making necessary corrections for the coating of rubber solution.

**Soil thin sections.** Samples were dried by methanol exchange of water (16). Soil thin sections were prepared following the procedure described by (1), by impregnating with Bakelite Hylam resin.

**Microstructure.** To to three thin sections, of size 3 x 4 cm\(^2\) were examined using a polarization microscope (Leitz). The various elements of structure were classified into pore space (4), physical fabrics (6), distribution fabrics (6) and orientation fabrics (5).

**Porosity measurements.** Thin sections were analyzed by image analysis (Quantimet 570) to measure total porosity and to characterize pores according to their shape and size (23). The picture point (pp) was 50 \(\mu\)m and the analyzed area was 4 x 4 cm\(^2\), avoiding the edges where disruption could occur. Four fields were analyzed. Pores were measured by their shape, which is expressed by the shape factor [\(\text{perimeter}^2/(4\pi\cdot\text{area})\)] and divided into regular pores (shape factor 1-2), irregular pores (shape factor 2-5) and elongated pores (shape factor >5). These classes correspond approximately to those used by (2). Elongated pores were further subdivided into size classes according to the width (22, 23).

**Results and discussion.**

**Friability.**

The relationship between tensile strength (Y), and aggregate size (V) for no-tillage (grassland) area are given in fig.1. This illustrates the assessment of friability. The results of the friability test are summarized in table 2.

**TABLE 2**

<table>
<thead>
<tr>
<th>Depth</th>
<th>Shallow tillage</th>
<th>Deep tillage</th>
<th>No-tillage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10 cm</td>
<td>0.24</td>
<td>0.24</td>
<td>0.28</td>
</tr>
<tr>
<td>12-22 cm</td>
<td>0.32</td>
<td>0.25</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Fig. 1. Relationship between tensile strength (Y) and aggregate size (V) for no-tillage area

Fig. 2. Plot of theoretical and exemplar shrinkage lines of observed data (water content vs. clod volume per unit mass of solids)
In cultivated soils friability ranged from 0.24 to 0.32. The friability values for top and sub-soil of deep tillage plots were similar, and the value for top soil of no-tillage plot was only slightly higher than that of cultivated plots. Interestingly, the sub-soil of shallow tillage and no-tillage plots showed higher values of friability than the other samples.

Friability is clearly a desirable soil property, if it is required to produce a seed bed composed of aggregates of proper size by tillage (9). Friability, k, was classified into different categories, namely, friable (0.10 ≤ k < 0.25), very friable (0.25 ≤ k < 0.40), and extremely friable (0.40 ≤ k < 0.67) (9). Broadly, all the samples fall under the category of very friable, and as such it may not be a problem to produce the required seed bed.

Swelling and shrinkage and specific volume dynamics derived from clod shrinkage. Indices derived from clod shrinkage studies can discriminate between different treatment histories and different field structure (19). Clod shrinkage data are plotted as reciprocal of bulk density vs. water content. A plot of theoretical and exemplar shrinkage lines of observed data (water content vs. clod volume per unit mass of solids) for four samples are given fig.2. Four indices derived from clod shrinkage studies are discussed, namely, n (slope of normal shrinkage line), θ₁ (value of θ, where residual shrinkage starts), P^ and a (specific volume of air-filled pores at the start of residual shrinkage) and α (specific volume of clod at θ=0). Th results are summarized in table 3.

### Table 3

<table>
<thead>
<tr>
<th>Tillage</th>
<th>Depth</th>
<th>n</th>
<th>θ₁</th>
<th>P^</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow tillage</td>
<td>0-10 cm</td>
<td>0.999</td>
<td>0.055</td>
<td>0.093</td>
<td>0.507</td>
</tr>
<tr>
<td></td>
<td>12-22 cm</td>
<td>0.982</td>
<td>0.066</td>
<td>0.089</td>
<td>0.520</td>
</tr>
<tr>
<td>Deep tillage</td>
<td>0-10 cm</td>
<td>0.978</td>
<td>0.063</td>
<td>0.095</td>
<td>0.525</td>
</tr>
<tr>
<td></td>
<td>12-22 cm</td>
<td>0.940</td>
<td>0.070</td>
<td>0.092</td>
<td>0.527</td>
</tr>
<tr>
<td>No-tillage</td>
<td>0-10 cm</td>
<td>1.381</td>
<td>0.045</td>
<td>0.138</td>
<td>0.528</td>
</tr>
<tr>
<td></td>
<td>12-22 cm</td>
<td>1.106</td>
<td>0.055</td>
<td>0.123</td>
<td>0.544</td>
</tr>
</tbody>
</table>

The greatest deviation in n from unity occurred in grassland (top soil, 1.381; sub-soil, 1.106). However, differences due to tillage were inconsequential. Indices derived from clod shrinkage studies can discriminate between different treatment histories and different field structure (19). Physical properties of adjacent cultivated and native pasture sites of sodic grey clay were compared, and that the cultivated site had a significantly better structure than the pasture site was inferred from the higher value of n (21). In contrast, in the present study, where the soil is an Alfisol, in no-tillage plots, the n values were higher than cultivated plots.

θ₁ values were higher in the sub-soil (= 0.070) compared to top soil (= 0.055) and they were lower for the grassland compared to the cultivated plots. They were slightly higher for deep tillage plots compared to shallow tillage. Samples from grassland showed a far higher value of P^ (= 0.13) than the cultivated (= 0.092), but a lower θ₁ and higher n, which may be related to the lower bulk density of the grassland area. The values of α did not show any specific trends, and the no-tillage area showed higher value of n (>1) and P^, and lower value of θ₁ than the cultivated, θ₁ may be a better index than α for Alfisol. Some of these observations are at variance with those available in literature. For example, n, α and P^ have consistently provided significant and sensible treatment differences (7), whereas, for grey Vertisol, it was reported that α was the most sensitive index to treatment effects (20).
Microstructure.

Microphotographs of some typical fabrics are given in fig. 3. and the descriptions are given below.

Shallow tillage


12-22 cm: Brownish red ground mass. Predominance of f-members. Iron accumulations more than in top soil. Sub-angular blocky. Vughs are fewer in number, but of different sizes and shapes. Very weakly expressed packing pores. Porphyric, chitonic. At few places papule-like material observed. Mo-insepic.

Deep tillage


No-tillage

0-10 cm: Dark reddish brown ground mass, f-members prominent. Frequent iron accumulations. Predominantly granular and very weak sub-angular blocky, rounded aggregates of biological origin observed. Packing pores, some vughs are large and branched. Porphyric, chitonic. Insepic, at places mosepic.


Most samples showed dominance of f-members. In the top soil of tilled plots, although packing pores were not well expressed, vughs of different sizes were prominent. In the sub-soils too, packing pores were weakly expressed, however, deep tillage resulted in more vughs than in shallow tillage. In no-tillage plots, the top soil was porous with packing voids. Vughs were found in both depths. The orientation fabric in top soil of tilled plots was insepic. In sub-soils it was insepic fabric, and in these papule-like material was observed. The plasmic fabric was better expressed in no-tillage plots, compared to the tilled plots. In top soil of no-tillage area, the plasmic fabric was insepic and at places mosepic, and in the sub-soil, it was in-mosepic.

The above descriptions reveal some differences in micromorphology between no-tillage and tillage plots. No-tillage plots with higher organic matter (and biological activity) has shown packing pores, particularly in the top soil, whereas, vughs, which are created by disconnection of packing pores due to settling and compaction, were more frequent in cultivated plots. Some of the observed vughs in the sub-soil of deep tilled plots may be attributed to soil mixing by tillage. Because of the dominance of f-members, the differences due to tillage were not properly expressed.

Porosity measurements. Mean values of total porosity, expressed as percentage of the total area of thin section occupied by pores, number of pores and porosity due to rounded, irregular and elongated pores are reported in table 4. Also included in the table are the pore size distribution, which was obtained according to equivalent pore diameter for regular and
Fig. 3. a) Shallow tillage, top soil, f-members predominant, composite granular and sub-angular blocky, vughs, porphyric-chitonic; b) No-tillage, top soil, granular, packing pores, vughs, porphyric-chitonic; c) Deep tillage, top soil, f-members predominant, granular to sub-angular blocky, packing pores, vughs, porphyric-chitonic; d) Deep tillage, sub-soil, relatively big vugh, porphyric-chitonic. All under partly crossed polarizers.

Fig. 4. Pore size distribution in sub-soil of deep tillage (left) and no-tillage (right) plots.
irregular pores and according to width for elongated pores. For two soil samples, the results are also presented as histograms in fig. 4.

In top soils, the total porosity formed by pores greater than 50 µm was highest in shallow tillage plots and lowest in no-tillage. However, under petrological microscope it was observed that no-tillage top soil was more porous. This anomaly may be attributed to the level of observation. Sub-soil of deep tillage plots showed the lowest total porosity, although vughs were noticed. Soil inversion by deep tillage seems to have made the difference. Total number of pores was highest in top soil of no-tillage plots, with a substantial decrease in the sub-soil. Top soil of deep tillage plots showed the highest number of pores, whereas, sub-soil showed the lowest. Top soil of shallow tillage plots showed slightly higher number of pores compared to sub-soil. The numerous small pores, both regular and rounded, contributed relatively little to total porosity, while few elongated pores gave a high proportion of the total porosity.

Elongated pores, expressed as percentage of total porosity were highest in top soil of deep tillage plots and sub-soil of no-tillage area, whereas, they were lowest in top soil of no-tillage area. Elongated pores in the size range 50-500 µm equivalent diameter, expressed as percentage of elongated pores was the maximum (100%) in top soil of no-tillage plots, whereas, they were lowest (30%) in top soil of deep tillage plots. However, when pores in the size class 50-500 µm, comprising of different shapes, were expressed as percentage of total porosity, they were lowest in top soil of deep tillage plots, with shallow tillage and no-tillage top soils showing similar values. The sub-soil of no-tillage showed the highest percentage.

For a thorough characterization of soil pores, the main aspects to be considered are pore shape and pore size distribution. Pores of 0.5 to 50 µm in equivalent pore diameter are the storage pores, while those of 50 to 500 µm are the transmission pores (11). For other soil types (other than Alfisol), total porosity formed by pores greater than 50 µm was significantly higher in samples of conventionally tilled plots than in no-tillage plots, however, the proportion of pores ranging from 50 to 500 µm was higher in no-tillage plots (22, 23, 25). A decrease in soil structure can be related to a decrease in the proportion of pore space present in transmission and storage pores (12, 25). The results of the present investigation suggest that the structure of top soil of deep tillage plot became less favourable. Thus, porosity measurements revealed some differences between tillage treatments and between tilled and no-tillage plots.

Conclusions. Studies on friability, specific volume dynamics from clod shrinkage data and microstructure have revealed differences between tillage and no-tillage plots, however, no assertions could be made with respect to differences between tillage treatments. Examination of pore size and shape distribution patterns seems to be useful in differentiating shallow and deep tillage, and tillage and no-tillage. Quantification of soil structure is difficult, and with the dominance of f-members as in the soils investigated, it becomes necessary to study the same, following a combination of methodologies, in order to interpret changes in structure due to anthropological effects.
TABLE 4

Mean total porosity expressed as percentage of total area, and porosity due to rounded, irregular and elongated pores

<table>
<thead>
<tr>
<th>Types of pores</th>
<th>Shallow tillage 0-10 cm</th>
<th>Deep tillage 0-10 cm</th>
<th>No-tillage 0-10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12-22 cm</td>
<td>12-22 cm</td>
<td>12-22 cm</td>
</tr>
<tr>
<td>Round pores</td>
<td>3.79</td>
<td>2.77</td>
<td>4.35</td>
</tr>
<tr>
<td>Irregular pores</td>
<td>5.00</td>
<td>1.87</td>
<td>3.74</td>
</tr>
<tr>
<td>Elongated pores</td>
<td>6.23</td>
<td>7.02</td>
<td>2.39</td>
</tr>
<tr>
<td>50-500 μm</td>
<td>5.64</td>
<td>2.14</td>
<td>2.40</td>
</tr>
<tr>
<td>500-1000 μm</td>
<td>0.61</td>
<td>4.72</td>
<td>0.00</td>
</tr>
<tr>
<td>1000-2000 μm</td>
<td>0.00</td>
<td>0.17</td>
<td>0.00</td>
</tr>
<tr>
<td>&gt;2000 μm</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total porosity (%)</td>
<td>15.02</td>
<td>11.65</td>
<td>10.47</td>
</tr>
<tr>
<td>Elongated pores</td>
<td>41</td>
<td>60</td>
<td>23</td>
</tr>
<tr>
<td>% of total porosity</td>
<td>47</td>
<td>37</td>
<td>23</td>
</tr>
<tr>
<td>Pores 50-500 μm % of elongated pores</td>
<td>90</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>% of total porosity</td>
<td>56</td>
<td>33</td>
<td>56</td>
</tr>
<tr>
<td>Total No. of pores</td>
<td>929</td>
<td>811</td>
<td>886</td>
</tr>
<tr>
<td>No. of regular pores</td>
<td>691</td>
<td>579</td>
<td>430</td>
</tr>
<tr>
<td>No. of irregular pores</td>
<td>210</td>
<td>197</td>
<td>86</td>
</tr>
<tr>
<td>No. of elongated pores</td>
<td>27</td>
<td>34</td>
<td>18</td>
</tr>
</tbody>
</table>

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Literature cited.


Soils and Archaeological Research

Convener: Linda Manzanilla (Mexico)

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PRESENTACION

Este simposio presenta puntos de vista de arqueólogos y etnohistoriadores sobre la importancia de los suelos para el estudio de las sociedades pasadas. Del lado de los arqueólogos, se propone al suelo como fuente de información sobre contextos sepultos y de datos paleoclimáticos. En el primer caso, se destaca que cuando una superficie de terreno ha sido usada como piso, se puede estudiar para determinar residuos químicos con el fin de comprender aspectos de la ocupación humana. Junto con técnicas geofísicas, la geoquímica del terreno en un sitio arqueológico permite comprender mejor las características del sitio sepulto sin necesidad de excavar gran parte de éste. Por otro lado, se establece una relación entre los objetos y arquitectura sepultos con los procesos pedogenéticos, proponiendo así secuencias evolutivas y cambios en los sistemas de plantas-suelos. También se aborda el caso de uno de los desarrollos urbanos preindustriales más vastos del mundo: Teotihuacan, en la Cuenca de México, y las características del paisaje en ese tiempo de la historia prehispánica. Para este efecto se analizan procesos de formación de suelos, eventos volcánicos y tectónicos, cambios climáticos y de vegetación, y actividades humanas. Por último, desde el punto de vista de la etnohistoria, se analizan códices nahuas de Tepetlaoztoc, en la Cuenca de México, para extraer clasificaciones de suelos y atributos de campos agrícolas.
The Old Soil as a Source of New Archaeological Information

Luis Barba. Instituto de Investigaciones Antropológicas, UNAM. Ciudad Universitaria, México, D.F. 04510.

Introduction.

For long time, soil has provided a great deal of information to archaeology. At the beginning of this relationship, edaphology provided stratigraphic methods to study the archaeological context. Later on Cornwall (1958) published one of the first manuals of soil methodology applied to archaeology and Limbrey (1975) successfully continued with this field research, updating the information. Since the early 30’s, the relationship between the ancient human settlements and soil chemical enrichment was established by Arrhenius (1963). Thereafter, soil has been studied to understand the transformation of archaeological materials after abandonment. Within this scope, Dowman (1970) published the first manual concerning the conservation of archaeological materials buried in soil matrix. More recently Shackley (1975) has made contributions to the relationship between sediments and archaeological research projects. The Archaeological Prospecting Laboratory of the Institute for Anthropological Research at the National University of Mexico is deeply involved in the study of the archaeological context. The beginning of this way to approach the study of any given archaeological site was following the increments in the concentrations of phosphates in soil used to locate and delimitate archaeological sites using analytical procedures published by Eidt (1977).

During the 60’s and 70’s, among European and American geographers it was common practice to use soil phosphate analysis to find and delineate human settlements. In 1977 our laboratory started to use this simple test to evaluate its usefulness in Mesoamerican archaeology. Results were successful, and as a consequence this technique was established to study the surface of archaeological sites prior to excavation. Some time later, we expanded to use a group of four simple tests to evaluate changes that human settlements produce. The study of chemical residues in ancient floors was started to understand dramatic changes in concentration in very reduced areas. These kind of studies have provided the foundations to understand the chemical enrichment of domestic floors as a consequence of everyday human activities.

Authors like Limbrey (1975) deal with the concept “intrinsic Information of soil” as opposed to the “information content in soil”. At the present, most archaeological excavation projects only recover the archaeological material content in the soil, including samples for pollen and phytoliths studies, but rarely attempt to recover any other type of information. In other words, only visible materials are recovered, while invisible evidence, such as chemical residues are not attended. In fact, once the materials are removed from the matrix and cleaned half of the information is lost.
Among many other problems, modern archaeology faces the challenge of reconstructing a puzzle with half of the pieces, and some of the absent pieces are lost when earth is removed.

Until very recently, it was unsuspected the modern possibilities of information provided by changes in physical and chemical properties of soil. One example is the recognition of fire pits or hearths through the use of indicators such as changes in total magnetic field, changes in magnetic susceptibility and increment in PH values. Even without the common oxidized red stains and ash, it is possible to infer the location of an ancient fire. Events like this are more common everyday in modern archaeology and is a clear example of the new kind of information provided by the context. As can be seen in this example, there is no traditional archaeological material involved, we are dealing with two changes in physical and one change in chemical properties of the soil matrix.

There is another important observation. Although it seems obvious, most changes produced in soil matrix are volumetric transformations. This is, we are not dealing with a flat surface, instead we must think of a volume of soil continuously modifying its properties through the exchange of ions, electrons, radicals, etc. and always in contact with the archaeological materials during hundreds of years. Considering the previous mentioned example of fire pits, there is also a soil volume with different physical properties as a consequence of heat exposure. Below the actual heated surface there is a volume of soil that has been dehydrated, oxidized and affected by thermo remnant magnetization as Bellomo (1993) demonstrates. This kind of basic research supports the possibility of soil study through the systematic sampling of archaeological soil in a 3 dimensional grid.

Recent Applications.

As it was mentioned before, the study of the distribution of some chemical compounds provides information concerning the use of any surface area. Thanks to the establishment of a methodology for the study of domestic activities in households it was possible to understand the relationship between chemical solutions discarded over the floor surface and human activities. Simple chemical tests determine large differences in concentrations, because only dramatic changes can be interpreted as constant or intensive activities. The study of presently inhabited rural houses permitted the registration of activities in order to relate them with the chemical analysis of samples obtained from the same floor. Results from this kind of experiments, (Barba and Ortiz, 1992) showed that the distribution of compounds in floors is closely related to human activities performed on it.

The excavation and chemical study of archaeological households brought the opportunity to apply this new methodology to look for contamination patterns on floors. One of the more recent examples has been the study of a domestic compound at Teotihuacan where more than 500 samples were obtained from the stuccoed floor. It has been shown that this kind of floor offers more advantages than the earthen kind, since there is little previous contamination. This is, in some cases modern houses can
be built over archaeological zones overlapping their chemical enrichment to the archaeological record. On the other hand, the lime plaster produced by heating the limestones and applied on a floor surface has almost no chemical contamination by the time the floor is constructed. This provides the certainty that all chemical contamination found in floor samples comes from activities performed on it.

The chemical analysis of the apartment compound floors at Teotihuacan permitted us to differentiate three internal subdivisions and determine each one of the apartments has its own area for food preparation and consumption zone, as well as an internal yard and other utility rooms. (Ortiz y Barba 1993). Final interpretation of the everyday life at this apartment compound was achieved by integrating all the available information, from the archaeological excavation, palobotanical and paleofaunistical analysis and most importantly, the chemical results, all under the PACT Project directed by Manzanilla (1993).

Applications in Conservation.

More recently, the mechanisms of deterioration of archaeological materials has been studied by focusing on the close relationship between the materials and their surrounding soil. It has been possible to observe chemical equilibrium and migration phenomena that produce transformations in both materials and soil, and in this way preserve or deteriorate the archaeological evidence.

In recent years, during the evolution of the field research of paleodiet in human bones, researchers became aware of the problems in the interpretation of chemical elements present in archaeological bones (Kyle 1986). It was very difficult to be sure if any chemical concentrations came from dietary sources or from soil migration. The study of both soil and bone, showed that there is a strong tendency towards chemical equilibrium, with some elements and compounds migrating from the soil into bone and vice versa.

Our laboratory has recently developed an approach to study both the archaeological material and the soil matrix simultaneously. In all study cases it has been possible to observe the changes in chemical composition that suggested migrations. An interesting example of this is the migration of phosphates from bone to soil and carbonates from soil into bone. In relation to these chemical changes, it was found that bone density decreased while bone porosity increased. Another interesting observation of the analytical results has been the tendency of bone PH and EH to acquire the soil conditions. It was found that the PH of living bone is very uniform, and its transformation is a time dependent process where the PH and EH values tend to reach soil conditions (Brito 1993).

It is clear that due to the chemical equilibrium reached, many archaeological materials suffer deterioration after they are removed from soil matrix. Our point of view is that equilibrium conditions should be determined prior to archaeological excavation. Is not enough to determine where and how deep to excavate using prospecting techniques because the excavation process can destroy archaeological materials simply because
chemical equilibrium is altered. One of the more drastic examples is the case of crystallization of chlorides in ceramic under marine conditions, but there are so many cases where excavated organic materials are lost due to drastic changes in environmental conditions. In order to avoid this risk, it is urgent to find the way to determine the equilibrium state of the system archaeological material - soil matrix prior to excavation, specially for organic materials.

For some archaeologists it is clear that soil matrix is one of the best packaging materials since most archaeological materials recovered from excavations have been over a thousand years buried and it is possible that they could remain even more time in the same state. This is a consequence of being very close to the equilibrium, which means that even in larger periods of time it could be little change in properties.

That is why soil matrix has proved to be one of the best package for archaeological material, the problem is that it also contain important information that must be recovered by the archaeologist.

**Physical Effects.**

Since early 50’s it was clear to archaeometrists that magnetic and electric effects could be a big help in locating buried structures. Magnetic and electric properties produced very useful information since changes in this soil properties suggested the placement of buried features non visible from surface. This kind of information can be used to prevent unnecessary excavation and in this way, preserve the archaeological context for future projects. There is a modern tendency to make the soil matrix transparent. All available geophysical techniques attempt to see through the soil. The dream of the archaeometrists is to be able to study the archaeological context from surface, without excavations, but we are still far from it. At the present, in order to understand what is going on under our feet, it is necessary to integrate many different techniques and interpret all them together, although the information gaps that make interpretation uncertain. Our experience shows that the only way to achieve a reasonable understanding of a buried archaeological site is through the integration of a methodology that encompasses all available techniques, and interprets them in a synoptic way (Barba 1989).

**Proposal.**

Soil must be considered as an archaeological indicator, it should not be discarded and it has to be studied under the scope of different sciences. When a soil surface has been used as a floor, it has to be studied to determine chemical residues, in addition to any other traditional sources of information to understand human occupations.

The prediction of the condition of the archaeological material could be an important contribution. We, as soil scientists, must try to find the way to measure the stability of the archaeological system in order to determine if it can be excavated or it has to leave intact in order to preserve it. As was mentioned before, a large amount of
research has been devoted to explain how to see through the soil matrix using geophysical techniques, but archaeology needs more than that. It is good to know where and how deep to excavate, but it is still necessary to know the conditions of the soil-material system in order to make the proper decision of whether or not to excavate. This could be a promising field where soil scientist and archaeology may work together to find solutions.

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Shackley, M.

**Acknowledgments.**

I must thank to Agustín Ortiz by his valuable help in the study of chemical residues on archaeological floors.
Figure 1. Distribution of fatty acids on the earthen floor of a modern domestic household in Tlaxcala, Mexico.
Figure 2. Distribution of phosphates on the stuccoed floor of an archaeological domestic unit at Oztoyahualco, Teotihuacan.
Figure 3. PH - EH plots from bone samples and their surrounding soil matrix showing the bones tendency to acquire soil conditions.
Experience in the Use of Archaeological Objects for the Study of Pedogenesis


Abstract. Ancient burial mounds with stone chest, stone chest cairns, clearance cairns, their stony coronal rings, antique fields with man-built stone heaps and baulks, etc. were used in comparison with natural soil formations for the study of pedogenesis. A gradual increase in the intensification is characteristic of Holocene pedogenesis. Taking an average annual increment in the storage of organic carbon as one conventional unit in the transgressional territory of the Baltic Ice Lake, that increment already consists of 1.5-2 in the zone of Ancylus transgression, but 3-5 in (under, above) the human installations of 2,000-2,500 years old. The composition of humus in weathering products and soil formations of different ages is similar showing a rather quick progress in qualitative pedogenetic features. Prevalent fulvicity of the early products of humification guarantee the formation of secondary clay, its transformation and gradual increase in the role of sesquioxides in the fixation of humus substances. The most intensive weathering and soil formation characteristic of the subatlantic period was ascertained by the means of a layeral investigation into any human installation whereas the character and origin of final products greatly depend on the initial texture and mineral potential of strata. Multigenetic origin and evolutionary connections of soils and soil cover were established by the help of their profiles aside and under archaeological objects. But identification of soils covered with deep town ruins, debris and fillings were of significance in the imagination of ancient soil catenas there where natural ones have been changed by human activities.

Introduction. Pedogenesis has been defined as a system of bridges linking a series of islands compared with soil compositional and propertive characteristics to those of agronomical and forestry origin (3). This connection tends to be impacted by the human activities during the history of mankind (2, 6). Therefore the interests of archaeology and soil science in the use of some same objects ought to coincide. Archaeologically dated objects can give us valuable information about the soil (ecosystem) situation before their installation, but also about the pedogenetic (ecosystem) phenomena both in the process of their existence and after their natural conservation for millennia. Vice versa, the genetic and analytical specification of soils in (under, above) ancient human installations allows us to reconstruct the life conditions of men in the past (16).

Trends and rates of pedogenesis as well as the evolution of soils have mostly been investigated on the basis of different natural Pleistocene and Holocene formations (1, 17) and only a few data admit the use of ancient human installations and agriculture for this aim (6, 8, 10). Since the early seventies the cooperation with archaeologists (16) has enabled us to obtain essential information about the soil genesis during the last millennia (12-15) by the use of weathering products and soil formations from different anthropogenous objects. Such
a cooperation made also possible to obtain information on the ancient soil mantle under the
human settlements and to compare its genesis to the modern situation.

Materials and Methods. Ancient burial mounds with stone chests, stone chest cairns, their
coronal rings, graves covered by flat and clearance cairns, antique fields with man-built stone
beaps, baulks (field walls), palings and fences, barrow embankments of fortified strongholds,
etc. represent the main objects in comparison with natural Rendzic Leptosols and also with
some Luvisols and Podzols of the northern Estonia (59°02'-59°20'N, 24°36'-26°20'E). A
series of buried soil profiles under the different Middle-Age buildings in Tartu (58°25'N,
26°40'E) was also investigated. Weathering products and soil formations under (in, above)
the anthropogenic installations as well as soil profiles were sampled by the way used in soil
science everywhere; analytical techniques were carried out by the methods described in
various reference books (9, 18). The total content as well as group and fractional
composition of humus was determined by the alternate acid-alkaline treatment after Tyurin-
Ponomareva volumetric method expressing the results obtained in the percentage of organic
carbon. Total nitrogen by Kjeldahl, nonsiliceous tithionite-extractable iron by Coffin,
amorphous oxalate-extractable sesquioxides and silica by Tamm were determined whereas
iron activity by Schwertmann was calculated. For the establishment of texture the pipette-
method by Katchinski with the Na-pyrophosphate treatment was used. The identification of
soils was done by the FAO concepts (4).

Results and Discussion. Archaeological Objects in the Employ of Pedogenetic Research. Ancient burial mounds with
stone chests (stone chest cairns) laid on dissoiled surface of limestone about 2,000 years ago
made it possible firts to conclude that except for the terrigenous material of limestone
during one year approximately 2.3 grams of medium and fine silt and clay per sq.m had
been formed for the progress of the Rendzic Leptosol of 8 cm thick later on the Baltic Ice
Lake transgression (12). More intensive weathering was noticed in the bottom of stone chest
during the subatlantic period - besides the terrigenous silt and clay of limestone nearly
34 g/m² of those of neosynthetic origin had been accumulated there during one year. The
weathering of limestone results in the enrichment in the amorphous iron of products (Table
1). Breakdown of carbonates and leaching of calcium leads to an increase in the ratio
between the first and second fractions of humus compounds connected with mobile
sesquioxides and calcium, respectively.

Differences in the intensity of weathering and pedogenesis as well as in the degree of both
argillization and brunification are mainly conditioned by the nature of organic matter (Table
1). Although soluble fractions constitute only one third of total organic carbon in the more
pure and young weathering product in the bottom of stone chest, its fulvicity tends to ensure
the continual formation of secondary clay there as well as between the cairn and subsoil
slabs of limestone. In the conditions of abundant presence of CaCO₃ humic acids (especially
the ones connected with calcium) prevail in the humus, the role of sesquioxides increasing
in the fixation of the products of humification parallel to the intensification of pedogenesis
and leaching of carbonates.

Further investigations of the nearly twice thicker Rendzic Leptosol under the same ecological
Table 1. Some characteristics of Rendzic Leptosols (10,000 years) and weathering products in stone chest cairns (2,000 years)

<table>
<thead>
<tr>
<th>Objects</th>
<th>Percentage of C:N</th>
<th>Clay, %</th>
<th>Ratios</th>
<th>Amorphous Fe₃O₄, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rendzic Leptosol in the Ice Lake zone:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A 0-8 cm</td>
<td>10.3 0.6</td>
<td>17.2</td>
<td>27</td>
<td>1.0 4.4 2.7</td>
</tr>
<tr>
<td>8-15 cm pedogenic product between slabs</td>
<td>8.4 0.6</td>
<td>14.0</td>
<td>23</td>
<td>1.6 1.1 2.6</td>
</tr>
<tr>
<td>Weathering product between subsoil slabs</td>
<td>6.5 0.4</td>
<td>16.2</td>
<td>24</td>
<td>1.4 0.8 2.6</td>
</tr>
<tr>
<td><strong>Weathering products in stone chest cairns:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top of burial mound</td>
<td>13.2 1.3</td>
<td>10.2</td>
<td>32</td>
<td>0.9 0.2 1.7</td>
</tr>
<tr>
<td>Between cairn slabs</td>
<td>4.6 0.5</td>
<td>9.2</td>
<td>33</td>
<td>0.3 0.2 2.1</td>
</tr>
<tr>
<td>In the bottom of stone chest</td>
<td>1.7 0.2</td>
<td>8.5</td>
<td>41</td>
<td>0.3 1.4 2.6</td>
</tr>
</tbody>
</table>

Conditions in comparison with the products of weathering both under from the limestone slabs of this profile and stone (0.6x0.7 sq.m of ground area) of the internal ring of stone chest cairn tend to demonstrate a clear decrease in humus accumulation with a simultaneous increase in the depth of a layer impacted pedogenetically (Table 2). As a result of an evident improvement in moisture relationship the more complete fixation of nitrogen in the heterocyclic molecules of humus (5) lead to an increase in the humus maturity evaluated by the C:N ratio. Continual formation of free fulvic acids and stable fulvicity ensure a rather rapid weathering and initial pedogenesis in the stone chest cairn installations which are by 7-8 thousand years younger than natural rendzina. The increase of the profile of the latter in depth is accompanied by an increase in fulvicity (relative narrow humic:fulvic ratio) mainly on the account of fulvates of calcium (narrow ratio between the first and second fractions of humus acids), the correspond orders being compared with those in rather young products of weathering (Tables 1,2).

In spite of an age, the percentage of amorphous sesquioxides in the materials investigated shows a stability. It means that an equilibrium between their mobilization, fixation and transformation tends to be characteristic of the progress of rendzinas. As organic matter, especially humus substances represent the motive power of soil formation and the soils are a direct result of interactions between organic agencies and mineral stratum, the rate of argillization of weathering products is in connection with the fulvicity of humus. But a slight tendency to the remnant accumulation of sandy fractions could be an assertion on the protective efficiency of the film of humins against their continual weathering. A considerable
Table 2. *Rendzic Leptosols (RL)* and weathering products (WP) in the territory of Baltic Ice Lake

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Natural RL 6 m from cairn</th>
<th>WP under from ring stone of cairn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-5 cm</td>
<td>5-15 cm</td>
</tr>
<tr>
<td></td>
<td>cm</td>
<td>cm</td>
</tr>
<tr>
<td>Total organic C, %</td>
<td>6.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Total N, %</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>C:N</td>
<td>10.0</td>
<td>9.0</td>
</tr>
<tr>
<td>% of total C:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>soluble fractions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>humic acids</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>free fulvic acids</td>
<td>25</td>
<td>22</td>
</tr>
<tr>
<td>hydrol. of 0.5 M H₂SO₄</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Ratios:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humic/Fulvic</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>1st fr./2nd fr.</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Nonsiliceous Fe₂O₃, %</td>
<td>2.8</td>
<td>3.9</td>
</tr>
<tr>
<td>Amorphous (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.0</td>
<td>2.9</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>SiO₂</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Fe-activity, %</td>
<td>71</td>
<td>74</td>
</tr>
<tr>
<td>Specific surface area, m²/g</td>
<td>203</td>
<td>160</td>
</tr>
<tr>
<td>Percentage of</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sand</td>
<td>48</td>
<td>57</td>
</tr>
<tr>
<td>silt</td>
<td>31</td>
<td>29</td>
</tr>
<tr>
<td>clay</td>
<td>21</td>
<td>14</td>
</tr>
<tr>
<td>Skeleton, %</td>
<td>2</td>
<td>34</td>
</tr>
</tbody>
</table>

High content both of sand and coarse silt of limestone origin on the background of calcareous skeleton ensures the progress of weathering and soil formation in calcareous conditions. For that reason the rate of argillization is quite slow.

These regularities were also announced in the retreat zone of the Ancylus Lake (Table 3) where near the town of Kunda (59°30'N, 26°30'E) besides natural *Rendzic Leptosol* of 7,000 (7,500) years old the three-aged soil formations from man-made stone heap (the first millennium BC) were studied. A pure brown weathering product was sampled in the depth of 43-47 cm from the top of stone heap under the last limestone slabs, below the former soil developed before the piling up of stones from an ancient field. The genetic origin of this material could be identified with that in the depth of 15-22 cm under the *Rendzic* profile developed during the last two millennia without an anthropogenous stony covering. A former
Table 3. Three-aged Rendzic Leptosols (RL) and weathering products (WP) in the territory of Ancylus transgression

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Natural RL</th>
<th>RL on stone heap</th>
<th>RL under stone heap</th>
<th>WP under last slab</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-5 cm</td>
<td>5-15 cm</td>
<td>15-22 cm</td>
<td>0-10 cm</td>
</tr>
<tr>
<td></td>
<td>cm</td>
<td>cm</td>
<td>cm</td>
<td>cm</td>
</tr>
<tr>
<td>Total organic C, %</td>
<td>5.8</td>
<td>3.9</td>
<td>3.2</td>
<td>7.3</td>
</tr>
<tr>
<td>Total N, %</td>
<td>0.7</td>
<td>0.5</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>C:N</td>
<td>8.3</td>
<td>7.8</td>
<td>8.0</td>
<td>9.1</td>
</tr>
<tr>
<td>% of total C:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>soluble fractions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>humic acids</td>
<td>74</td>
<td>83</td>
<td>82</td>
<td>75</td>
</tr>
<tr>
<td>free fulvic acids</td>
<td>22</td>
<td>19</td>
<td>24</td>
<td>19</td>
</tr>
<tr>
<td>hydrol. of 0.5 M HSO₄</td>
<td>8</td>
<td>10</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Ratios:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humic/Fulvic</td>
<td>0.5</td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>1st fr./2nd fr.</td>
<td>0.8</td>
<td>0.8</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Fe₂O₃, %: total</td>
<td>2.8</td>
<td>2.8</td>
<td>2.9</td>
<td>3.2</td>
</tr>
<tr>
<td>nonsilicicous</td>
<td>2.7</td>
<td>2.5</td>
<td>2.8</td>
<td>2.2</td>
</tr>
<tr>
<td>amorphous</td>
<td>2.5</td>
<td>2.5</td>
<td>2.1</td>
<td>1.6</td>
</tr>
<tr>
<td>Fe-activity, %</td>
<td>92</td>
<td>100</td>
<td>75</td>
<td>73</td>
</tr>
<tr>
<td>Total Al₂O₃, %</td>
<td>12.2</td>
<td>10.6</td>
<td>10.8</td>
<td>13.3</td>
</tr>
<tr>
<td>Amorphous Al₂O₃, %</td>
<td>0.7</td>
<td>1.1</td>
<td>1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>SiO₂, %</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Spec. surface area, m²/g</td>
<td>190</td>
<td>161</td>
<td>156</td>
<td>240</td>
</tr>
<tr>
<td>Percentage of:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sand</td>
<td>55</td>
<td>59</td>
<td>57</td>
<td>50</td>
</tr>
<tr>
<td>silt</td>
<td>28</td>
<td>26</td>
<td>27</td>
<td>29</td>
</tr>
<tr>
<td>clay</td>
<td>17</td>
<td>15</td>
<td>16</td>
<td>21</td>
</tr>
<tr>
<td>Skeleton, %</td>
<td>1</td>
<td>16</td>
<td>23</td>
<td>11</td>
</tr>
</tbody>
</table>

Soil surface was found in the mid of stone heap at the same level with the surface of natural uncovered soil. To compare the latter with the former one both were sampled in two depths whereas the location of the former topsoil was in the depth of somewhere 30-35 cm from the modern top of stone heap under the stones piled. Ancient man-built stone heap was covered with thin Rendzic Leptosol younger by 4,500-5,000 years of its natural vicinity.

The impact of stony covering is expressed first in the evident stoppage of humus accumulation, but in an increase in the degree of humification on the background of former solubility and fulvicity of humus (Table 3). This tends to result in the slowness of pedogenetic argillization and remnant accumulation of both of skeleton and sandy fractions in the former Rendzic profile under the stone heap. Humus of deep weathering products
below the first ground limestone slabs is much more humic and less fulvic under the natural profile than that under the conditions of nearly half-metre covering. It is notable that a young topsoil on stone heap is up to by 25% more humous and argillic of its more older analogue, being probably due to the permanent grass-sward (out of tillage impacts) and putting of weeds and post-harvest residues as complementary organic sources there. Such a phenomenon was repeatedly fixed on ancient stone baulks and man-made heaps of the other locations (13, 15).

Sesquioxides relationship is likewise similar in different-aged products of weathering and soil formations (Table 3), whereas amorphous iron greatly prevail over the crystalline and siliceous forms of the latter. Only about 10% of alumnum is amorphous. Undoubtedly ferric products of weathering are able to accumulate without the further crystallization in situ in the kind of Fe-humic-fulvic complexes even in the conditions of high earth-alkaline saturation. Magnesium (the total content of 1.7-1.9%) may be included in the hydrous sesquioxides and therefore on the background of low aluminium:magnesium ratio (in the limits of 2-3) some losses of silica and fixation of iron in the hydroxy coatings and soil allophanes could also take place (7). In spite of considerable amounts of free fulvic acids the solubility of iron compounds is poor. Only a slight migration of Fe-fulvic chelates takes place making the external surfaces of ground limestone and limestone slabs brown.

Prevalent fulvicity of the early products of humification guarantee the formation of secondary clay as well as the transformation of hydromicas (illite) into mixed-layered neoformations and a little chlorite (11). X-ray diagrams (Fig. 1) show that hydromicas (probably not only of terrigenous origin from limestone weathered, but also as biogenic product of Holocene processes) are unstable with mixed-layered hydromica-vermiculite and chlorite formations everywhere, the lability increases in depth in more pure products of weathering. Some traces of montmorillonite were found in the older natural rendzina profile (11).

Taking, on the bases of these investigation a mean annual increment in the storage of organic carbon as one conventional unit in the transgressional territory of the Baltic Ice Lake, that increment already consists of 1.5-2 in the zone of Ancylus transgression, but 3-5 on the human installations of 2,000-2,500 years old. It means that the intensification of humification in the course of time is characteristic of Holocene pedogenesis. In spite of differences in the storages of total organic carbon, the composition of humus in weathering products and soil formations of different ages are quite similar showing a rather quick progress of qualitative pedogenetic features.

To confirm the regularities above that testify human activities, the comparative investigations were carried out with alvar meadow and arable Rendzic Leptosols, different-aged weathering products from stone chest cairns and ancient stone heaps (13). There were no essential differences in the carbon and nitrogen content between the natural alvar meadow rendzina and the embankment material of stone heaps (Table 4). A lower C and N content was characteristic of arable rendzinas, although it was higher than that in young burial materials, especially in the stone chests and in the bottom of cairns. A multistage laying of stones (slabs, pebble, etc.) can be assumed, as a result of which the favourable
Figure 1. X-ray diagrams from clay fraction (11).

(1) A 0-5 cm of natural Rendic Leptosol, (2) A 5-15 cm, (3) weathering product under the ground slabs, (4) top (0-10 cm) of stone heap, (5) under the upper stones and slabs there, (6) buried soil under the stone heap, (7) under the slabs in depth of 40 cm from the top of heap, (8) weathering product under the last ground slab.

(I) initial air dry sample + Mg treatment; (II) saturated in ethylene glycol; (III) 350°C treatment; (IV) 550°C treatment.
Table 4. Comparative characterization of *Rendzic Leptosols* and weathering products from some archaeological objects (Iru near Tallinn)

<table>
<thead>
<tr>
<th>Objects</th>
<th>C</th>
<th>N</th>
<th>C total</th>
<th>N amorph.</th>
<th>Fe-activity</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Rendzic Leptosol on alvar meadow</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A 0-5 cm</td>
<td>8.9</td>
<td>1.0</td>
<td>4.9</td>
<td>3.4</td>
<td>69</td>
<td>26</td>
</tr>
<tr>
<td>A 5-10 cm</td>
<td>7.1</td>
<td>0.8</td>
<td>5.8</td>
<td>3.8</td>
<td>65</td>
<td>23</td>
</tr>
<tr>
<td>10-15 cm on the upper side of limestone slabs</td>
<td>5.5</td>
<td>0.6</td>
<td>6.1</td>
<td>4.1</td>
<td>66</td>
<td>20</td>
</tr>
<tr>
<td>Ground side of limestone slabs</td>
<td>3.9</td>
<td>0.7</td>
<td>6.2</td>
<td>4.0</td>
<td>64</td>
<td>22</td>
</tr>
<tr>
<td><em>That on arable alvar</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A 0-5 cm</td>
<td>6.5</td>
<td>0.7</td>
<td>4.1</td>
<td>3.0</td>
<td>72</td>
<td>24</td>
</tr>
<tr>
<td>A 5-10 cm</td>
<td>5.5</td>
<td>0.6</td>
<td>4.6</td>
<td>3.2</td>
<td>69</td>
<td>21</td>
</tr>
<tr>
<td>A 10-20 cm</td>
<td>5.0</td>
<td>0.6</td>
<td>5.0</td>
<td>3.2</td>
<td>62</td>
<td>22</td>
</tr>
<tr>
<td><em>Ancient stone heaps on alvar</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper part of those:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>loamy sand (n = 7)</td>
<td>8.7</td>
<td>1.0</td>
<td>3.7</td>
<td>2.9</td>
<td>76</td>
<td>18</td>
</tr>
<tr>
<td>loam (n = 6)</td>
<td>8.6</td>
<td>1.1</td>
<td>4.0</td>
<td>2.5</td>
<td>62</td>
<td>25</td>
</tr>
<tr>
<td>Medium part (n = 9)</td>
<td>4.5</td>
<td>0.6</td>
<td>5.2</td>
<td>3.4</td>
<td>67</td>
<td>23</td>
</tr>
<tr>
<td>In the bottom of heaps on the limestone slabs (n = 10)</td>
<td>2.9</td>
<td>0.4</td>
<td>5.4</td>
<td>3.6</td>
<td>69</td>
<td>27</td>
</tr>
<tr>
<td><em>Stone chest cairns</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burial mound (n = 2)</td>
<td>2.6</td>
<td>0.4</td>
<td>5.5</td>
<td>2.9</td>
<td>55</td>
<td>32</td>
</tr>
<tr>
<td>Under that (n = 2)</td>
<td>1.6</td>
<td>0.3</td>
<td>4.9</td>
<td>2.0</td>
<td>41</td>
<td>34</td>
</tr>
<tr>
<td>Under the stones and slabs</td>
<td>2.1</td>
<td>0.4</td>
<td>3.6</td>
<td>1.5</td>
<td>42</td>
<td>26</td>
</tr>
<tr>
<td>In the bottom (n = 3)</td>
<td>1.4</td>
<td>0.3</td>
<td>3.6</td>
<td>1.1</td>
<td>32</td>
<td>25</td>
</tr>
<tr>
<td>Bottom of stone chest (n = 5)</td>
<td>0.4</td>
<td>0.1</td>
<td>1.8</td>
<td>1.1</td>
<td>58</td>
<td>26</td>
</tr>
</tbody>
</table>

conditions for the progress of plant sward and humus accumulation were provided. On the background of these great differences in the quantitative characteristics there were no differences in the composition of humus, the soluble fraction also consisting of 60-70% of the total and the humic:fulvic ratio being above one. The content of organic carbon and nitrogen in the weathering products on the ground side of limestone slabs in soils is markedly lower than that on the upper side of slabs. But under the ancient stone heaps and stone chest cairns the C and N status is greatly lower than in the weathering products on the upper slabs of natural *Rendzic Leptosols*. It may be concluded that the deepening of the *Rendzic* profile is first of all due to the plant roots, the transformation products of which enrich the weathering product in humus and nitrogen. Due to the better moisture relationships, the process of argillization is more intensive under the stone heaps and burial.
mounds. This process is also accompanied by an intensive formation and accumulation of nonsiliceous iron compounds whereas the presence of their crystalline forms is noticeable.

Ancient arable territories near the Rebala village, about 20 km from Tallinn to the east and 0.5 km from the Baltic glint to the south, are located on *Rendzic Leptosols of Late-Yoldian - Early-Ancylian* age (about 9,000 years). Man-built stone baulks (palings, fences) of limestone and rare of crystalline blocks, boulders and cobble gathered during the ancient tillage separate this territory into small fields. Besides them a lot of burial mounds with stone chests and stone chest cairns have been arranged on flat or gently sloped ground limestone hillocks. Thus, a whole complex of anthropogenous installations is located there whereas different weathering products and soil formations on baulks, under and between their slabs, barrow walls, coronal stones, in the bottom of stone chest, etc. are less than 2,000-2,500 years and are younger by 6,500-7,000 years than *Rendzic Leptosols* in neighbourhood (15). In addition to this first publication an average characterization of the objects described is presented in Table 5.

**Table 5.** Averaged characterization of *Rendzic Leptosols* (RL) and weathering products (WP) of limestone in ancient fields, stone baulks and stone chest cairns (Rebala village)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>RL in (on)</th>
<th></th>
<th>Subsoil of RL</th>
<th>WP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fields</td>
<td>trans. to baulks</td>
<td>stone baulks</td>
<td>betw. coron. wall stones</td>
</tr>
<tr>
<td>Total org. C, %</td>
<td>10.0</td>
<td>10.4</td>
<td>13.8</td>
<td>8.9</td>
</tr>
<tr>
<td>Total N, %</td>
<td>1.3</td>
<td>1.2</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td>C:N</td>
<td>7.7</td>
<td>8.7</td>
<td>9.6</td>
<td>8.9</td>
</tr>
<tr>
<td>% of total C:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>soluble fractions</td>
<td>69</td>
<td>64</td>
<td>47</td>
<td>62</td>
</tr>
<tr>
<td>humic acids</td>
<td>18</td>
<td>20</td>
<td>12</td>
<td>18</td>
</tr>
<tr>
<td>free fulvic acids</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Ratios:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humic/Fulvic</td>
<td>0.5</td>
<td>0.6</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>1st fr./2nd fr.</td>
<td>1.1</td>
<td>1.4</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Nonsiliceous Fe$_2$O$_3$, %</td>
<td>7.2</td>
<td>7.2</td>
<td>7.0</td>
<td>10.1</td>
</tr>
<tr>
<td>Amorphous Fe$_2$O$_3$, %</td>
<td>4.3</td>
<td>5.0</td>
<td>4.5</td>
<td>6.3</td>
</tr>
<tr>
<td>Al$_2$O$_3$, %</td>
<td>1.1</td>
<td>1.2</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Fe-activity, %</td>
<td>60</td>
<td>70</td>
<td>62</td>
<td>62</td>
</tr>
<tr>
<td>Spec. surface area, m$^2$/g</td>
<td>336</td>
<td>338</td>
<td>375</td>
<td>321</td>
</tr>
<tr>
<td>Percentage of sand</td>
<td>67</td>
<td>72</td>
<td>71</td>
<td>70</td>
</tr>
<tr>
<td>silt</td>
<td>21</td>
<td>20</td>
<td>27</td>
<td>20</td>
</tr>
<tr>
<td>clay</td>
<td>12</td>
<td>8</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Skeleton, %</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>9</td>
</tr>
</tbody>
</table>
Considerable enrichment of any weathering products in humus and nitrogen as well as in humic substances tends to show both root and microbial activity forced deep in and under stony installations where seasonal alternation of moistening with perched water and drying up can also ensure humification and fixation of the products, respectively. These phenomena characteristic of accumulative pedogenesis in general are especially favoured between the stones of the coronal wall of stone chest cairn as well as in the same extent between the stones piled up to the ring wall of burial mound. These objects are quite similar to the subsoil of natural Rendzic formations above the ground limestone floor. The greater humousness (with less soluble and a little less humic humus) of young Rendzic Leptosols on stone baulks can also be interpreted as an effect of post-harvest residues collected there and permanent sward which was surely absent in tilled fields not only of ancient agriculture, but also much more later. Any traces of ploughing in stone baulks have not been found. But otherwise, the modern impact of alvar-meadow situation is of significance in the balanced stabilization of humus state in different surface localities. Only a slight tendency to an increase in the rate of humification, a higher quantity of humus substances bound up with mineral particles (hydrolysate of 0.5 M sulphuric acid) and an enlargement of the ratio between the first and second fractions (connected with sesquioxides and alkaline-earth oxides, respectively) tend to show the effects of tillage there. Both the argillization and ferrugination of soil and weathering products are characteristic of and similar to their representatives of different ages. It is possible that some unstable hydromica (illite) formations (11) can transform into R₂O₃-hydroxides already in the young products of weathering, but especially in the process of intensive pedogenesis. This in its turn results in a slight decrease in the clay content and in an intensive brown (reddish-brown) colour of solum, alike it takes place in the course of allitisation (3, 4).

The data obtained and discussed stimulated our interest to study some soil formations in (under) the man-built objects from the later period. Remnant installations and territory of the ancient fortified stronghold at Varbola (59°02’N, 24°32’E) from the 12-13th centuries were more suitable for this purpose. Archaeological excavations connected with the opening, cleaning out and restoration of the western gate of the stronghold made possible to sample the middle part of the ruined and denudated slope of wall embankment directly aside the gate (Table 6) whereas modern soil on surface cannot be older than 640-650 years - formed after the final breakage of stronghold in the mid of the 14th century. This Rendzic formation is nearly twice more humous than its analogues described in this paper. It can only be compared with thin Rendzic Leptosols in virgin alvar forests and meadows rich in kinds of herb layer (12). The percentage of soluble fractions is 40-50% here, the humic:fulvic ratio (0.4) and ratio between the first and second fractions (1.0) indicate to the prevalence of highly saturated humic-fulvic complexes. The ferrugination is weak probably due to the essential enrichment of sloppy topsoil in calcium in the process of denudation of the upper part of wall embankment. Lateral migration of clay formed is also possible.

Soils of cultural layers under the wall ruins must be some hundred years older, from the time of real human activity in the stronghold. After breakage of the latter the pedogenesis (natural and cultural) has evidently been stopped (Table 6). Except the degree of ferrugination and the content of clay, the main soil features are similar to those in the other objects whereas it is of necessity to give special emphasis to a great degree of humification.
Table 6. Soil formations on the external slope of the wall embankment aside the western gate of Varbola fortified stronghold (12-13th century)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Modern soil on surface</th>
<th>Cultural layer under wall ruins</th>
<th>Tops of sandy embankment</th>
<th>till under 1st slabs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>upper part</td>
<td>lower part</td>
<td></td>
</tr>
<tr>
<td>Total org. C, %</td>
<td>19.2</td>
<td>4.1</td>
<td>3.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Total N, %</td>
<td>1.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>C:N</td>
<td>12.8</td>
<td>10.2</td>
<td>8.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Nonsiliceous Fe₂O₃, %</td>
<td>0.5</td>
<td>0.8</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Amorphous Fe₂O₃, %</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Al₂O₃, %</td>
<td>0.3</td>
<td>0.4</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>SiO₂, %</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Fe-activity, %</td>
<td>60</td>
<td>50</td>
<td>71</td>
<td>67</td>
</tr>
<tr>
<td>Spec. surface area, m²/g</td>
<td>325</td>
<td>155</td>
<td>146</td>
<td>42</td>
</tr>
<tr>
<td>Percentage of sand</td>
<td>57</td>
<td>72</td>
<td>74</td>
<td>92</td>
</tr>
<tr>
<td>silt</td>
<td>27</td>
<td>19</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td>clay</td>
<td>16</td>
<td>9</td>
<td>12</td>
<td>4</td>
</tr>
</tbody>
</table>

(25-35% of total C) typical of human-influenced soils in general (1). Upper sections of both sandy and tília materials in (under) the wall embankment could probably be the former different-aged surfaces of soil as their (although weak) humousness, ferrugination and iron activity ascertained are neither characteristic of unchanged calcareous till nor any sandy sediments. It is evident that former pedogenesis was stopped and its signs were mostly effaced in the process of establishment and exploitation of stronghold.

The collection discussed can be completed by the soils and products of weathering from the courtyard (the total area of 2 ha) of the Varbola stronghold (Table 7). At that the upper slabs of both the dwelling-house floor and soil bedrock were mostly found in the depth of 40-50 cm from the modern surface of courtyard. Only in places the bedrock limestone was opened near the surface, but it was obviously also covered by man-mixed and -changed fine earth of highly heterogeneous origin. In the Middle Ages a part of the courtyard was used as a burial-place (graveyard). That is why it is possible to draw a conclusion of the main progress of pedogenetic activities there during the last half of millennium. Rather equal levels of organic carbon (3.0-5.5%), nitrogen (0.2-0.4%) and nonsiliceous iron (0.5-0.7%) in sandy and loamy sandy Anthrosols are comparable with those in Anthro-Rendzic Leptosols (Table 7) on the local bedrock microhillock. Loamy weathering products from the late 12th to the early 13th centuries are not different from their more older analogues (Tables 1-5) whereas the impact of improved moisture relationships under the deep cultural layers tend to be evident.
Table 7. Rendzic Leptosols (RL) and weathering products (WP) in the ancient stronghold

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>RL in courtyard</th>
<th>50 years RL on limestone</th>
<th>WP from 12-13th centuries between</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-10 cm without pebble</td>
<td>10-20 cm with pebble</td>
<td></td>
</tr>
<tr>
<td>Total organic C, %</td>
<td>6.4</td>
<td>4.5</td>
<td>15.7</td>
</tr>
<tr>
<td>Total N, %</td>
<td>0.6</td>
<td>0.4</td>
<td>1.0</td>
</tr>
<tr>
<td>C:N</td>
<td>10.7</td>
<td>11.2</td>
<td>15.7</td>
</tr>
<tr>
<td>% of total C: soluble fractions</td>
<td>49</td>
<td>53</td>
<td>45</td>
</tr>
<tr>
<td>% of total C: humic acids</td>
<td>20</td>
<td>21</td>
<td>13</td>
</tr>
<tr>
<td>Ratios:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humic/Fulvic</td>
<td>0.9</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>1st fr./2nd fr.</td>
<td>0.9</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Nonsiliceous Fe$_2$O$_3$, %</td>
<td>1.3</td>
<td>1.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Amorphous, %</td>
<td>Fe$_2$O$_3$</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Al$_2$O$_3$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>SiO$_2$</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Fe-activity, %</td>
<td>54</td>
<td>55</td>
<td>63</td>
</tr>
<tr>
<td>Spec. surface area, m$^2$/g</td>
<td>155</td>
<td>119</td>
<td>270</td>
</tr>
<tr>
<td>Percentage of</td>
<td>sand</td>
<td>67</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>silt</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>clay</td>
<td>11</td>
<td>10</td>
</tr>
</tbody>
</table>

Complete humus accumulation in the general limits of 11-21% of organic carbon in the layer of some millimetres was found even within only half of a century (Table 7) on limestone slabs piled up by archaeologist Erkik Laid immediately prior to the World War II in the process of cleaning and restoration of the ancient stronghold draw-well. At present these slabs are covered with herb and moss vegetation and leaf litter. Except ferrugination, the other features (humus relationships, specific surface area, textural parameters) are quite close to the qualities characteristic of full-developed Rendzic Leptosols. It enables us to sum up that the qualitative progress of Rendzic formation on limestones is rather quick, but (with the exception of the humousness of pedogenetic products) the development of quantity indices (thickness, supplies, etc.) proceeds slowly increasing in depth only by a tenth or hundredth millimetres per year. The transformation of weathering products in anthropogenous installations is completely going on by the Rendzic type of pedogenesis, but the progress of argillation and accumulation of ferruginated loamy (clayey) products testify the probable evolutionary connection of Rendzic Leptosols with Calcaric Cambisols.

Investigations carried out on fluvioglacial sands (the percentage of sandy and clayey fractions more than 94 and less 5, respectively) enabled us to ascertain that the progress of
Podzolization is also quite quick (Table 8). Some groups of burial mounds alike endmorainic sandy hillocks on the coastal slope of outwash plain were the habitats of pine stand of Oxalis-Vaccinium site type and covered with ground litter of Moor-Moder type of 5-6 cm in depth. Although the Podzol on burial mound is only 700-800 years old and a lot of thousand years younger than its natural analogue on the neighbourhood plain, there are no differences in their morphology, humus and some physico-chemical relationships. The biological weathering of sandy fractions and accumulation of silty and clayey ones as well as the mobilization and fixation of iron in its crystalline form tend to be more intensive under the modern ecological situation in the burial mound. Repeat sampling in different parts of mound showed the same regularities.

**Table 8. Sandy Podzols in Jõuga (59°08'N, 27°24'E)**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Upper part of burial mound from 13th cent.</th>
<th>Natural soil aside burial mound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A(E)</td>
<td>B(h)</td>
</tr>
<tr>
<td></td>
<td>6-10</td>
<td>10-20</td>
</tr>
<tr>
<td>Total organic C, %</td>
<td>1.7</td>
<td>0.8</td>
</tr>
<tr>
<td>C:N</td>
<td>17.0</td>
<td>18.7</td>
</tr>
<tr>
<td>% of total C:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>soluble fractions</td>
<td>43</td>
<td>78</td>
</tr>
<tr>
<td>humic acids</td>
<td>24</td>
<td>23</td>
</tr>
<tr>
<td>free fulvic acids</td>
<td>5</td>
<td>35</td>
</tr>
<tr>
<td>Ratios:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humic/Fulvic</td>
<td>1.4</td>
<td>0.4</td>
</tr>
<tr>
<td>1st fr./2nd fr.</td>
<td>1.3</td>
<td>5.0</td>
</tr>
<tr>
<td>Nonsiliceous Fe$_2$O$_3$, %</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Fe-activity, %</td>
<td>55</td>
<td>48</td>
</tr>
<tr>
<td>Amorphous SiO$_2$, %</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Percentage of</td>
<td>sand</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>silt</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>clay</td>
<td>4</td>
</tr>
<tr>
<td>pH (H$_2$O)</td>
<td>5.5</td>
<td>4.8</td>
</tr>
<tr>
<td>pH (KCl)</td>
<td>5.0</td>
<td>4.4</td>
</tr>
<tr>
<td>B.E.C., me/100 g</td>
<td>7.6</td>
<td>4.5</td>
</tr>
<tr>
<td>Mobile Al$^{3+}$, mg/100 g</td>
<td>0.5</td>
<td>7.3</td>
</tr>
<tr>
<td>Base saturation, %</td>
<td>50</td>
<td>18</td>
</tr>
</tbody>
</table>

Furthermore, two important phenomena are worth of mentioning. First, podzolization of sands seems to begin from the formation and accumulation of humus, the aggressive fractions of which will be liable to downward migration after the partial solution of colour coatings on quartz. It will result in an increase in fulvicity in depth as well as in initial signs of the formation of humus-illuvial horizon. Second, humicity of humus typical of relatively
developed weak Arenic Podzols does not tend to be accidental, also in case of their young sandy analogues. Similar morphological and analytical data have been discussed in Aleksandrovski's review (1). During the whole Holocene the podzolization is characteristic of sandy deposits up to the present time and at a great rate. Its development is impossible on any loamy calcareous materials, in spite of the rate and trends of weathering activity. Under the conditions of deficiency in moisture characteristic of fluvioglacial sands studied the podzolic profile differentiation is always weak even in the soils of Late-Pleistocene age (1, 19). The development and relative stabilization of both Podzolic and Rendzic formations do not take thousands of years (17) as demonstrated by sufficient qualitative characteristics in dated archaeological objects.

Archaeological objects in the description of former soil mantle. In the region of prevalent occurrence of Cambisols and Luvisols (58°30'-59°25'N, 25°30'-26°45'E) the parent material is loamy calcareous yellow-grey till the pedogenetic neoformations of which in burial mounds can be distinguished with difficulties. Like the stone chest cairns in alvar landscape, the clearance cairns used here in the first millennium BC were established on dissoiled locations (15, 16). Our intuitive assumption that only the humus horizon was then defined as a soil was assured after the opening of clearance cairn at Tarbja village in the western part of the region mentioned. Fully developed Luvisol (A-EL-Bmt-C) profile was present there whereas all horizons were nearly twice thinner than there natural averages (Table 9). It is possible that former A-horizon was nevertheless withdrawn before the foundation of chest cairn and formed once again below the latter from the lessivaged horizon during the last two millennia. Soluble humus is rich in Ca-fulvates there, but rather inactive humic compounds are also present, indicating the eventual weak humification under the influence of fulvates migrated from above. High similarity between great number of basic diagnostics confirms the synchronous argilization and lessivage on calcareous till already during the Ancylus and Littorina Stages before the ancient human inhabitants. The lessivage of humus and eluvial horizons was probably intensified as a result of tillage during the last millennia with a simultaneous argilization of B-horizon in situ. Any symptoms of former and/or modern podzolization were established.

For obtaining the information about former soil mantle in town landscapes, where anthropogenically unchanged forest-parks, private gardens, etc. are absent, the only way is to use objects of archaeological, engineer-geological and historico-architectural excavations. So it was done in Tartu City with different-aged buildings on the ruins of former installations as well as on various fillings. In some places natural soils have been buried in the depth of several metres. The most interesting two-storied profile of Dystric Cambisol on Eutro-Dystric Podzoluvisol was opened aside and under the foundation-wall of Dome Church on the territory of only some square metres. Up to now this is the only sampled soil object preserved under the building from the 14th century. Another Podzoluvisolic profile near the ruins of St.Maria Church was excavated under from asphalt and fillings of the 18th century in so-called "Provost Field". They both are highly similar to forest and arable Dystric Podzoluvisols (Dystric Cambisols) of the Baltic Region. The presence of yellow-brown horizon enriched in amorphous iron immediately under the humus horizon substantiates its pedogenetically diagnostic character originated from broad-leaved forests of Littorina Stage. It can neither be identified as a result of agricultural activity nor hydrogenic accumulation.
Table 9. Luvisols on yellow-grey calcareous till

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Natural soil profiles (n=50)</th>
<th>Profile under the clearance cairn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A EL B</td>
<td>A EL</td>
</tr>
<tr>
<td>Depth, cm</td>
<td>25 23 25</td>
<td>13 8 19</td>
</tr>
<tr>
<td>C:N</td>
<td>10.7 9.3 8.5</td>
<td>9.8 13.0 7.6</td>
</tr>
<tr>
<td>soluble fractions</td>
<td>21 17 10</td>
<td>22 5 8 4 14 9</td>
</tr>
<tr>
<td>free fulvic acids</td>
<td>0.7 0.4 0.3</td>
<td>0.5 0.2 0.3</td>
</tr>
<tr>
<td>1st fr./2nd fr.</td>
<td>0.7 0.4 0.3</td>
<td>0.5 0.2 0.3</td>
</tr>
<tr>
<td>Clay, %</td>
<td>18 19 30</td>
<td>14 20 31</td>
</tr>
<tr>
<td>Mol. ratios in clay:</td>
<td>25 23 25</td>
<td>13 8 19</td>
</tr>
<tr>
<td>SiO₂/R₂O₃</td>
<td>2.5 2.4 2.5</td>
<td>3.2 2.4 2.6</td>
</tr>
<tr>
<td>SiO₂/Fe₂O₃</td>
<td>10.8 10.1 9.6</td>
<td>10.3 9.5 9.4</td>
</tr>
<tr>
<td>SiO₂/Al₂O₃</td>
<td>3.3 3.2 3.4</td>
<td>4.7 3.3 3.5</td>
</tr>
<tr>
<td>Al₂O₃/K₂O</td>
<td>6.6 7.0 5.7</td>
<td>5.1 6.5 6.6</td>
</tr>
</tbody>
</table>

Concretions and iron-manganese nodules at the juncture of layers with different texture represent the relics of former perched water impact. In the condition of covering with buildings the modern stagnation of perched water and gleyization are absent there.

Man-carried technogenic inhumation of these Dystric Podzoluvisols (Cambisols) from the Early Middle Ages and continual absence of the replenishment of fresh organic residues resulted in a decrease in their humus percentage and storages, although the degree of humification (on the account of humic compounds conserved) was increased. Except some mobile oxides, the main compositional and property characteristics do not differ from their analogues in nature. But data on the changes in humus relationships tend to confirm the modern processes of humus degradation under the conditions of extensive agriculture.

Eutro-Calcaric Cambisols were found deep under several layers of the ruins near the Gun-Powder Cellar from the 17th century. Parent fluviglacial calcareous gravelly sand is rich in feldspars (Q:Fs ratio 4-6 in sandy fraction), micas (up to 7% in the fraction of 0.1-0.05 mm) and carbonates. As a result of ancient pedogenetic argillization the initial clay content (4.4%) has increased up to 12.4 and 8.0% in humus and metamorphic-accumulative (Bm) horizons, respectively. There are no signs about physical sedimentation and it is difficult to suppose that argillic Cambisolic profile could develop under the stones of ruins in the absence of organic influx. Humus (1.2-2.7% organic carbon) in normally developed A-horizon is Ca-humic - contrary to modern natural Cambisols which are characterized by R₂O₃-fulvic-humic complexes. Besides relative large C:N ratio (14-16), such humus status
tends to be the greatest deviation of these buried soils from their natural analogues. Apparently one cannot exclude the fact that the intensive pedogenesis stopped here on the slope of the river valley already at the beginning of the foundation of Tartu settlement before the 11th century whereas the profile opened represents the product of long-term conservation.

A little lower exposition of weakly developed Arenosols were found under the multilayered ruins of town installations. Pedogenesis on the fluvio-glacial and deluvial sands rich in quartz and poor in feldspar-mica association has been weak. In the conditions of shortage of organic C (nearly 1-1.5%) the profile differentiation has not taken place and the soils formed probably up to thousand years ago can be compared with natural nondifferentiated Arenosols in arid forests of Cladonia site type or dry heath meadows of Hieracium - Antennaria (Festuca ovina) type. Nowhere in the boundaries of town the Arenosolic sandy formations extend to the modern surface.

The lower third of valley slope as well as the narrow belt of the valley near terrace (deeply under the western foundation of the modern Department Store) different Gleyic formations covered with ruins from the 12-16th centuries were found. Gleyization is relic in its origin representing in the weak differentiation of soil profile in the kind of temporary changes in oxydation-reduction relationships. A slight eluvio-accumulative differentiation can be connected with a gradual fall in the ground water table in course of time. The high level of ground water could be one of the agencies which inhibited the ancient profile development of sandy Gleysols there. Afterwards under the deep town covering the absence of organic influx had missed the pedogenetic realization of water regime changes. The same can be applied to Eutric and Histic Gleysols in valley flat under the ruins, debris, fillings and cultural layers of several metres in depth. It seems that the compaction of histic horizons has been changed under the pressure of buildings and fillings. Thin transitional horizons between histic and gleyic ones testify that the further paludification of Gleysols is the only phenomenon in the progress of Histosolic formations. It looks that peat (histic horizon) has not been removed before the filling of valley flat and foundation of town buildings. At that river regression must be gradual.

As regards to the different-aged cultural layers their thick massif (up to 3-4 metres) covers all the catena (from Cambisols to Histic Cleysols and Eutric Histosols) having no signs of pedogenetic differentiation. They resemble mostly the topsoil material of Podzoluvisols, Luvisols and Cambisols from the surroundings, outside the town, than the material of graded local sediments from the same river-valley. It means that during the history of town management the soil matter was transported into gardens and courtyards from the tilly plain of neighbourhood, but also from the Dome Hill and valley slope. In the process of repeated fires, destructions and other collapses this soil material was changed into ground one, mixed and covered with fillings, ruins, debris, etc. The data obtained as a result of analysis of these layers are of significance from the archaeological point of view, but not from the aspects of pedogenesis.

Conclusions. The accumulation of humic-fulvic humus is characteristic not only of natural pedogenesis on mineral strata under the influences of vegetation and microbial activities, but
also in (under, above) different human installations being impacted by the same biogenic agencies in the conditions changed. A great collection of archaeological objects as burial mound layers, stone chest cairns, clearance cairns, ancient stone baulks and palings, barrow embankments, etc. represent the ideal facilities for the investigations into processual advanced pedogenesis. The formation of humus relationships there is going on by the natural types of pedogenesis in correlation with the development of argilization, ferrugination (brunification, rubification), lessivage or podzolization depending on the texture and chemism of mineral strata. The use of different-aged archaeological subjects enables us to conclude that the qualitative progress of any interactions between humus substances and parent mineral material is rather quick resulting in the formation of pedogenetic diagnostics during decades or hundreds of years. Except the humousness of pedogenetic products the development of quantity features (thickness, storage, etc.) proceeds slowly, especially in the conditions of deficiency in moisture or its excess.

On the basis of morphological, analytical and classificational characterization of soils aside and under burial mounds, stone chest cairns, clearance cairns, ancient buildings, etc. it is possible to form extended imagination about the multigenetic origin and evolutionary regularities of separate soil types and whole soil cover in the territory investigated. Identification of the soils covered with deep ruins, debris and fillings of human settlements (towns) is of significance in the restoration of ancient soil catenas to construct changes in continuum of plant-soil systems.

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Literature Cited.


Natural Resources and the Development of Prehispanic Teotihuacan: Preliminary Results of the Analysis of Soils

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Introduction. The initial development of the prehistoric urban center of Teotihuacan, located in the northeastern part of the Basin of Mexico, began about 100 BC. The ceremonial center of the city was erected on a lava platform north of the San Juan River, in an area of abundant volcanic rock, the primary raw material used for the construction of its magnificent pyramids, temples and residential structures. Habitation areas developed around the religious center, in a consistent grid pattern oriented 15° east of true north. The city ultimately grew to cover an area of at least 20 km², extending to the lower and middle slopes, on lands with lower agricultural potential where shallow soils and an average rainfall of about 700mm were cultivated mainly by rainfall-dependent agricultural techniques. These conditions led to the development of irrigation systems, thus permitting the growth of the settlement area. Demographic and areal growth of Teotihuacan was promoted by the domain and exploitation of vast obsidian deposits which allowed the urban center to strategically control the trade in raw materials and finished products.

For about 600 years, from approximately AD 100-750, Teotihuacan was the major metropolis, not only in the Basin of Mexico, but in all of Mesoamerica. Its cultural impact was felt throughout Mexico, including the Maya region, the Gulf Coast and Oaxaca, as well as highland Guatemala.

Soil Characteristics and Dynamics. In order to understand what the landscape of the Teotihuacan region may have been like during the period of prehispanic cultural development, it is necessary to look at a variety of evidence, including soil formation processes, volcanic and tectonic events, vegetation and associated climatic change, and human exploitative activities. All of these factors are closely interrelated during the Holocene.

Field observations and laboratory analyses show that deposits of pyroclastic volcanic sediments are the most important kind of parent material for the soils of the Teotihuacan Valley. Based on the way in which deposition takes place, two basic classes can be distinguished: a) those which were deposited on inundated lands (hydromorphic conditions) and subjected to decanting (hydrocinerites); and b) those which were deposited directly by volcanic winds or ashfall, generating breccia, tephra and tuff under atmogenetic conditions.

Both types were often re-worked later by wind and water which transformed them into heterogeneous deposits of eolocinerites, fanglomerates, colluvium and alluvium.

A description of the processes of soil genesis characteristic of the Basin of Mexico in general allows us to recognize phenomena which are specific to the Teotihuacan Valley.

Pedogenetic Regions. The Basin of Mexico is an eminently volcanic zone, and the composition and age of eruptive materials is a direct determinant of the genetic and morphological characteristics of the soils. Other factors such as slope gradient and drainage have been important elements of edaphic processes, which determine in large part the local changes affecting taxonomic soil orders.

It should be remembered as well that tepetates (hardpans) constitute around 65% of the foundation of superficial soils in the Basin and, as such, greatly influence their evolution.
Also, it can be inferred that most of the deposits suffered an immediate sequential transformation, consequence of the agents and processes resulting from eruptive activity, such as compaction, sealing and propilitization which are often manifested by hardening characteristic of the tepetates. The global effect of such processes is characterized by an intense alteration of the surface in which the material is scaled by a clay-like film, thus impeding the penetration of humidity and preserving the mass almost unchanged up to the present time.

In general, three pedogenetic regions are distinguishable in the Basin of Mexico (1). In each the genetic processes controlling soil evolution have suffered different environmental influences, and as such present a complex range of paleogenetic traits which substantially complicate attempts to explain profile morphology.

Atmogenetic and hydromorphic soil conditions reflect the effect of surface or subsurface water movement. Based on the distribution of profiles analyzed from the Teotihuacan Valley, an idealized transect constructed from Cerro Gordo, across the alluvial plain to the Patlachique Range shows three pedogenetic areas: two atmogenetic zones, (a) above 2300m, and (b) between 2300m and 2260m, and a hydrogenetic zone, (c) below 2260m, in the lowest part of the valley. The transitional atmogenetic area on the slope has suffered most of the erosive processes, the result of climatic change as well as tectonic movements.

The formation of atmogenetic types on the mountains depends greatly on the intensity of precipitation in relation to the resistance of the soil to runoff, determined by the degree of saturation, hydraulic conductivity and by the field capacity.

The formation of hydromorphic soils is due to the influence of topographic aspects (form and size of the catchment area) and climatic factors. By comparison the two types differ not only insofar as topography is concerned (plains vs. depressions), but also with respect to age of the surfaces; while atmogenetic accumulation is restricted to relatively old surfaces, hydromorphic accumulation can occur on more recent surfaces. While the atmogenetic type is autonomous - with the exception of wind transported accumulations which are never as abundant as their parental material - the hydromorphic type is dependent upon its own catchment area and it was frequently enriched by volcanic constituents rather than the products of erosion.

Vertic Cambisols with both superficial and deep duric phases originate on the surface. On the other hand, the absence of melanization under conditions of reduction by gleization is not clearly discernible, suggesting that the material was not situated below a permanent cover of water, nor were conditions adequate for the formation of a dense vegetation cover which would reduce the possibility of an the integration of organic material and its minimal mineralization.

Under more favorable paludal conditions, the mineralization of organic materials is not spectacular either. For example, Flores (2) reports maximum values below 1% in gleyic soils from Tlapacoya in the bed of Lake Chalco, suggesting a limited development of vegetation in the lake margins which still persists.

The majority of the soils in the Teotihuacan Valley can be grouped generically into two basic orders: Inceptisols, or incipient soils; and Entisols, or recent soils (1). The first includes soils which present slightly developed diagnostic horizons. The second is characterized by the virtual absence of genetic horizons, partly due to their limited advancement in their development and also to degradation or disappearance as a result of erosion. In both cases the influence of the parental material is clear insofar as the latter maintains a primary mineral structure.

Most Entisols are situated in higher or lower elevations in the valley, while Inceptisols are dominant on high, middle or lower slopes.

Other important orders occur on the middle and lower slopes and in depressions, such as Mollisols and Vertisols. Compared with Entisols and Inceptisols, the pedogenesis of these soils is more developed, with characteristics such as melanization in the case of Mollisols and haploidization in the case of Vertisols.
Detailed studies of Holocene pedogenesis are necessary for the identification and determination of the impact of agriculture and its influence on morphogenetic processes occurring during cold-warm/wet-dry climatic changes, or in the diagenesis of pyroclastic ashes, breccia and lava, and the conservation of biota. In any case, soils have suffered morphological and genetic modifications following burial by volcanic or erosive processes, in addition to exposure and erosion derived from natural and cultural morphogenetic processes. Such changes must have had a profound influence on the transformation of the natural and cultural landscape in the valley. However, too little is known at the moment to permit an evaluation of the role of human activities in these processes.

The beginning of the Holocene marked a change towards warmer more humid climates that provoked a rise in lake level in the lacustrine depression. At the same time processes of hydric erosion and soil leaching began in which materials were carried to lower elevations resulting in the destruction of soils in formation, arresting processes of concentration of calcium carbonates (CaCO₃), siderite Fe₂(CO₃)₃ and rhodochrosite. Furthermore, the intensive washing of higher elevations where the fusion of glaciers provoked the abundant flow of material, provoked the burial of large areas by heterogeneous colluvial and alluvial deposits which made up the final phases of the fluvioglacial deposits derived from volcanoclastic, glacial and acolic materials containing diverse minerals and with different degrees of weathering.

This process affected large areas of the upper slopes of the Basin of Mexico, including the sierras Ajusco, Las Cruces, Tepoztlan, Pachuca, Tezontlapan, Tepozan, Rio Frio, Patlachique, Calpulalpan and Nevada. The Mollisols were completely carried off, partially or completely exposing the tepetates derived from the tuffs belonging to the Lower Becerra, Tacubaya and Tarango geological formations. This material suffered a differential transformation as a result of the mixing of fresh components products of contemporary vulcanism, primary and secondary clay minerals, carbonates, feldspar, quartz, oxides and volcanic glasses formed a heterogeneous parental matrix. Alternating dry-cold and humid-warm periods occurred which provoked in situ transformations in which clays and iron oxides, carbonates and soluble silica solidified and hardened the subsoil, forming hardpans and fragipans. Superficial horizons were covered by new deposits of pyroclastic materials in which deposits of caliche were segregated.

All of these polygenetic materials determine most of the pedogenetic characteristics and variability on a local level such as the Teotihuacan Valley. Their morphology shows evidence for abrupt changes provoked by discontinuous processes of edaphic formation, such as translocation, leaching, enrichment and hardening, all of which took place at different rates of intensity in different areas, giving origin to complex soils which are generally classified as Inceptisols, Entisols and Mollisols.

Soils Derived from Volcanic Tuff. These sediments are generally loose when dry and friable when wet. Silt and fine sand content is high (50-70%); they are easily compressed. Characteristic colors range from pale to yellowish brown, 10YR7/3 to 6/8 on the Munsell scale. They originate from air laid tuff/ashfall deposits, although authors such as Heine and Schoenhals (1973) attribute the origin of similar materials in the Valley of Puebla to wind action. We believe that the material acquired its characteristics during and not following the eruptive emission of pyroclasts, after which the silt and loose fine sand were reworked by deflation. In any case they recognize that the mineral particles are only minimally spheroid, suggesting that they were transported over short distances with little intensity.

The material presents a relative abundance of phytoliths, generated from roots that only prosper in pulverized material. Furthermore, based on their similarity to loess, the content of iron hydroxides and accumulation of laminates or veins of carbonates suggest subhumid climatic conditions.

Sedimentological Analysis. Sedimentological analyses of these materials show certain characteristics associated with wind erosion. Sedimentological curves of soils derived from materials deposited by wind action demonstrate a well-defined classification of the material, especially particles falling between 50 and 500 microns in diameter. This suggests a genetic relation in the formation of the deposit, defined essentially by the transportation of particles by saltation, the most important wind-related action, in which particles between 15 a 350 microns (average 150-200) are moved, in other words those which are sufficiently light to
be lifted but too large to remain in suspension. In general the low proportion of particles above 500 microns indicates the inability of the wind to transport them. In addition, the low proportion of particles below 50 microns suggests the predominance of uni-directional winds that incorporate the small amount of material in suspension within the deposit during the depositional process.

Based on the previous description, we observe that the horizons represented by the curves from profiles No. 5 and No. 7 show four groups of particles of which the two central predominate with percentages from 10 to 80%. These correspond to the material transported by saltation, which demonstrate a high level of energy based on the accentuated form of the central part of the curves. This profile is located in a uni-directional "wind corridor" in which suspended particles are incorporated into the deposit during its formation.

Mineral Composition. The mineral fraction of the soil conserves its original mineralogical heritage of tuff, andesites and riolites. Mineral composition varies according to the time and type of emission. Most important for the formation of soils is the volcanic glass content, which is the most susceptible to weathering. Devitrification and generation of silicic acid affects the subsoil forming a hard material referred to as tepetate (hardpan) (4).

Sediments Derived from Ash Flows. Ash flows produce deposits characterized by clear, white or gray riolitic, riodacitic and andesitic sands. These are abundant in the Sierras of Rio Frio, Cerro Colorado and Cerro Gordo. They present a high quartz content in the middle sand fraction. 14C dates place these deposits between 22,335 + 1562 BP and 40,000 + 2055 BP (5) in the Sierra de Rio Frio (Telapon) south of the Teotihuacan Valley. Under conditions of slight humification and weathering, these materials form soils of the orders Andosol, Inceptisol, and Mollisol.

Sedimentological Analysis. Curves representing deposits formed by ash flow (fine particles falling through the atmosphere) do not present a clear classification of the material. The curves tend towards a logarithmic form where the heavy material is heterometric up to intermediate sizes followed by a more homogeneous form in the part corresponding to finer material. Thus the curves show three sections, from poorly to well-defined: the first (200-500 microns) clearly shows the separation corresponding to the initial fall of heavier material. In the second (50-500 microns) a mixed depositional process is registered, which is why a notable change in particle size occurs, probably the result of a violent deposition of fanglomerates. The third reflects a second classification of the material by decantation, of heterometric medium and fine silt. Finally, a fourth section (not shown) includes very fine material less than 2 microns. The relative quantity of this particle size may be indicative of some form of deflation. Typical profiles showing these characteristics are indicated in Fig. 1.

Given the dispersion of these sites in the valley and their similarity insofar as the characteristics typical of formation by deposition of material decanted by the atmosphere, it is possible to conclude that volcanic activity has been the main geomorphic process during long periods under cold-dry climatic conditions. This conclusion is based on the fact that the materials forming these deposits are not re-worked, nor do they show much evidence of weathering, as would be expected if conditions had been more humid and warmer.

Mud Flows and Fanglomerates. These are comprised of deposits of heterometric gravels, rocks and boulders, packed together in a matrix of fine sandy-silt tuff. These materials were transported by torrential mud flows whose origin is unclear although they probably derived from intense precipitation associated with the volcanic eruption itself. An example of this process is the torrential mudflows which occurred during and after the eruption of El Chichonal in 1982. In the Teotihuacan Valley, volcanic activity provoked fluid mudflows that conveyed fine silty clays which consolidated the heavier clastic materials.

Sedimentological Analysis. The curves obtained from the analysis of these materials present 4 to 6 different groups of particle size: 2 or 3 with medium sized particles (50 to 500 microns) and the rest encompassing the finer particles (2-50 microns). The action of wind flow is evident here, possibly related to base surge winds during volcanic eruption, a situation combining the influence of the wind at the time of deposition.
together with the volcanic event that caused it, with a continual process of hydric and wind-related action that modify the deposit over time.

Profiles 11 and 12 (Figure 2) show evidence for the liberation of large amounts of energy at the time of the event and, consequently, the deposition of mid-sized particles is significant. In both pits the percentage of this material is around 60% while finer particles comprise around 25%, indicating a moderate to well-classified structure.

**Caliches**

Caliches represent laminar deposits or veins of different thickness, extension and continuity. According to some authors, they represent an edaphic response to humid environmental conditions. Hilger (6) indicates that in Btv horizons of Cambisols (clay soils) in the Valley of Puebla the thickness and continuity of laminas or veins of caliche increase with depth. He explains this observation as a product of CaCO3 precipitation, associated with fluctuations of the phreatic level. However, it is more likely that the formation of caliche is due to a remineralization of the alkaline minerals at the time of the volcanic deposit (propilitization) or also to dissolutions from posterior hydrothermal action and finally to leaching, during which the in situ mineralized calcareous silt crusts located within deposits of tuff or other volcanic products, including hydrothermal deposits, dissolve more easily.

Crusts, laminas and veins develop more commonly in mid- or lower slopes at 2260-2300m a.s.l. suggesting that an intense lateral hypodermic washing process occurred on the higher slopes, transporting and depositing large amounts of CaCO3 for the length of the slope and thus creating interformational laminas or veins.

G. Werner (7) cites Sabelberg and Rhodenburg to suggest that calcareous material may originate as a secondary deposit within volcanic tuff, later appearing on the surface as a consequence of erosion where it is recovered and re-worked by morphogenetic or edafogenetic processes.

It should also be noted that accumulation of primary caliches can occur as a result of propilitization and hydrothermalism in pyroclastic materials, particularly immediately following their deposition and consolidation. Proof of this is found in deep deposits where caliches are found in the form of thick veins developing in an upward direction.

All of the foregoing observations are contrary to the classic concept that caliches form during warm-dry climatic conditions (8), forming calcareous crusts when the average temperature falls between a minimum of 19° and a maximum of 24-30° with precipitation between 500 and 1250 mm.

**Holocene Deposits**

Fluvial and marginal lacustrine deposits during the Holocene originated from diluvial, proluvial and alluvial processes which mixed with volcanoclastic materials, including tuff, ash, breccia, tuff sediments, agglomerates, pumice, scoria, etc. All of these materials accumulate in different forms along the middle and lower slopes creating a complex stratigraphic situation. In particular the sediments of tuff which has been re-worked by water and wind remain as superficial fill in plains and depressions, where they mix and interdigitate with sediments from eolocineritic pyroclastic flows from middle and lower slopes and from decanted hidrocineritic materials in palustrine and lacustrine beds.

**Sedimentological analysis.** The typical curve for materials deposited by water decantation presents a series of breaks which give it a step-like appearance (Figure 3) where the predominant textural groups and their physical-chemical characteristics are well defined. The flow of materials such as coarse and medium sand, are deposited first, followed by stages of relaxed activity and new flows of fine material (such as coarse, medium and fine silt), and the general tendency for the finest material (silt and clay) in suspension to be deposited by decantation at the end is clearly observable. Profiles No. 9 and No. 14 demonstrate this pattern. In a profile of 3m observed on a Q4 terrace in Teotihuacan a sequence was established as represented in Figure 4.
Figure 2

CURVAS GRANULOMETRICAS
Perfil 92-11 "Talud S. de Patlachique"

CURVAS GRANULOMETRICAS
Perfil 92-12 "Rancho Tlajinga"
CURVAS GRANULOMETRICAS

Perfil 92-9 "Chinampas"

CURVAS GRANULOMETRICAS

Perfil 92-14 "Sn. Lorenzo Tlalmimilolpan"

Figure 3

355
Figure 4
An intense melanization process or marked conditions of reduction by gleyization are not clearly observable, suggesting that the material was not permanently covered by water but was always highly saturated under environmental conditions appropriate for the formation of a dense vegetation cover.

The aforementioned pattern serves as a model with which to compare the predominant environmental conditions during the last phases of the Holocene, which is basically cold and dry. Thus the dominant environmental conditions favored morphogenetic rather than pedogenetic processes, manifest in mineral materials showing little evolution, and corroborated by a preponderance of soils that clearly maintain their geological-geomorphological features.

Conclusion. Pyroclastic materials, particularly from ashfalls, are broadly distributed within the Basin of Mexico, including the Teotihuacan Valley. Although Pleistocene deposits are extensive and profound, large areas have been deeply interred below one or more Holocene volcanic ash strata. In some areas of superficial Holocene deposits, Pleistocene deposits are still visible within the soil profiles where they occur as cyclic profiles of type IIA, IIB, IIBAB, IIC, or also BA, BB or BC.

Based on the 14C age of weathered pyroclastic deposits in the Teotihuacan Valley, the following sequence of soil horizons is proposed:

<table>
<thead>
<tr>
<th>PERIOD OF INTEMPERIZATION</th>
<th>HORIZON SEQUENCE</th>
</tr>
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<tbody>
<tr>
<td>Less than 1000 years</td>
<td>C or (A)/C</td>
</tr>
<tr>
<td>1000 - 2500 years</td>
<td>(A)/C, A/C, A(B)C</td>
</tr>
<tr>
<td>2500 - 3000 years</td>
<td>A/(B)/C</td>
</tr>
<tr>
<td>More than 3000 years</td>
<td>A/B/C</td>
</tr>
</tbody>
</table>

Atmogenetic and hydromorphic soils reflect the effect of surface or subsurface water movement, which differs fundamentally in geomorphic position, geochemical accumulations and ecological properties, and can be differentiated with reference to climate and changes in their base level. Based on the distribution of profiles analyzed from the Teotihuacan region, an idealized transect constructed from higher elevations to the alluvial plain depicts three pedogenetic areas: two atmogenetic zones, (a) above 2300m a.s.l. and (b) between 2300 and 2260m a.s.l.; and a hydrogenetic zone (c) below 2260m a.s.l. occupying the lowest part of the valley.

The transitional zone on the slope has suffered most from erosion resulting from natural causes, such as vulcanism, tectonic movements, and temperature changes, and from human activities like agriculture and forest utilization. Although the latter has not been adequately studied, most authors believe that agriculture and related deforestation provoked environmental changes that had drastic consequences for Teotihuacan civilization.

In the Teotihuacan Valley, the soils are predominantly Inceptisols, Entisols and Mollisols. All have suffered morphological and genetic modifications resulting from burial as a consequence of volcanic or erosive processes, as well as the effects of exposure and erosion caused by natural and cultural morphogenetic processes. The natural and cultural landscape of the Teotihuacan region must have been greatly affected by such changes, but in fact very little evidence is available which allows a clear distinction between the role of human activities and natural events.

Some authors have argued that agricultural expansion and consequent deforestation of the surrounding hills during the splendor of Teotihuacan provoked significant erosion. However, pollen and phytolith evidence obtained from partially dated soil profiles in the region suggests that the pine-oak forest was still present to some degree during the height of the urban center. That might indicate that agricultural techniques were not as destructive as some have suggested. In any case, the size of the urban population together with that of surrounding rural communities in the valley far surpassed the potential agricultural productivity of the region, making it clear that additional subsistence products must have been obtained from elsewhere in the...
Basin of Mexico and neighboring regions. In fact, charcoal and lime production and, especially, the use of wood as fuel for ceramic manufacturing may have been much more destructive. In this case the forest cover would have been devastated, promoting severe erosion in addition to microclimatic variation.

A temporal framework for the interpretation of soil formation processes in the Teotihuacan Valley is necessary, in order to differentiate natural features (volcanic and tectonic influences, climatic change) from the impact of human activities. The study of soil profiles in conjunction with stratigraphic pollen and phytolith assemblages which provide evidence for climatic conditions will allow the development of a model which seeks to explain how the population modified the surrounding landscape, and how such activities may have been related to the fall of Teotihuacan and its eventual abandonment in the mid-eighth century AD.

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Sixteenth Century Nahua Soil Classes and Rural Settlement in Tepetlaoztoc

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**Introduction.** Five hundred years have passed since the encounter between Europeans and the native cultures of Mesoamerica. During the interim, much has been learned of the functioning and achievements of Mesoamerican civilizations. Certain domains, such as art, religion, calendrics, ethnic history, linguistics, and writing received early and sustained investigation. Other realms, such as native sciences, mathematics, and technology are relatively recent themes of scholarly inquiry.

Because support for Mesoamerican high civilization necessitated a highly productive agrarian sector, indigenous environmental knowledge presumably was systematic and complex, particularly in the area of agriculture. In the realm of soils, the existence and attributes of a native soil classification can be inferred from two, unique Nahuatl codices from Tepetlaoztoc in the eastern Basin of Mexico. In addition to soil types, native scribes recorded other attributes of agricultural fields in these manuscripts, so the role that soils played in rural settlement structure can be assessed for the Contact period.

**The Data.** The *Codex Vergara* (Ms. Mex. 37-39, Bibliothèque Nationale de Paris) and the *Códice de Santa Maria Asunción* (Ms. 1497 bis., Biblioteca Nacional de México) are pictorial manuscripts drawn ca. 1543-1544. The latter (hereafter, the *Asunción*) is analyzed here, since it provides the largest data corpus. The 80 folios of the *Asunción* depict agricultural parcels pertaining to each of 186 commoner households in 11 named localities in an area situated today in the modern Tepetlaoztoc Barrio of Asunción (analysis excludes one unnamed locality)(Fig. 1). Generally each household’s landholdings are drawn twice, once in a *milcocoli* convention in which soil type and perimeter dimensions are shown, and again in a *tlahuelmatli* convention in which field area is indicated along with a repetition of soil type (Fig. 2)(1, 2).

**Figure 1**

Location of Tepetlaoztoc in the eastern Basin of Mexico 8 km northeast of Texcoco (map adapted from [3]).
Although the number of agricultural fields in each record should be identical, missing data from one locality and several household discrepancies result in a total of 593 milcocoli fields but only 519 tlahuelmatli fields.

Figure 2

Agricultural parcels of Martin Quemach drawn A in the tlahuelmatli convention with area measurement and soil type and B in the milcocoli convention showing perimeter dimensions and soil type. Note the “house” calli glyph on the upper margin of the first parcel indicating a house garden. (Códice de Santa María Asuncion, f.20v and 10r).

Nahua Soil Taxonomy in Tepetlaoztoc. Soil type of each field is indicated glyphically in the central portion of the field drawings. Soil glyphs are composed of a limited number of graphic elements: dots, stone, mat, spine perforator, green maize stalk, eye, water, and hill. Most soil glyphs are combinations of two or three of these elements. Detailed differences in shapes and size of stones, angles of spines, position of dots, and the like create approximately 104 variants. For the area of approximately 200 ha recorded in the codex, campesinos today recognize only three generic-level soils and one non-soil taxon; the technical classification yields three soil types (4). Thus, it is highly unlikely that each of the 104 variants recorded in the Asunción represented a distinct soil. Comparison of the glyphs of each field as they appear in the two land registers leads to the same conclusion. Nevertheless, many of the variants may represent attempts to show one or more of the defining criteria of the class, soil intergrades, or they may record descriptive phrases labeling some outstanding feature of the soil rather than the soil type lexeme.

Based on a lexical reading of grapheme combinations, probable glyphic meanings derived from other indigenous manuscripts, and contemporary Nahua and Tepetlaoztoc campesino soil nomenclature (5), the variants group into 19 taxa at three taxonomic levels: seven generic, nine specific, and three varietal. Examples of glyphic variants and partitioning of three generic-level taxa are shown in
Figures 3-5. Inferring from Nahuatl oral descriptions of soils compiled in the sixteenth century Florentine Codex (6) and from attributes of the soils in Tepetlaoztoc today, alluvium (atoctli), clay (tezoquitl), yellow (tlalcoztli), and sandy (xalalli) soils were inherently the most productive soils whereas tepetate (tepetatlalli), hillslope (tlaixtli), and stony (tetlalli) soils were the least productive (7). Generic-level taxa glyphs are shown in Figure 6.

Figure 3

Taxonomic relations of the Nahua soil class atoctli, alluvium.

A, generic-level alluvium

B, species-level clayey alluvium

C, species-level sandy alluvium

D, species-level gravelly alluvium

E, varietal-level sandy, gravelly alluvium

Figure 4

Taxonomic relations of the Nahua soil class tezoquitl, clay.

A, generic-level clay

B, species-level sandy clay

C, species-level gravelly clay
Figure 5

Taxonomic relations of the Nahua soil class tepetatlalli, tepetate,

A, generic-level tepetate

B, species-level sandy tepetate

C, species-level clayey tepetate

D, varietal-level sandy clayey tepetate

Figure 6

Generic level soil classes in Santa Maria Asuncion.

A, atoctli alluvium

B, tezoquitl clay

C, tlalcoztli yellow soil

D, xalalli sandy soil

E, tepetatlalli tepetate

F, tlaixtli hillslope soil

G, tetlalli stony soil
Soils and Settlement Structure. In addition to soil types, some agricultural fields have a “house” glyph depicted on the upper margin (See Fig. 2). Usually each household has one such field listed first next to the name of the household head. The “house” glyph quite likely reads “Here is the house garden (calmíl; pl. calmílli) of household x.” The indigenous, two-fold classification of fields, those with “house” glyphs and those without, reflects the system of maguey agriculture that prevailed in drier parts of the piedmont, many aspects of which are still observable today. House gardens, one of two elements in the system, are typically found adjacent to residences and are managed intensively. Milpas, the second element, are planted away from the residences and are managed less intensively. In the case of localities recorded in the Asunción, all fields were within thirty minutes walking distance, so that the parcels fit the criterion of infields as defined by Killion (8).

The data suggest that location of house gardens was conditioned by soil type. In three-quarters of the communities (eight of 11), most calmílli parcels were located on fertile soil, including alluvium, clayey, yellow, and sandy soils (Table 1). The adjacent residential structures as well would have

<table>
<thead>
<tr>
<th>Locality</th>
<th>Num. of Calmílli</th>
<th>Total Area</th>
<th>Ave. Area</th>
<th>Num. of Calmílli</th>
<th>Total Area</th>
<th>Ave. Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tlancomolco</td>
<td>23</td>
<td>13.28</td>
<td>.5772</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Antecontla</td>
<td>14</td>
<td>6.67</td>
<td>.4764</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Chiauhuenco</td>
<td>7</td>
<td>3.97</td>
<td>.5674</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Chiauhtlan</td>
<td>8</td>
<td>4.13</td>
<td>.5161</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Conzolán</td>
<td>8</td>
<td>4.54</td>
<td>.5673</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Tlantozcac</td>
<td>9</td>
<td>5.34</td>
<td>.5932</td>
<td>2</td>
<td>.87</td>
<td>.4343</td>
</tr>
<tr>
<td>Cuitlahuac</td>
<td>4</td>
<td>2.34</td>
<td>.5856</td>
<td>1</td>
<td>.22</td>
<td>.2237</td>
</tr>
<tr>
<td>Cuauhtepuztitla</td>
<td>38</td>
<td>12.60</td>
<td>.3317</td>
<td>26</td>
<td>8.23</td>
<td>.3163</td>
</tr>
<tr>
<td>Tlaltecahuacan</td>
<td>3</td>
<td>1.86</td>
<td>.6214</td>
<td>2</td>
<td>.85</td>
<td>.4243</td>
</tr>
<tr>
<td>Zapotlan</td>
<td>1</td>
<td>.26</td>
<td>.2600</td>
<td>1</td>
<td>.97</td>
<td>.9693</td>
</tr>
<tr>
<td>Tlanchiuhca</td>
<td>6</td>
<td>4.47</td>
<td>.7451</td>
<td>11</td>
<td>5.72</td>
<td>.5195</td>
</tr>
<tr>
<td>Total</td>
<td>121</td>
<td>59.46</td>
<td>.4682</td>
<td>43</td>
<td>16.86</td>
<td>.3921</td>
</tr>
</tbody>
</table>

1 includes irrigated alluvium; yellow, clay, and sandy soils
2 includes hill slope, tepetates, and stony soils
3 derived from milcocoli record; tlahuelmatli record shows 7 calmílli in 5.92 ha.
been sited on the most productive land available, rather than on the least productive. Cases in which	house gardens were located on poor soils, such as tepetate or stony soil, may be explained by
examining individual household landholdings. In most instances, all lands of these households were
of poor quality. For example, in Tlanchiuheca no better land was available to eight out of the 11
households whose calmilli were on poor land. No better land was available to 18 out of 26 households
(70 percent) in Cuauhtepuztitla, and none to the household in Zapotlan. Only a total of five
households in Tlatecahuacan, Tlantozac, and Cuilahuac are exceptions to the general pattern.
Given a choice, therefore, houses and house gardens were located on the most productive soils.

Soils and Parcel Size. In addition to affecting the siting of house gardens and adjacent residences,
might soil variations have played a role in structuring the size of individual fields? If households
were to share equally in food production capacity, as an egalitarian view of commoner society holds,
then fields of fertile soil should have been smaller in area than fields of poorer quality soils. If true,
then village field patterns can be predicted. Where good soils prevailed, a greater number of field
parcels would be expected. Parcels of poor soils would have been larger and fewer in number. Since
field patterns are difficult to reconstruct archaeologically, demonstration of this relationship would
aid interpretation of archaeological remains.

In this case study of Tepetlaoztoc, the number and size of fields do not systematically vary with soil
type. For example, contrary to an expected pattern, the mean area of fields of tepetate, a poor soil,
was similar to the mean area of fields of the best soil available (atoctli). In fact, the mean areas of
all poor soil parcels was less than those of the good soil fields (Table 2). It is true, however, that at
the high end of the range in field area, the largest fields recorded are those with the poorest soils.
Nevertheless, clearly soil quality is not a good predictor of land fragmentation within commoner
villages and hamlets. Apparently those responsible for land distribution within the tlaxilacalli did
not adjust parcel size for soil type. Historical, demographic and social processes must account for
field size and number rather than soil quality.

Discussion and Conclusions. Sixteenth century textual accounts of Nahua culture in highland
Mexico document the existence of indigenous soil classification. The pictorial records from
Tepetlaoztoc add new dimensions to our understanding of native culture, for they illustrate the
linguistic complexity of the Nahua soils domain, and especially striking, its written expression in
hieroglyphs. Similar records are unknown for other cultures in the New World, and I am aware of
only one analog for non-Western written soils records, that from China in the fifth century B.C. (9).

The hieroglyphic records attest to the systemic and linguistic stability of the classification system
used by the Acolhua-Nahua of the eastern Basin of Mexico. Interpretation of the hieroglyphs
presented here suggests that the Nahua classification was taxonomically structured and included at
least 19 soil taxa. Of the seven generic-level taxa, four refer to fertile soils and three to poor soils.
Because the Nahua painters recorded not only soil types but also linear and areal dimensions of
agricultural fields, the records provide data useful in interpretation of archaeological remains of these
communities, most of which were abandoned and disappeared by the mid-sixteenth century.
The settlement pattern of the 11 hamlets and villages comprising the tlaxilacalli of Santa María
Asunción was conditioned by soil types of the territory. Good soils rather than poor ones were
Table 2. Area of Parcels by Soil Class in Santa María Asunción (tlahuelmatli record, in hectares)

<table>
<thead>
<tr>
<th>Soil Class</th>
<th>Number of Parcels</th>
<th>Total Area in Tlaxilacalli</th>
<th>Mean Area per Parcel</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good Soils</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>alluvium</td>
<td>29</td>
<td>9.22</td>
<td>.3178</td>
<td>.023-1.052</td>
</tr>
<tr>
<td>clays</td>
<td>132</td>
<td>50.40</td>
<td>.3818</td>
<td>.020-1.098</td>
</tr>
<tr>
<td>yellow</td>
<td>186</td>
<td>61.50</td>
<td>.3307</td>
<td>.003-1.092</td>
</tr>
<tr>
<td>sandy</td>
<td>65</td>
<td>21.86</td>
<td>.3363</td>
<td>.070-0.980</td>
</tr>
<tr>
<td>Poor Soils</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>tepetates</td>
<td>256</td>
<td>82.59</td>
<td>.3226</td>
<td>.031-1.625</td>
</tr>
<tr>
<td>hillslope</td>
<td>63</td>
<td>14.12</td>
<td>.2242</td>
<td>.039-1.190</td>
</tr>
<tr>
<td>stony</td>
<td>149</td>
<td>34.90</td>
<td>.2342</td>
<td>.028-1.057</td>
</tr>
</tbody>
</table>

Data include parcels from a locality unnamed in the codex.

preferred for siting residences and adjacent housegardens. Soil types did not determine size of agricultural parcels, however. Small parcels characterize both poor and good soils, and mean parcel size, in fact, was smaller for poor than for good soils. The largest fields, on the other hand, occupied the poorest land. For the archaeologist, soil type may help predict location of domestic architecture and household refuse in the zone, but soil type is of lesser value in the search for field boundaries upon which to reconstruct the agricultural landscape.

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Climate induced change of Third Millenium B.C. soil landscapes in Northern Mesopotamia


Introduction. Retrieval of archaeological and soil-stratigraphic data at the site of Tell Leilan recently demonstrated that the 2200 B.C. collapse of the Third Millenium B.C. rain-fed civilization of northern Mesopotamia on the Habur plains of Syria coincided with a marked increase in aridity and wind circulation, subsequent to a volcanic event.¹ These results refresh the old problem of the almost synchronous, late third millenium, region-wide disturbances of South-West Asia that have been alternatively related to invasion, earthquakes, drought or still larger disasters. The aim of this paper is to examine the soil-stratigraphic record of the 2200 B.C. abrupt climatic change that induced a severe landscape deterioration on the upper Khabur plains.

Materials and Methods. The upper Khabur plains has an arid continental Mediterranean climate, with a North-South 400-200 mm annual rainfall gradient. An active wind circulation considerably increases the hydric deficit in summer. The region is formed of a large number of gently undulated valleys, flooded by ephemeral streams and filled by a few m thick Holocene proluvial, calcareous rich, loam. The large number of archaeological sites (tells) preferentially distributed along the valleys indicate that the region has been intensively occupied from the Seventh to the Second Millenium B.C. The present study reports results mainly obtained from soil-stratigraphic survey in Tell Leilan region (Wadi Jarrah basin) and Kachkachok/Abu Hgeira/Abu Fur region (Wadi Rijlet Aaouji basin, 60 km to the West). Soil transects were studied along long trenches dug from the foot of archaeological sites across to the nearby active flood plain in order to compare buried soils below well dated occupation layers with surface soils. Soil stratigraphic data were also obtained from various contexts (ditch/earth wall fortification, residential deposits) in the large Third Millenium B.C. town of Tell Leilan in order to examine the evolution of environmental conditions from the period of mature state control (Akkadian imperialism, 2300-2200 B.C.) to the collapse of the Akkadian domination with regional desertion (occupation Habur hiatus 1: 2200-1900 B.C.) before reoccupation of the site at 1900 B.C. Undisturbed soil samples for micromorphological examination and bulk samples for chemical and mineralogical characterization were systematically collected from the successive horizons of buried and surface soils identified in the field and from the well defined stratum within Tell Leilan archaeological sequence that represents the occupation Habur hiatus 1.

Results and Discussion. Soil-landscapes exploited for the Akkad empire agricultural production had a good structural stability characterized by an intense biological reworking during the wet season that reduced the loss of soil by hydric and aeolian erosion. The occurrence of moderately expressed calcic horizons with secondary carbonates regularly distributed throughout the all profile, with minor evidence of leaching, indicate slow percolation under a Ustic moisture regime.
The seasonal contrast between the hot-dry summer and the cool-wet winter was then broadly similar to the present, although larger calcitic nodules suggest slightly warmer temperatures. This was followed by the deterioration of soil-landscapes with three distinct phases that is well documented at Tell Leilan by the micromorphology of the Habur hiatus stratum, and could be correlated with the Abu Hgeira soil record.

The first phase coincided with the accumulation of aeolian sand-sized pellets, with high amount of volcanic glass, that derived from erosion of the surrounding soil cover and long distance aeolian transport. Intense biological reworking suggests the maintenance of a seasonal contrast similar to the one prior to the tephra fall. Difference between the tephra fall at Tell Leilan (weakly altered fine silt-sized particles) and Abu Hgeira (well sorted, well rounded, fresh fine sands) indicate differential regional dispersion of the tephra. Major and trace element composition of the tephra suggest they derive from a calc-alkaline volcanic center of the Anatolian-Caucasian region.

During the second phase, deposition of calcareous silt with finely fragmented phytoliths, volcanic particles and gypsum crystals indicates a severe increase of aeolian deflation and maintenance of high amount of dust in the atmosphere due to a regional air warming. Abundance of slaking crusts fragmented by dessication, limited biological activity and absence of pedogenic carbonate all mark the establishment of an aridic soil moisture regime with low rainfall, high evaporation and violent runoff induced by occasional heavy rainstorms at the bare soil surface. Comparison with modern circulation pattern suggests that the attenuated seasonality and extended aridity during this phase are the local manifestation of a weakened cyclogenesis in Mediterranean and Near Eastern regions.

The third phase is represented by the accumulation of aeolian sand-sized pellets of locally derived calcareous soils with abundant highly weathered volcanic particles. Occurrence of diffuse pedogenic carbonates, partial reworking by biological activity, coarse textural features indicate a progressive rainfall increase simultaneously to the reduction of wind turbulences. Identification throughout the entire region of the wind-related deposit suggests that an undulating aeolian blanket of variable thickness, depending upon local moisture conditions, partly covered the Habur plains. Simultaneous deposition of gravel beds in the valleys indicate that slopes were frequently dissected by torrential wash and that soil-landscapes remained highly sensitive to erosional degradation. Restoration of a good structural stability of the soils that were formed while the region became reoccupied (after 1900 B.C.), with marked increase in biological activity, development of calcic horizons, minor evidence of hydric and aeolian erosion mark the progressive reestablishment of climatic conditions similar to the present ones.

The 2200-1900 B.C. abrupt climate change thus induced a considerable degradation of land-use conditions for some decades that was concluded to have played a pivotal role in the disruption of the imperialized agricultural production controled by the Akkadian state power. Although the soil-landscape data provided are restricted to a region with specific climatic conditions, we suggest that the magnitude and the trend of the changes observed in soil dynamics should imply a significant modification of climatic boundary conditions of large scale impact. This conclusion raises the question of the causative linkage between the desertion of the upper Habur plains synchronous with the collapse of the Akkadian empire, the simultaneous population movements and increases in southern Mesopotamia and similar large-scale "collapse" phenomena that simultaneously affected the Agean, Egypt, Palestine and Indus.

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Soil and Archaeological Research

Gong Zi-Tong, Liu Liang-Wu. Institute of Soil Science, Academia Sinica

ABSTRACT

China has a long history, a distant source and a long stream. There are an enormous amount of the remains unearthed at the sites excavated in our country. Paleosols are often used as stratigraphic unit for archaeology, and used for recovering environment then. On the contrary, the distribution status of the sites and their remains uncovered also show movement of cultivated land, soil characteristics and soil evolution. Therefore, soils, especially paleosols are closely related to archaeology.

Zhoukoudian group of Feking Man Site includes 13 layers deposite with a thickness of 40 m, dating at 0.7—0.23 Ma BP. The buried soils at the site are widespread, consisting of argillic horizon and carbonate horizon or calcareous nodule horizon, in general. The characteristics of the buried soils within loess-like deposit are between cinnamon soils and yellow cinnamon soils, according to particle size, silica-alumina ratio of clay fraction, clay mineral and micromorphological analysis. It indicates that the climate of Feking Man's time was warmer and humider than that of North China today, but showed a tendency to become a little drier from middle to late Pleistocene.

Homutu Site contains four layers of cultural deposite super-imposed one upon the other. It is in the fourth
layer that mixed material accumulated by rice cultivated, and its stalk, leaves and husk, with average thickness of 40 cm, are found. It suggests that embryonic paddy soils in Yangtze basin formed about 7000 years ago. In addition, a number of bone ssu-spades also presented in the layer. And a large area of peat horizon underlying topsoil have been reserved near the site. From the above mentioned, it can be inferred that the farmland around the site was low-swamp, and presence of bone ssu-spades was closely related to reclaiming and draining swamp. But those soils today have become meadow paddy soils, of which peat horizon already is relict feature.

Bonpo Site occurs in terrace II, covering an area of about 50000 m². Dense sites show the movement status of cultivated land at that time. It is estimated that the land was cultivated for 1-3 years, then must lie fallow for 7-8 years due to decrease of soil fertility. ^14C dating of the layers at the site proves the movement of living area then with cultivated land. Therefore, Bonpo agriculture belonged to the moving stage of agriculture.
An International Framework for Evaluating Sustainable Land Management

Convener: Julian Dumanski (Canada)
Co-convener: Enrique Ojeda Trejo (Mexico)

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Rising populations competing for limited land resources have focused attention on the need for increasing food production, while preserving the resource base and decreasing land degradation. This has prompted discussion on the sustainability of current land management systems.

Sustainable land management (SLM) has emerged as a global issue in securing enhanced productivity and performance of land resources, consistent with minimising adverse effects on the environment. To achieve this there is an urgent need to develop and implement appropriate technologies and policies for more effective land management which are sustainable over time. Significantly, SLM was high on the priority list of AGENDA 21 of the United Nations Conference on the Environment and Development, held in Rio de Janeiro, June, 1992. Also, the Consultative Group on International Agricultural Research (CGIAR) reported recently that the CG must address sustainable land use management as a matter of priority in the coming years.

Decisions on whether or not a particular land use is sustainable in a given environment over a stated period of time can potentially be assessed using a framework approach. With this in mind, a number of international agencies, led by the International Board for Soil Research and Management (IBSRAM), have collaborated to host two international workshops on sustainable land management. The first was in Chiang Rai, Thailand, in 1991, which resulted in the formation of an international working group to further the development of the framework, and the second was in Lethbridge, Canada, in 1993, which focused on indicators to be used for evaluation of SLM.

This symposium brings together the major developments on SLM to this point in time. The symposium includes papers on the major issues of sustainability and sustainable agriculture, the proposed structure and a critique of the framework, a case study application of the framework, development of indicators for SLM, and some comments on future directions. Discussions evolving from this symposium will be used by the international working group as guidance for future initiatives.

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Symposium Convenors
Progress towards an International Framework for Evaluating Sustainable Land Management (FESLM)

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Introduction. Efforts to develop a Framework for Evaluating Sustainable Land Management (FESLM) have arisen out of concern for the foreseeable consequences of population growth and natural resource degradation. The prime mover in this initiative is the International Board for Soil Research and Development (IBSRAM) with strong support from FAO, ISSS, IFDC, ICRAF, TSBF, Soil Management CRSP of the United States, Agriculture Canada and more recently, the World Bank. Aid Agencies from Australia, Canada, Switzerland, Germany and the USA have also lent considerable support.

In September 1991, at Chiang Rai, Thailand, IBSRAM organized an international conference on Evaluating Sustainability. From this, a Working Party was created and specifically charged to develop a Framework. Since then, the Working Party, which has international membership, has met three times: in Nairobi and in Washington in 1992, and in Lethbridge, Canada in June 1993. Work on the drafting of an explanatory text of the Framework has proceeded between these meetings. Although the Framework is still far from complete, the time has come to attract interest in its aims, and to encourage contributions towards its improvement from as wide an audience as possible.

In industrialized countries of the North, with their own land management problems of overproduction, resource degradation and 'set aside', it is not easy to appreciate global problems associated with the need to increase food production due to population growth. However, discussions and publicity surrounding the UNCED Conference in Rio, two years ago, has sharpened awareness of the extent to which population growth is increasing global demand for food, fibre and other products of the land (IDRC, 1992). The human population grew by 91 million last year, and at current growth rates, today's population will double by 2030 (Worldwatch Institute, 1993). Such statistics have led to the question of whether the human species is not a suicidal success (Tickell, 1993).

At the same time, there is increased recognition that the earth's land resources are finite. In the past, new production needs could very often be met by opening up more land, but today, from a global viewpoint, few untouched fertile areas remain. By the end of the century, almost all increased production will come from land already being cultivated.

'Sustainability' is a measure of the likelihood that a particular form of land use will remain well suited to its site through a defined future period. Good land management has always been seen to be desirable; now it must be seen to be critical to the survival of significant numbers of mankind. Production must be sustained, indeed, increased, but so too must the essential qual-
ties of the land resources. 'Sustainability' needs to replace 'suitability' as a measure of the fitness of a particular form of land use management.

The Approach. 'Sustainable land management', in the context of the FESLM, has been defined as follows (Dumanski and Smyth, 1994):

"Sustainable land management combines technologies, policies and activities aimed at integrating socioeconomic principles with environmental concerns so as to simultaneously:

- maintain or enhance production/services (Productivity)
- reduce the level of production risk (Security)
- protect the potential of natural resources and prevent degradation of soil and water quality (Protection)
- be economically viable (Viability)
- be socially acceptable (Acceptability)."

These five considerations - Productivity, Security, Protection, Viability and Acceptability - have been described as the 'pillars' of the FESLM. Some trade-offs between these requirements may have to be accepted, but in principle, if projections suggest that within a certain time span a particular land use system will fail to meet any one of these 'pillar' requirements, then that system should be regarded as 'unsustainable'. The length of time over which sustainability is measured is a matter for debate - it need not be the same in all circumstances.

It is recognized that many environmental, economic and social factors will interact to determine whether any particular land use system is sustainable. Obviously it is not feasible to identify, much less examine and compare, every conceivable factor in any one evaluation. Instead, the aim is to identify the most significant factors - those which, by their current expression and perceived trends, provide the most powerful indications of likely sustainability. It is by the assessed interaction of these selected factors, which are called 'Indicators', that sustainability is evaluated. For many indicators, it is believed it will be possible to identify specific levels or 'thresholds', which, if exceeded, will predicate unsustainability.

The Framework. The Framework itself seeks to provide a systematic, logical procedure - a pathway - along which relevant factors can be identified and sorted to yield Indicators and Thresholds of sustainability. The general sequence of stages in the application of the Framework is shown in Figure 1.

The pathway proceeds through five main stages. The first two stages serve to define:

1. The Objective - the purpose of the land management system evaluated
2. The Means - the practices, inputs and circumstances relevant to the system

These first two stages define the subject matter of the evaluation - its 'terms of reference'. Together, they provide a complete description of the land use system and its situation - a description of reality at the site if, as will be the case most often, it is the current land use which
is being evaluated. If, during the subsequent analysis, a need for changed inputs or practices seem desirable to achieve sustainability, these can be tested on an hypothetical basis by altering the 'Means' statement and re-running the evaluation. Each time the evaluation is re-run in this way, it tests an alternative form of land use.

Stages 3, 4 and 5 form the analytical part of the FESLM:

3. Evaluation factors - identification of all physical, biological, economic and social factors which potentially bear on the sustainability of the system

4. Diagnostic criteria - establishment of 'cause and effect' relationships between factors; collecting evidence of trends in these relationships on the site; projecting a pattern of these future trends

5. Indicators and Thresholds - identification of the conditions of sustainability on the site.

The importance of Stage 3 lies in ensuring that not a single significant factor is overlooked; one overlooked factor could invalidate the whole investigation.

Stage 4 is the heart of the FESLM. At this stage:
- interactions between the factors are examined and their relative importance determined;
- the trends of change on the site are identified; and
- the general pattern of future change, against which individual changes must be evaluated, is projected.

One should neither exaggerate nor underestimate the difficulties of Stage 4. A great deal is already known about the relationships involved, but the need for more research will certainly be identified. In the absence of a crystal ball, at least four ways of projecting the probable future exist:

1. OBSERVATION: existing evidence on the site itself (eg. evidence of erosion, overgrazing, poor stewardship)
2. HISTORICAL RECORDS: revealing trends that may extend knowledge
3. GEOGRAPHICAL EVIDENCE: showing trends on comparable sites
4. THEORY: application of models proven elsewhere

In Stage 5, the conclusions of Stage 4 are brought together in the identification and valuation of Indicators, and where possible, Thresholds (specific to the site and the objective use).

In practice, the Framework is much more complex, and can be envisaged as an hierarchical tree; starting with a single Objective and branching downwards through each stage of the pathway.

Discussion at the recent 'International Workshop on Sustainable Land Management', held in Lethbridge, Canada (Dumanski, 1993) centred on the identification of Indicators of sustainability. Brainstorming sessions to single out critical indicators in a number of broad global environments served to emphasize the great variety in such factors, particularly when
comparisons are made between factors important in different fields of specialization (eg. physical, biological, economic and social).

Recognizing this diversity, plans for the FESLM include provision for separate, but parallel, investigation and evaluation of factors in these different fields. This allows different specialists to work through the FESLM’s analytical Stages 3, 4, and 5 almost independently. If need be, this can take place at different times and using different data bases, provided always that all the information is brought together and its interactions evaluated in reaching the assessment endpoint.

In the structure of the FESLM, the separate investigations in parallel can be envisaged as vertical columns cutting across the horizontal stages of the Framework, creating a matrix. The matrix concept is valuable in that it emphasizes the horizontal and vertical relationships within the evaluation process, all of which need to be considered and checked in validating conclusions.

The final assessment endpoint is achieved by using the criteria established at Stage 4 to project and compare the developing local status of each Indicator factor against the expected pattern of environmental change in the years to come. The latter is based on the local trends of change identified in Stage 4, set against a background of generally accepted regional and global change.

In a brief summary it is not possible to touch upon all of the issues addressed by the FESLM. For example, the Framework recognizes the need to evaluate both the active effects of a land use on its surrounding environment and passive effects upon the land use wrought by changes in surrounding areas. The Framework is scale neutral, meaning it is intended for use on single fields or substantial regions, but differences of scale present problems of approach.
Furthermore, recognizing in many circumstances that a Yes/No answer to sustainability is neither simple nor satisfying, the Framework includes proposals for classifying sustainability.

The Way Ahead. A descriptive text of the FESLM as a working document has been published (FAO, 1994). Distribution of the working document is intended to attract advice and constructive criticism from a wider scientific audience than has had the opportunity to contribute to the FESLM to date.

At the same time, generous donor support will allow work to start in the immediate future on field projects designed to test FESLM procedures and principles in several parts of the world. The experience and findings of these field projects will focus attention, it is hoped, on those parts of FESLM theory that are most relevant and valid, and provide credibility to the whole approach. Work is concurrently in progress in Canada on the development of an expert system that will allow for the computerization of FESLM procedures. Further meetings are planned at which these efforts will be co-ordinated, and a Symposium specific to the progress and problems of the Framework is included in the programme of the 15th Congress of the ISSS in Acapulco, 1994.

Summing up his concern for the suicidal tendencies of the human species, Tickell (1993) writes:

"We need a value system which enshrines the principle of sustainability over generations. Sustainable development may mean different things to different people but the idea itself is simple. We must work out models for a relatively steady state society, with population in broad balance with resources and the environment."

We may add that to achieve these aims one of the first requirements is a system for evaluating sustainability.

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Issues of Sustainability and Sustainable Land Management

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I. INTRODUCTION

Widespread concern about survival of mankind from global to individual levels has contributed to popularize the concept of sustainability. Over the last decade papers have been written and meetings held in increasing number to analyze the scientific and practical implications of sustainability. All dimensions of the human and natural contexts have been scrutinized: the sustainability of mankind as a whole, those of society, development, resources whether renewable or not, their management and so forth. An abundant literature on these subjects is now available. However, some fundamental questions have not yet been given proper or complete answers. This article intends to address some of the epistemological issues concerning the definition, assessment and implementation of the sustainability concept in general and more specifically in relation to land management for agricultural purposes.

II. DEFINITION ISSUES

Sustainability looks like a kaleidoscope whose many facets mirror large conceptual variations. Each scientific discipline contributing to its definition and each practitioners group applying it to an object of concern such as land management add a different dimension to the concept. Dimensions, in turn, are scale-dependent as they vary with time and space.

A. Multifaceted

Sustainability as used in the environmental policy and research arena is a complex, sometimes controversial concept. Complexity is compounded when applied to agriculture since the term sustainable farming system is given many acceptations. Qualifiers such as low-input, ecological, organic, regenerative and alternative are used either as synonymous surrogates or, conversely, clearly differentiated variants (Lockeretz, 1990). Confronted with such semantic discrepancies, some scientists who believe that an improved model of agricultural development and a sustainable land management system cannot be properly implemented without previous conceptualization, continue searching for a multifaceted however unifying and consensual definition (Brown et al., 1987; Francis and Youngberg, 1990). In contrast, others who are more involved in production fields claim for action and implementation instead of further conceptual refinement (Allen et al., 1991).

When referring to concrete objects of concern, sustainability tends to address issues as global in their impact however diverse in their nature as resource dereliction, deforestation and ozone layer depletion, but also the durable maintenance of specific eco- and sociosystems or a combination of those. Sustainable land management, for instance, might be seen narrowly as the mere application of proper technology, or broadly as a lasting and working equilibrium between all resources or factors involved in the land concept from biophysical (climate, water, soil, plant), to social (land tenure, labour, demographic pressure, etc.), to economic (capital, market, etc.).
B. Multidimensional

The standpoints, perspectives and expectations of people using the terms sustainability and sustainable land management depend on the project objectives and consequently on the specialization fields involved.

Ecologists concentrate mainly on the stability (or fragility) of ecosystems as a function of beneficial (or detrimental) relationships between the biophysical constituents of the environment, although ecological models don’t neglect economic implications of ecosystem productivity, use and preservation.

Comparatively, the agronomic point of view might be considered narrow. Agronomists, however, while still aiming at maximum productivity of conventional agricultural systems, pay increasing attention to fertility enhancement through integrated biological mechanisms acting in agroecosystems.

In contrast, sociologists have a larger view striving for a welfared society and putting emphasis on social variables like organization of work, unemployment, migrations, etc. "Issues such as poverty and hunger are as central to achieving agricultural sustainability as those of soil erosion and adequate farm returns" (Allen et al., 1991). In the trend of sustainability, integrating social, environmental, and economic issues is strongly recommended.

To many economists, economic efficiency, often associated with political issues, controls sustainable development. For instance, increase of oil or timber export is encouraged often without considering its possible destructive environmental impacts. Profit maximization through conversion of money into goods or services, could just as easily be taken as objective since sustainable systems maximize resource conservation subject to a profit constraint by minimizing degradation (Ikerd, 1990).

Politicians’ viewpoints are often confined to short-term plans. To most politicians, particularly in developing countries, stability within time spans of three to five years is the matter, rather than sustainability. Planning for sustainable land use may receive attention on the condition that it will generate electoral plus-values.

In many countries, environmental degradation is a by-product of development with ample contribution from conventional agricultural practices. In contrast, sustainable land management carries a strong environmental quality commitment. It aims at controlling soil erosion through diversified crop rotation and conservation-oriented tillage practices. The incorporation of organic and green manures, legume cropping and biological control of insects, weeds and diseases intend to reduce water and soil pollution by agrichemicals below critical loads.

The above standpoints used to be much more reductionist and discipline-oriented before sustainability acquired its current popularity. The concept has obviously helped identify problems and generate transdisciplinary approaches (Lokeretz, 1990).

C. Multiscalar

1. Spatial variability. The concept of sustainability carries different meanings when used at different spatial levels according to the geographical variations of natural and human resources from local to global scales. Since sustainable agriculture and land management aim at substantially reducing the use of fossil energy and synthetic chemicals, the importance of the natural resource base is proportionally increased. Farming by soil and climate, through capitalizing farmers’ expert knowledge as traditional systems did from tropical shifting cultivation and home-garden horticulture to the earlier triennial crop rotation agriculture in Western Europe, will partially replace high-cost external inputs. At variable spatial levels, agro-ecological conditions as controlled by latitudinal and
altitudinal bioclimatic zonations supply variable climate-soil potentials which determine the biophysical mechanisms and levels of sustainability in agro-ecosystems. The terms of agro-ecologic sustainability, for example, vary from arid areas where the efficient harvesting and application of water control the sustainable land management, to the humid tropical areas where the nutrient conservation and cycling do it. Stewart et al. (1990) highlight the degree of difficulty for developing sustainable systems under different temperature and rainfall conditions.

Similarly, the geographic diversity of social, economic and institutional conditions determines spatial variability of sustainability. At international level, while industrial countries are undertaking a swing from conventional, highly mechanized and specialized production systems towards more integrative low-input farming to promote sustainable agriculture and land management, developing countries have embarked on the opposite strategy to promote aleatory sustainable development. At national levels, the terms of sustainability may vary drastically between high-yielding monocultural regions and depressed polycultural enclaves. In regional and local contexts, exposed to intensive land use conflicts such as in peri- and interurban tissues, agriculture may not be sustainable at all whatever land management system might be implemented, due to real-estate speculation and the land plus-values generated by the urban sprawl. In general terms, the choice of sustainability indicators and the determination of threshold values have to take into consideration the spatial variability of the natural and human conditions controlling sustainability.

2. **Time variability.** Whatever the definition of sustainability, the term refers to productive performance of a system over time. The questions are how long a system can last without being disturbed, and what is the time period a disturbed system needs to recover. The magnitude of time, whether for disturbance or resilience, depends on the intensity and kind of land management, the latter being a function of population pressure and land use type. Under natural conditions most land systems are intrinsically long-term sustainable. In a not distant past, land was used respecting long-time proven sustainability rules such as fallow periods and other traditional soil and water management practices. Time for resilience was available and the maintenance of an agroecosystem was longer. With increasing population pressure, land has to be more intensively used and more marginal land has to be put into production. Both conditions lead to endangering the short and medium-term sustainability of land quality.

A crucial question is how to evaluate the time component of sustainability and estimate the longevity of a land system used under specific management practices. Lal et al. (1990) consider a period of 5-10 years for agronomic productivity, and 5-10 decades for soil and environmental features. Fresco and Kroonenberg (1992) suggest for agroecosystems at the local and regional levels to consider the time scales of both internal and external processes acting on the system. In Iran, for example, traditional irrigation systems and water management practices (ghanats, bands, pot irrigation, etc.) which were socially and ecologically integrated, quickly collapsed when agriculture underwent modernization, but had taken ages to reach a co-evolutionary equilibrium status (Farshad and Zinck, 1993).

### III. ASSESSMENT ISSUES

#### A. Uncertainties of the method

To assess sustainable land management a set of questions has to be answered in a stepwise approach:

- What is the object and object property(ies) to be assessed?
- What is the use - purpose of the object?
• What specific type of use is intended?
• What are the characteristics of sustainability indicators?
• What are the relevant indicators and their reference values?
• What are the assessment techniques?

1. An unequivocal identification of the object to be assessed. In the present case, land regarding its sustainable management is the object of concern. Land is recognized as one of the components of the life support system together with air, water and biota. Because of intimate relationships between these components of the ecosystem and between them and externalities belonging to the sociosystem, it results difficult to assess the sustainability of land management in isolation and delineate a clear departure from the sustainable management of the other natural resource bases.

2. A clear statement about the purpose of land use, land being a resource base for a large array of uses including agriculture, range, forestry, engineering, sanitation, recreation and natural ecosystem preservation. The sustainable management of the object "land resource" can only be assessed against and in the context of a specifically stated use purpose. The frequent and accelerated substitution of land uses in space and time in particular in highly dynamic interface areas such as urban fringes and coastal zones, the combination of multipurpose land uses on individual production units, and the intricate spatial distribution of competitive land uses, enhance the need for a combined sustainability assessment of natural resources in spite of the intrinsic complexity of such an undertaking.

3. The selection of a reference model for agricultural development in whose context sustainable land management is intended to be assessed, ranging from techno-industrial agriculture to several versions of alternative agriculture and to primitive shifting cultivation. Conventional high-input agriculture is increasingly questioned because of its negative impacts on the environment and the deteriorating quality of life in rural communities. In contrast, alternative farming systems based on the agro-ecological systems and synergism approach are actively promoted (Dcerd, 1993). As a consequence, a new agricultural paradigm is emerging where sustainable land management is more a knowledge-based, instead of input-based, system of farming. Similarly, shifting cultivation and other indigenous knowledge-based farming systems are rehabilitated. Sustainable land management is specific to each agricultural model and farming system, and generalizations are hazardous to establish.

4. The determination of the quality requirements that potential indicators should exhibit to qualify as means for assessing and measuring sustainability. It is unlikely that each indicator could meet all ideal quality requirements.

5. The selection, testing and validation of specific indicators to assess sustainable land management for agricultural purposes, including the identification of standard values to compare various land management systems and practices, and threshold values to distinguish between sustainability and non-sustainability. Indicators and their values are the instrumental parts controlling the implementation of any given framework for sustainable land management assessment. However, the selection of indicators meeting established quality requirements, their hierarchisation according to their differentiating capability, and the determination of reference values have to face many criteria and data contingencies.

6. The setup of an assessment approach and its supporting evaluation and measurement techniques. There is a large variety of more or less suitable techniques, but these are not necessarily interchangeable and rather time-span specific. Long-term sustainability cannot be assessed the same way as short-term sustainability and requires the implementation of techniques pertaining to, among
others, the historical and archaeological research fields.

Hereafter it is intended to concentrate on issues concerning parts (4) and (6) of the above methodological scheme.

B. Quality requirements of sustainability indicators

Since sustainability as a comprehensive concept cannot be measured in itself, it is aimed at determining its intensity levels and time horizons. Therefore appropriate indicators must be selected, tested and validated. The choice of sensitive indicators is a crucial issue as these will be the operational means to qualitatively evaluate and quantitatively measure sustainability. Thus, a good indicator should be endowed with a set of characteristics making it a valuable diagnostic tool. An ideal indicator would be unbiased, sensitive to changes, predictive, referenced to threshold values, data transformable, integrative, easy to collect and communicate (Liverman et al., 1988). It is unlikely that all potential indicators would fully satisfy all these quality requirements.

1. Freedom from bias. Complete freedom from cultural and geographical bias is hard to achieve as many indicators are rather ethnocentric and, therefore, far from universal applicability. Value judgements as to the relative quality of the land to be sustainably managed and the variable ability of the social groups to sustainably manage the land within specific farming systems strongly influence the selection of appropriate indicators.

2. Sensitivity to changes and variability. Sensitivity to temporal changes, spatial variability and social distribution is a fundamental diagnostic quality. Indicators must help detect rates of change over time and opportunely identify land management trends leading to or departing from conditions identified as sustainable. Unfortunately, many indicators are of limited applicability because data are not retrospective enough, not collected at the right time intervals, not timely available and not up-to-date to easily elaborate time series indicators for trend analysis.

A time-sensitive indicator must also be a good predictor and early warning tool allowing to monitor and anticipate, through extrapolation of established time series or simulation modelling, undesirable evolution trends towards non-sustainable management conditions.

Similarly, the spatial variability of land conditions and the diversity of social structures influence the selection of relevant indicators as their sensitivity varies from local to regional to national to global scales.

3. Provision of standard and threshold values. Although the limit between sustainability and non-sustainability might be a fuzzy one, a good indicator should help position a given land management system, in its present status and evolution trend, in relation to this critical, sometimes irreversible frontier by means of standard reference values. It is also desirable that such values be indicative of the reversibility of a given land degradation process leading to non-sustainability and the possible cost of controlling it.

Similarly, within the large span covered by sustainability, threshold values are needed to determine more discrete sustainability classes. Yield gap analysis, for instance, when applied to a wide range of values from farmers' yields to calculated maximum yields, contributes to establish a hierarchy of sustainability levels according to variable management conditions such as land quality, affordable technology, socio-economic constraints, environmental tolerance, etc.

4. Ease of data collection. The use of indicators needs the provision of appropriate data. Their implementation is frequently limited because of large quantitative data gaps, but also because of qualitative inappropriateness concerning the scale and nature of measured variables.

On the other hand, sustainable land management is a dynamic concept which requires not only data on the initial boundary conditions of the land system but also diachronic data to monitor the
system's evolution. Data monitoring systems, especially multiple-objective systems, are expensive and difficult to operate in particular as regarding (inter)institutional constraints.

5. Versatility of data transformation and communication. To be meaningful to designing sustainability indicators raw data have to be transformed into more elaborate tools such as change rates, depletion ratios, risk and vulnerability indices, which allow to compare current status to initial land conditions, assess land fragility towards given management practices and address spatial variability of land quality. Such composite indicators are more efficient for evaluating sustainability than single-variable indicators, but more difficult to establish and implement because of scaling and weighting of their various components for which expert judgement and multivariate statistical techniques are to be combined.

Indicators must also be efficient, easy-to-understand tools to communicate information on sustainability issues to users from farmer to policy-maker to politician. Graphics, computer demonstration programs and video simulation games have revealed to be good communication means.

C. Need for integration of approaches and techniques

The concurrent use of a large variety of assessment tools is necessary to embrace the whole width of sustainability, even when restricted to the domain of agricultural land management. Efforts are being made to integrate concept attributes and analysis techniques in more comprehensive frames to encompass the multiple facets of land sustainability (Dumanski et al., 1991). Similarly, a systematic inventory of suitable methodological approaches and supporting techniques currently used in several fields of land resource studies has been made (Farshad and Zinck, 1993).

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<th>Land evaluation approaches</th>
<th>Retrospective approaches</th>
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<td>• Attribute rating and matching techniques</td>
<td>• Archaeological data analysis</td>
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<td>• Productive potential estimation</td>
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<td>• Agroecosystem analysis</td>
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<td>• Carrying capacity modelling</td>
<td>• Soil micromorphology studies</td>
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<th>Co-evolutionary approaches</th>
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<td>• Agricultural system analysis</td>
<td>• Conventional expert knowledge</td>
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<td>• Cultural landscape and landuse analysis</td>
<td>• Indigenous knowledge</td>
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Approaches and techniques vary from very general such as different types of landscape analysis to more specific such as crop yield estimation. They also span from retrospective postdiction to anticipatory prediction. Some of the techniques have been used for broad resource studies, in particular human resources. Their successful application to the more specific purpose of sustainable land management has still to be proven.

Present-day sustainability levels can be assessed through implementation of qualitative or quantitative land evaluation (lato sensu) techniques. Functional equations, algorithms, indices and models are used to estimate land suitability, crop yields, agro-ecosystem productivity, land carrying capacity and environmental deterioration, and their effects on sustainability.

In contrast, the historical retrospective intends to dig into the past to identify valuable practices having led to sustainable agriculture. Although ancient agricultural systems may not be economically
viable today, they can provide lessons for present land use planning. There are several ways to
reconstruct the anthropogenic impact on the environment, from history to archaeology to
palaeopedology.

Along the way from the past back to the present, the co-evolution approach aims at monitoring
the parallel evolution, either sustained or disrupted, of both socio- and ecosystems. The co-
evolutionary process generates reciprocal responses of these two closely interacting systems aiming
at mutual, long-term sustainability. Cultural landscape analysis has provided many examples of
successful agro-systemic co-evolution as well as cases of sudden disruption of lengthy and hardly
built-up equilibrium situations, from slash-and-burn agriculture in the humid tropics to the traditional
irrigation practices in arid regions.

Along a similar research line, the extraction, collection and conceptualization of knowledge
embodied by living practitioners from extensionist to advanced farmer to indigenous people, allow
to identify proven sustainability practices and constraints in accordance with geographical and socio-
ethnic variations.

IV. IMPLEMENTATION ISSUES

Conceptualization and assessment of sustainable land management have to be translated, at
the end, into applicable alternative models. The implementation of proposed options has to be
further tested and monitored against ground truth conditions and application constraints.

A. System quality criteria and contextual conditions

To be sustainable a land management system is expected to comply with a set of intrinsic
properties such as proposed by Altieri (1989) for sustainable farming systems: diversified in time
and space, dynamically stable, promoting conservation and regeneration of natural resources,
productive and self-sufficient, based on economic potential, adjustable to socially and culturally
acceptable technology, self-promoting and providing self-help potential.

But to be applicable to the real world, a sustainable land management alternative must, in
addition to complying with internal quality requirements, be malleable to external conditions
belonging not only to the farm environment but also to the political and institutional contexts. Such
external conditions have been stereotyped as technological feasibility (productivity and production
security), economic viability, political desirability, administrative manageability, social acceptability
and environmental soundness (Virmani and Eswaran, 1990).

Internal qualities and external conditions are so complex that it might be doubtful whether any
single land management system can satisfy all of them at optimum level. On the other hand, since
sustainability is site-specific, the reference values of the selected system quality criteria change
according to geographic variations. Furthermore, externalities such as political priorities and market
elasticity are dynamic time variables imposing short-term adaptation constraints on farming systems,
which might be seen conceptually and practically contradictory with sustainability.

B. Application constraints

Constraints or even resistance forces are found in the many dimensions of sustainability as
applied to land management, from agro-ecological, agronomic, technological, social, economic,
institutional, to political. Constraints are perceived mainly at two levels, the farm level where
application takes place and the policy-making level where many of the applicability conditions are
set. In each case, sustainability is influenced by externalities operating at other decision levels. For
instance, at farm level sustainability is controlled by the (limited) resources of the production unit
but also by national and international policies (e.g. GATT). Policy-making, in turn, is conditioned
by global level programs (e.g. Agenda 21, birth control programs) but cannot ignore the ground level
constraints.

Constraints to the application of sustainable agriculture and land management lie in the fields
of research, education, political promotion and farm management (Lockeretz, 1990; Reganold, 1990).

More research should be carried out on alternatives to chemical fertilizers and the cycling of
nutrients in agro-ecosystems; the biological control of pests, weeds and diseases; crop mixtures and
rotations; cover crops and tillage practices; alternative crops and germplasm; the integration of
livestock and cropping systems.

Research results on viable alternatives must be more efficiently transferred to the farmer
showing proof of their profitability. Field demonstrations, written pamphlets, TV and video
messages, farmer-to-farmer networks are proper means to educate people on the direct advantages
to the producers and the long-term benefits to society.

Institutional, legislative and political promotion are indispensable. Since sustainable land
management is strongly tied to crop diversification, crop subsidies and price supports for sustainable
farming produces would stimulate farmers to shift from land deteriorating monocultures to
polycultural crop rotations without losing farm-support funds. The negative effects of non-
sustainable management should also be sanctioned by taxes compensating for soil erosion and water
pollution through agrichemicals.

But it is at farm level that major constraints are likely to arise. The application of sustainable
land management practices might not show immediate effects on productivity maintenance,
reinforcing farmers' innate risk aversion. The reduction of agrichemicals will cause lower crop
yields, fortunately compensated by lower production costs so that the net returns may be still similar
to those of high-yielding conventional farming systems. But economic benefits will have mainly
long-term effects in contrast to the short-term reimbursement obligations of production loans. From
a more technical point of view, farmers adopting sustainable management practices must implement
a proper conversion strategy, changing the management on one field at a time to avoid placing the
whole farm at risk. This implies also that farmers need increased knowledge on the agro-ecological
mechanisms controlling productivity. Additionally, sustainable land management practices are in
general labour-intensive, which might result in bottlenecks in industrialized societies.

V. CONCLUSION

Sustainability is a concept as difficult to define as it is to put in practice. Furthermore, the
concept is as old as mankind, but societies have frequently transgressed its precepts resulting in land
degradation, water shortages, and environmental pollution. Recently, a resurgence of interest has
brought the concept of sustainability back to the international scene of discussion by scientists,
decision-makers and practitioners. Some of the main problems are how to determine a proper stage
of sustainable equilibrium between the natural resource base and its exploitation, to evaluate as
quantitatively as possible the sustainability level reached by a given agricultural system at a
determined moment, and to monitor the changes effecting it.

Current research trends on sustainable land management aim to answer this kind of questions
through the development of a conceptual and methodological framework for evaluating the impact
of land management practices on sustainability. Such an approach emphasizes sustainability as the
reflection of an equilibrium between available land resources and their management in present-day conditions. In contrast, the lemma of learning from the past to face our future by promoting soil utilization in harmony with nature, puts the accent on scrutinizing past experiences to identify viable solutions to current sustainability issues. For such a purpose, the historical retrospective and the co-evolutionary paradigm may reveal being good approaches to extract lessons from past land management successes and failures.

REFERENCES


Evaluating Sustainable Land Management: are We on the Right Track?

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Introduction. This short paper does not seek to review the whole large field of literature that has grown up around the concept of sustainability in agriculture during the past six years. Principally, it addresses the 'Framework for Evaluating Sustainable Land Management' (FESLM) initially proposed by Dumanski et al., (1991), carried forward by Smyth (1992), and most recently discussed by Dumanski and Smyth (1993). However, this leads us to some wider considerations concerning the estimation of sustainability. These include problems inherent in trying to combine ecological with socio-economic sustainability in any one framework; problems of basing analysis on the FAO Land Evaluation (FAO, 1976); problems of spatial and temporal scale and, finally, some more basic considerations regarding what is important and why. In common with FESLM itself, we restrict our analysis to the question of arable management of land (not excluding, but not specifically referring to, mixed farming and agroforestry), and do not consider pastoral land use. This latter involves a number of parallel considerations, but the important question of 'carrying capacity' of livestock is additional, and is not considered here.

FESLM AND ITS CONTRIBUTION

The FESLM Approach. The basic requirement of a FESLM, as set out by Dumanski et al., (1991), is a scale-free evaluation procedure that can be approached equally from the field and macro-regional levels. The foundation they propose is the FAO (1976) Framework for Land Evaluation, which assessed and classified land suitability in relation to specific forms of use in relation to the physical, social and economic context of the area concerned, comparing different potential uses through comparison of the benefits obtained, and inputs needed on different types of land. In practice, though not in principle, the FAO methodology has been generally used in relation to monocropping systems, thus excluding a large part of small farming agroecosystems from its domain of operation.

In the initial formulation, FESLM took account of hierarchical approaches to evaluation (e.g. Allen et al., 1984) and of the indicators of unsustainability in mountain environments proposed by Jodha (1990). Dumanski et al. (1991: 40) went on to propose that the objectives for FESLM should be:

To develop a science-based, international framework for evaluation of sustainable land management practices, which simultaneously: maintain or increase production, reduce the level of production risk, do not deplete soil and water quality and achieve environmental stability, [and] are economically viable and acceptable.

A subsequent international working group went further by offering the following definition, as quoted by Dumanski and Smyth (1993: 9):

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1 The acronym for this framework appears, shall we say, unstable. Dumanski et al. (1991) use FSLM whereas Smyth (1992) prefers FESLM, which we have adopted here. By not referring to either Dumanski and Smyth (1993) adroitly avoid the issue.
Sustainable land management combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as simultaneously: maintain or enhance production/services (productivity); reduce the level of production risk (security); conserve the quality/potential of natural resources (conservation); [and in addition] be economically viable (viability) and be socially acceptable (acceptability).

This emphasis on socio-economic considerations in parallel with biophysical considerations was in line with the FAO Land Evaluation, but whereas suitability evaluation is for the moment and the immediate future, sustainability has to be viewed in the long term. This represents a significant constraint and leaves sustainability as a nebulous concept.

The charge of developing such a system was given to A.J. Smyth who has prepared, through two partial drafts, a system that seeks to meet this objective (Smyth, 1992), discussed in part by Dumanski and Smyth (1993). In summary, Smyth has designed an approach that proceeds, in parallel in the physical, biological, economic and social domains, through three stages once the system under investigation is defined. In the first stage, relevant factors are determined and, in the case of the physical domain in particular, these are conceived in terms of 'land qualities' (FAO, 1983), being meaningful subdivisions of the total environment within which evidence of stability or instability might be encountered. The second stage is diagnosis, identifying which components exhibit current or recent change, analysing the causes of these changes. For this purpose, observation, historical evidence, comparison with other areas and even theoretical models are employed to develop criteria to determine the likely status of different diagnostic factors at future times.

After this collection of evidence comes the third stage, which embraces the most important conceptual contribution of the system. This is the determination of indicators and thresholds. Then follow assessment, validation and implementation. The system is set out in the form of a 'master framework', whether universal or for major ecological regions, and a 'local framework' in which only elements relevant to the site, and scale, are examined.

Difficulties Specific to FESLM. Perhaps by design, perhaps by default FESLM remains tightly bound to, and constrained by, the approach developed for FAO Land Evaluation. As noted above this methodology has been directed at monocropping systems and in this respect it achieved early success (Dent and Young, 1981). Quite clearly FESLM can be expected to build upon this success which may be assumed to reflect an inner strength in the methodology. By the same line of reasoning, however, the general omission, by way of examples, of suitability analysis of complex mixed cropping systems deserves comment. Is it just a lack of opportunity or is it pointing towards a distinct weakness in the approach?

2 The concept of thresholds, between sustainability and unsustainability, seems to draw on the 'separatix', or conceptual boundary condition between the two stable equilibria - forest and grassland - attainable respectively under sustainable and unsustainable shifting cultivation, proposed by Trenbath et al. (1990). In no small degree, it relates to the view that ecosystems under interference, or socio-political systems under pressure, may quite suddenly collapse. For the latter, the collapse of communism in Eastern Europe offers a clear analogy, while the former can be traced back quite readily to Holling's (1978: 30-32) 'instability', where a system can quite suddenly 'flip' from one state to another after seeming to absorb incremental disturbances. Later developments in chaos theory are also relevant. While Smyth may mean less by 'thresholds' than this, the notions are none the less relevant. Also appropriate to this discussion are indices such as 'soil life' proposed by Elwell and Stocking (1984), 'residual suitability' and 'production half-life' of the soil (Biot et al., 1989). However, it needs to be emphasized that these types of indices are based on assumed levels of soil replenishment and soil formation though it is clear that such topics are poorly understood (see Paton, 1978).
an approach. FESLM has inherited? On a similar level it becomes necessary to ask whether or not FESLM is little more than a refinement of suitability evaluation. This is not the place to discuss these issues but they are matters of importance and warrant fuller treatment. In the case of the latter it relates to scale which is commented upon below.

Turning specifically to FESLM Smyth has been able to develop a set of criteria and indicators for the physical variables, deriving these quite largely from the FAO Land Evaluation. In the physical domain, each diagnostic variable implies an hypothesis, making simpler the determination of indicators and the estimation of thresholds. At the most recent stage seen by us, the rest of the multi-disciplinary task remains a set of three black boxes. The end result has to be an assessment of sustainability in each of these areas, so that if in any one the use is found to be unsustainable, modifications need to be made in other areas. Perhaps partly because of the evident problems in making such a synthesis, sustainability is defined over the sort of time span relevant to the parent FAO Land Evaluation. About 25 years is regarded as the limit of prediction; and the dividing line between 'sustainable' and 'unsustainable' is placed as low as five years.

Not many would agree. To most students of agroecosystems, a sustainable system must mean a set of practices which will be repeatable on the same land, without loss in the capability of that land to support production, over a period which — while notionally indefinite — is perhaps better defined in more measurable terms as the span of at very least between one and two generations. We can identify systems in which sustainability can, historically, be measured over hundreds of years. 'Without loss of capability' does not mean there is no loss of soil or fertility at all, or any change in biota, but it does mean that the land remains productive, and that loss rates can be controlled and replaced by a modest and regular programme of inputs.

A second specific problem is that FESLM does not really address the question of scale. Again, this arises from its genealogy as a descendant of the FAO Land Evaluation. Since this latter is related to suitability of land for specific crops it necessarily operates principally at the field scale, and the FESLM 'general framework' is merely an enlargement of the 'field'. However, it is evident that this enlargement has not been embraced by all those involved and it is questionable whether or not FESLM, as presented, can effectively operate at broader scales. While detailed analysis of sustainability does require a field-by-field approach, we need to be able to generalize over community lands and agroecosystems as a whole. Within these larger frameworks rotations are practiced, land-management systems may vary spatially, and inputs can be shifted from one site to another. This is important because parts of the whole may be managed unsustainably while other parts are managed sustainably. And yet, it is the whole that matters. Presumably it is the future status of the least sustainable units (or patches in ecological parlance) that influences the success of the whole system but this may not always be the case, depending on the impact of various externalities — especially economic factors. Nevertheless, it is this level of analysis that requires attention.

1 One of us, when at another university, found that postgraduate students experienced considerable difficulty in applying land-suitability evaluation to complex subsistence cropping systems, even when such systems were simplified for the purpose of instruction. In comparison, the same type of exercise on a single cash crop proceeded in a fairly straightforward manner.

2 It should be feasible to combine physical and biological criteria of sustainability, at least of evaluations at a smaller scale, since the state of biota and land are closely and causally related. Indeed, remote sensing work on land degradation relies largely on an interpretation of land cover, and a principal indicator of the condition of the soil under natural-fallow systems is the composition and growth of the vegetation. While pests and diseases are more variable, there is increasing knowledge of the conditions of their incidence and, in many cases, management.

3 Capability*, a term employed by Blaikie and Brookfield (1987: 6), refers to the intrinsic qualities of land in relation to production; it embraces soil fertility, structure, biota, depth and above all 'resilience', or ability to withstand and recover from shocks such as drought or excessive rain.

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As an alternative viewpoint we suggest that the framework should focus on this broader scale i.e. at the level of agroecosystems in the first instance since this would appear to be a scale that is suited to developing a solid biophysical platform. Within such areas it is possible to substitute more sustainable for less sustainable uses as evidence of stress arises. Again, we can demonstrate cases in which this is done, often spontaneously. It is therefore a pity that the hierarchical approach drawn on in the Dumanski et al. (1991) paper has not been drawn on more strongly in FESLM.

We draw attention particularly to the suggestions of Lowrance et al. (1986), following Douglass (1984). They offer a hierarchical approach to the study of sustainable agriculture that is capable of wider generalization. They distinguish 'agronomic sustainability' at the level of the field, where the objective is sustained yield. This fits into 'microeconomic' sustainability at the level of the farm, where it is possible to shift inputs between different fields. In turn, this nests into 'ecological sustainability' at the level of a whole agricultural landscape, where the objective is maintenance of life-support capacity over longer time scales. Finally, it is necessary for the success of any sustainable strategy to aim for 'macroeconomic sustainability' which determines the conditions of production. Even though drawn up in an American context this approach, shifting attention recursively between management of a specific resource, the local and larger organizational and regional systems where management takes place, and the state, would seem to offer a structure within which the sustainability of diverse small-farming systems might more readily be analyzed.

LARGER PROBLEMS

The Place of the Socio-economic Context. We have suggested that inclusion of socio-economic considerations in a single sustainability analysis cripples predictability. One focuses primary attention on the latter, and the biophysical part of the analysis becomes an examination of the specific consequences for the soil and vegetation of the change taking place. An excellent example of such an approach, very well crafted and set out, is provided for the rapidly changing Chiang Mai region of Thailand by Rerkasem and Shinawatra (1988), respectively a soil-fertility specialist and a resource economist. Fundamentally, what they are studying is the sustainability of the modern changes, rather than of the system. There are good reasons why this should be so. The behaviour of socio-economic variables is totally different from that of physical and biological variables, and many socio-economic trends are readily reversible. While it is clear that an ecologically sustainable land management system which relies on low input costs and high output prices cannot long remain feasible in the absence of these conditions, prices can be very unstable indeed, and comparative advantage may shift between regions as Rerkasem and Shinawatra (1988) demonstrate. Moreover, there are many cases in the developing world where low labour-input costs may rely on coercion or the large-scale use of immigrant labour, legal or illegal. Both are highly subject to reversals in public policy. Fertilizer subsidies, where they are an element, are even less reliable. The age- and sex-composition of farm labour forces is increasingly affected by off-farm income opportunities, and these too vary according to economic cycles. In western agriculture, much that was economically sustainable in the 1970s became decidedly unsustainable in the 1980s as an international credit squeeze and market oversupply took its toll. Such changes, important to individuals as much as it is to the global economy, remain outside the bounds of prediction even by supposedly rational, economic theorists. It is not sensible to talk of sustainability of a management system over any extended period, even one as limited as 25 years, in these circumstances.

Analysis of the socio-economic environment of land management is essential, but it should have a purpose, or purposes, different from that of studying sustainable land management. In the first place it establishes the boundary conditions at any time for any given set of management strategies. Second, it explains the pressures on farmers which may inhibit use of sound management practices. Carried down to the household level, it
establishes the feasibility of many labour-demanding adaptations. Moreover, it helps establish how far the farm household is in fact dependent on the produce of its land, and therefore likely to be more or less willing to invest in the future. All this sets the conditions for ecological sustainability or unsustainability, and its analysis is an essential part of any sustainability exercise, but it is either preliminary or subsequent to the evaluation of sustainable land management, not an integral part of that exercise. It follows from this line of reasoning that the approach adopted by FESLM in granting equal status to four factors (physical, biological, social and economic) is inappropriate.

The Proper Domain of Sustainability Analysis. It is our view that sustainability can only refer to the sustainability of management practices in the context of their management of the biophysical milieu. Moreover, it must relate not only to sites, but also to farming systems — or agroecosystems — as a whole, since practices are substitutable within them. It must be based on the nature of the physical environment, its qualities or capabilities, its sensitivity to interference, and its resilience of ability to recover. These are the fundamental parameters, and it is their management that should be under scrutiny. Use of the crop-based FAO Land Evaluation is, in this context, a dangerous distraction. Sustainability begins with the land, its waters and biota, each piece of which has its distinctive attributes. An agroecosystem uses several pieces of this environmental complex, so that while its parts need to be analysed separately, they also need to be put together to determine whether the system is sustainable. Hierarchical approaches are thus in the highest degree relevant, and should have a prominent place. But economic and social elements provide the context to determine what, at any given time, may be feasible. They yield a range of possibilities and impossibilities, but are not part of sustainability as such. We also identify another role in which they are relevant in our concluding section.

The Stability, Sensitivities and Resilience of Land. As noted above a case can be made for claiming that agricultural sustainability should, in the first instance, be assessed at the level of agroecosystems. A useful starting point is to consider these systems in terms of ecosystem dynamics on the assumption that the behaviour of an agroecosystem in some ways reflects the intrinsic qualities of the original ecosystem which has since been modified. Perhaps the most important feature concerns the stability of the system since within FESLM the so-called 'pillars' of sustainable land management infer stability and many land management practices can be interpreted as measures to enhance productivity and security. Nevertheless, ecological systems remain dynamic and subjected to various perturbations that influence subsequent behaviour which, according to various theorists (e.g. May, 1972; Holling, 1973) can be unpredictable. Following Blaikie and Brookfield (1987: 11-12) the essential dynamics or stability of agroecosystems can be expressed in terms of sensitivity and resilience. Treating both as vectors, with recognizable low and high endpoints along a continuum, provides a basis for defining four broad categories with very different behaviours (in an ecological sense) and in which the potential sustainability differs (Fig 1):

Class 1. A robust ecosystem of low sensitivity and high resilience. Very poor management of the resources is required to seriously degrade it and there remains a strong potential for very sustainable agroecosystems to develop. The earliest known forms of intensive cultivation over long periods is from such areas especially wetlands.

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6 Blaikie and Brookfield (1987:10-11) use the term sensitivity to refer to the degree to which a land system undergoes changes by natural processes following modification of that system by people. Resilience refers to the ability of the system to restore its capability and/or to recover from a perturbation. This meaning is intended to incorporate, in part, the sense applied to this term by Holling (1973, 1978:11) where 'resilience is a property that allows a system to absorb and utilize (or even benefit) from change'.

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Class 2. A delicate ecosystem of high sensitivity and high resilience that responds well to suitable management but reacts strongly to perturbations. Providing sound management is maintained sustainable agroecosystems can develop but they are not of the same quality as Class 1.

Class 3. A difficult ecosystem in which low sensitivity and low resilience means that once certain thresholds are exceeded it is very difficult to restore capability, and the land may be permanently degraded. Such lands are marginal in terms of sustainability. Historically it is these lands that, whilst initially productive, collapsed as the resource base was destroyed.

Class 4. A fragile ecosystem of high sensitivity and low resilience that easily degrades and does not respond to normal management practices. Any agroecosystem that strongly tests this fragility can become unsustainable within periods as short as a decade.

Very relevant to the present discussion is an example provided by Bayliss-Smith (1991) in which the concepts of sensitivity and resilience were used to explore the vulnerability of agricultural production systems in the highlands of New Guinea. Four broad environmental zones were recognized: the humid central valleys, the seasonally dry eastern highlands, the humid high altitude zone, and the per-humid highland fringe. Within these environments particular combinations of variables were used to assess their vulnerability or — in the context of this paper — sustainability. The least vulnerable environments (Class 1) are the wet lands in the central valleys where fertility is maintained. In contrast the most vulnerable areas (Class 4) were those with erodible steeper slopes in a drier zone where fire restricts successional changes towards natural reforestation. In the same way the status of various social groupings can be evaluated and, in this example, it is young children, young women and displaced people that are most vulnerable in highland societies.

This approach provides a basis for understanding the dynamics of the environment that influence stability and management in which an agroecosystem is a part. An initial classification of an agroecosystem in terms of resilience and sensitivity will assist in assessing potential sustainability. In this context FESLM's indicators, criteria and thresholds can be directed at helping to define this status. The advantage of this approach is that it recognizes from the outset that there are different dynamic categories of sustainability at the level of agroecosystems that are distinguishable by biophysical factors alone. This represents a significant rationalization. At this stage social and economic factors can be introduced next and foremost amongst these is an assessment of management strategies designed to reduce risk so as to secure adequate production. In this context the adopted strategies can be expected to reflect the stability of the biophysical realm. In marginal situations a common practice is to follow the adage of not placing too many eggs in the one basket by cropping several different strips of land with various micro-environmental differences so as to hedge bets against various type of adverse conditions. This strategy is applied in the Bangladeshi flood plains (Brammer, 1991) and in the mountains of Peru (Goland, 1993).

The Question of Trends. One element in FESLM concerns the elucidation of trends. It is not, however, central. We suggest that the analysis of trends should have a more fundamental place in sustainability analysis, for many agroecosystems are changing, or are being changed, and there have been major changes in the past. There is substantial body of research on farmers' practices and knowledge relating to small farmers in the developing world and, while it indicates that there are many areas in which farmers have failed to adapt their practices in time to avoid such severe environmental degradation as to render their habitat useless, it also demonstrates the contrary in other areas. The same

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7 This literature, and its context, are discussed in another paper involving one of us: Brookfield and Padoch (in prep)
is equally true of 'modern' capitalist or socialist farming. Historically, demographic, social, political and economic change have been major forces determining long term variation in land management practice. In modern times, change is accelerated in almost all areas and, coupled with higher population mobility, technical innovation, and new forms and sources of information, is destabilizing the slow methods of adaptation which have served quite well, in many parts of the world, in the past. Significant change in farming systems is, in some areas, documented over periods as short as one generation. While many systems remain basically unaltered, change is increasingly being urged where it is not spontaneously occurring.

It ought to follow that attention should be paid to trends, both toward ecological sustainability and away from it, as well as static sustainability — as in FESLM. In this context, an absence of farm-system adaptation under growing pressure on a deteriorating environment is a trend away from sustainability, sometimes accelerating. Trends toward unsustainability may be rapid or slow, often in demonstrable relationship to the sensitivity/resilience matrix discussed above. Where there have been innovations, it is an unfortunate but widely repeated experience that the period of time before symptoms of unsustainability appear may range from only a few seasons to as much as a century — as in the case of some dry-land salinization. This is where the use of comparative experience can be of the greatest importance in signalling possible trends that are not yet evident at any particular site.

The study of trends also needs to take account of soil-forming processes as well of degrading processes. The roles of biological activity, and of other slope processes, on soil formation are not new discoveries, but their development into an alternative framework is an essentially new field (e.g. Paton, 1978; Paton et al., in prep.). This suggests, however, that under favourable conditions topsoils may form in periods as short as decades rather than over centuries or millennia as is often assumed. It also suggests that a serious decline in soil fauna may herald a rapid trend away from sustainability. It opens a new dimension to the important question of resilience of agroecosystems, and suggests that a much more complex linkage of factors is involved in the formation of pedological provinces than is considered in the traditional climatic and deterministic approach of soil zonalism. This is of critical importance for any evaluation of land that seeks to project more than a very short time ahead, which is what sustainability analysis is, after all, about. Trends in ecological sustainability can well be studied by an adaptation of the notion of thresholds which is FESLM's outstanding contribution.

Analysis of the dynamic nature of the socio-economic environment also has a major important part to play in such a study of trends, explaining the conditions under which trends in management practices either arise, or fail to arise. An important question to be determined is whether and where thresholds are allowed to be approached and passed without adaptation, and where and when adaptation does occur. Equally important is the speed with which innovations, especially new crops, are matched by modifications of practice in the management of land for their cultivation. Moreover, we need to try to understand why. A large, and perhaps even more relevant task is delineated.

Conclusion. A final question needs to be asked. While we can recognize sustainable systems, in the ecological sense, where they have endured for a hundred years or more, it is in general much easier to recognize unsustainability. For a recently-established land

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8 Recently, Andersen (1990) has suggested a scheme for using ant communities, especially indicator taxa, to evaluate the changing status of terrestrial ecosystems in Australia.

9 As Schmink et al. (1992: 8) remark, 'the important question now is not which traditional practices, as practiced in the past, are sustainable, but rather which conditions cause people to conserve their resources, and which conditions favor destruction, or overexploitation of local resources.'
management system we can say that the diagnostic elements appear to be stable, and that the system therefore appears to be sustainable, but we cannot be sure that thresholds are not being approached. Sustainability itself probably has to remain a relative concept, a vector along which at one extreme we can be reasonably confident of a sustainable future, while at the other there is abundant evidence of ongoing degradation and imminent collapse. This cautious approach might, indeed, be a much sounder way in which to view the problem rather than to try to be precise in our aim at what is a moving target.


Figure 1 Categories of potential sustainability of agroecosystems.
Development of Indicators and Thresholds for the Evaluation of Sustainable Land Management

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Abstract. The recently-developed Framework for Evaluating Sustainable Land Management (FESLM) provides a logical pathway for assessing the probability of sustainability. Central to the operation of the Framework is the identification of development of indicators and thresholds. Whereas an indicator is used to measure changes in key attributes, usually over time, a threshold provides a baseline against which sustainability can be assessed. A direct measure of sustainability using indicators is difficult, and indirect surrogates are often easier to establish. There is less information on threshold values for indicators, except for primary indicators such as soil acidity. Because of the dependence of some threshold values on soil type, it seems highly likely that a range of values will be required for a particular indicator. There have been few case studies involving indicators and thresholds for SLM. Examples of soil and land suitability for the production of Hevea brasiliensis (rubber) in Malaysia and for the management of sloping lands for annual crops in the Philippines are discussed. Biophysical indicators and thresholds for sustainable rubber production appear to be reasonably well-understood, particularly those relating to climate and soil physical factors. For sloping lands in the Philippines, economic indicators give a clearer picture of trends and sustainability.

Background. The concept of "sustainable development" first gained prominence with the publication of Our Common Future by the World Commission on Environment and Development in 1987. The Earth Summit held in Rio de Janeiro in 1992 substantially enhanced thinking on sustainability issues and developed an action plan (Agenda 21) for making development more environmentally, socially, and economically sustainable. In particular, the need for an integrated approach to the planning and management of land resources was highlighted in Chapter 10 of that document. Sustainable land management (SLM) has now emerged as a major global issue which is receiving considerable attention from scientists, developers, and policy makers.

Evaluation of the sustainability of land management requires that there be an adequate methodology by which reliable and objective assessments can be made. What has emerged in the last two years or so is the thinking that sustainability, in the land-use context, is multi-faceted in terms of definition and conception. Thus, not only are resource-availability limits a major issue, but economic viability, environmental impact, social justice, and biodiversity are embodied in the concept of sustainability (Dumanski et al., 1991). There are also spatial and temporal dimensions to sustainability, leading to a dynamic concept (Smyth and Dumanski, 1993) which has direct and major implications for the evaluation of SLM.

Decisions as to whether or not a particular type of land use is sustainable in a given environment over a stated period of time can potentially be assessed using a framework approach. The FAO Framework for Land Evaluation (FAO, 1976) has proved useful in assessing the suitability of land-use alternatives but it
cannot be used to assess sustainability or the probability of sustainability being achieved. As pointed out by Smyth and Dumanski (1993), however, the FAO Framework has proved to be a wise starting point for developing a Framework for assessing sustainability.

A major outcome of an international workshop on "Evaluation for Sustainable Land Management in the Developing World", held at Chiang Rai, Thailand, in September, 1991, was the setting up of an International Working Group to develop a Framework for Evaluating Sustainable Land Management (FESLM). The prototype Framework developed functions as a logical pathway for the assessment of the probability of sustainability by seeking to connect the form of land use with the range of environmental, economic, and social conditions which collectively determine whether a particular form of land management is sustainable or will lead to sustainability.

The Framework basically consists of five levels which can be grouped as follows: Levels 1 and 2, describing the Objective and the Means, respectively, indicate what will be evaluated; Levels 3, 4, and 5, describing the Evaluation Factors, Diagnostic Criteria, and Indicators and Thresholds, respectively, indicate how the evaluation will be carried out. It is with Level 5 in the Framework that this paper is concerned. The establishment of indicators and thresholds, as defined below, is an essential component of the evaluation of SLM using the recently-developed Framework.

Definitions and Requirements. The term "indicator" is used in quite diverse ways, according to the subject of concern and its context. In a generic sense, indicators may be defined as "variables whose purpose is to measure change in a given phenomenon or process" (Kumar, 1989). Indicators have been used to assess performance (the "performance indicators" used in education for example) or impact (the "impact indicators" of environmental or developmental assistance assessment). In the context of land management, or more specifically of agriculture, indicators can relate to sustainability (Hamblin, 1992) or, as is more frequently easier to assess, to unsustainability (Jodha, 1991). Before discussing the conceptual basis for identifying and developing indicators for SLM it is necessary to establish the requirements of indicators.

It is generally accepted that indicators should be verifiable objectively and replicable (Kumar, 1989). Significantly, they need not be quantitative and although direct measurements are preferred, they may be take on a surrogate or proxy form. What is clear is that a change in a given indicator can only be measured with respect to time. It is in this regard that indicators of SLM potentially find their most use.

Thresholds may be defined as levels of indicators beyond which a system undergoes significant change. The concept of "threshold" values for indicators in the FESLM is similar to that of critical values for the diagnostic factors in the FAO Framework for Land Evaluation (FAO, 1983) but an important difference is that in the FESLM there is only one threshold value for each indicator (Smyth and Dumanski, 1993). With regard to SLM, the threshold value may be regarded as the level of that indicator beyond which the particular system of land management is no longer sustainable.

It follows that the basic requirement of a threshold value is to provide a baseline figure against which sustainability can be assessed. As discussed below, such baseline figures are not always available and, once again, it is trends over time that are likely to be more important in the assessment of SLM.

Identification and Use of Indicators. Conceptually, indicators may be regarded as symptoms of behaviour in complex systems, they are used as diagnostics of the underlying status of the system.
Whereas indicators of human health (such as body temperature and blood pressure) and of economic status (such as Gross Domestic Production) are widely understood, environmental indicators which reflect ecosystem condition and status are usually less rigorously defined and less comprehensively researched.

There has been a recent spate of interest in the use of indicators in environmental and agricultural monitoring (OECD, 1992; World Bank, 1992; Smyth and Dumanski, 1993); much of this has been driven by international perceptions on the rate and extent of increase in man-induced environmental degradation. Indicators chosen to predict such effects of anthropogenic interactions with natural resources may fail to provide clear information and will almost certainly fail to predict the trend and rate of change to the environment unless they are (i) based on substantial research into the mechanisms and processes of interaction between the various components of the system and (ii) are monitored in a regular and comprehensive way.

The identification and development of indicators of sustainable (or unsustainable) land management is in its infancy, although recent attempts have been made to assess their role in the evaluation of SLM using the Framework (Eswaran et al., 1993; Smyth and Dumanski, 1993). Because social and cultural goals for land use differ from country to country, definitions as to what constitutes sustainable land management systems and thus the indicators which are useful for evaluating sustainability, vary accordingly. For example, the range of descriptions of SLM, espoused by OECD country members, demonstrates the difficulties in establishing a consensus definition. Whereas France sees the retention of current and historical rural landscapes as essential, the Netherlands sees the retention of agricultural productivity as being most significant; the United States leans towards the preservation and restitution of native ecosystems, and Australia and New Zealand envisage that market forces will be the main dictator of land use in their respective countries (OECD, 1992). Consensus in establishing appropriate indicators for evaluating SLM across national boundaries is consequently rather complicated.

Whereas there is little published information on the identification and development of indicators for SLM, in general, more is known about the application of indicators for sustainable agriculture. Eswaran et al. (1993) consider that part of the reason for this is that SLM is site specific and this requires locally-applicable indicators. It is important to establish the commonality of indicators of SLM, in contrasting resource management domains, so that the extent to which the use of particular indicators can be generalized in the application of the Framework can be determined. Good progress in this direction was made at the recent International Workshop on Sustainable Land Management for the Twenty-first Century held at Lethbridge, Canada in June, 1993 (Dumanski, 1993). Further work is required as a matter of priority if progress is to be made.

A useful example of the development of important primary indicators of sustainable agriculture is provided by the work of a multi-disciplinary group in Australia (Hamblin, 1992) which evaluated several agricultural systems in terms of management level, production base, and resource base. The matrix developed shown in Table 1 assumed that the indicators could be measured or reported, and that they reflected good or bad agricultural practices.

What is clear from the developing literature on indicators and their applications is that a direct measure of sustainability is difficult, indirect surrogates often being easier to establish. This arises, in part, from the fact that their use entails future prediction of a situation where current assumptions may not be valid. Similarly, the operationalization of sustainability is usually not easy and approaching sustainability from
Table 1 -- Major primary indicators of sustainable agriculture developed for some agricultural systems in Australia -- based on Hamblin (1992)

<table>
<thead>
<tr>
<th>Agricultural system</th>
<th>Level of management</th>
<th>Production balance</th>
<th>Resource base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain-fed systems</td>
<td>Farm management skills; cash flow, equity, planning</td>
<td>Water-use efficiency; yield area$^{-1}$ rainfall$^{-1}$</td>
<td>Soil health; pH, nutrient balance, biota</td>
</tr>
<tr>
<td>High-rainfall pastures</td>
<td>Production area$^{-1}$, animal weight ha$^{-1}$</td>
<td>Plant growth/cover; percent greenness, species area$^{-1}$</td>
<td>Soil bio-indicators; worms, termites, etc. numbers and species</td>
</tr>
<tr>
<td>Low-rainfall rangeland</td>
<td>Management capability; planning debts, asset condition, record keeping</td>
<td>Animal health and performance; meat, fleece, weight gain</td>
<td>Pasture and soil condition, percent bare ground pasture composition</td>
</tr>
<tr>
<td>Irrigated crops and pastures</td>
<td>Farm and district profitability; cost/benefit, debt equity</td>
<td>Water-use efficiency; water-table trends, water used</td>
<td>Soil health; infiltration rate, subsoil compaction</td>
</tr>
<tr>
<td>High-rainfall tropical systems</td>
<td>Diversity of production; number of land uses or crops</td>
<td>Water quality, surface water composition, pesticides, sediments</td>
<td>Soil productivity; pH and organic-matter trends, soil structure</td>
</tr>
</tbody>
</table>
an unsustainability standpoint is usually more practicable. Jodha (1991, 1993) has made good progress in this regard and has categorized types of negative changes as indicators of unsustainability which are related to the resource base and resource use. In the context of the resource base, such negative changes may be directly visible (e.g., landslides, reduction in irrigation water flow, etc.), they may be changes in response to resource degradation (e.g., changes in type of animal and from deep-rooted to shallow-rooted crops, etc.), or they may be potentially negative changes due to development interventions (e.g., excessive dependence on subsidies, ignoring traditional experience, etc.).

A further point to take on board when considering indicators of land quality with regard to sustainability is that economic and social factors must be taken into consideration. Thornton (1993) lists several economic "factors" or "qualities" which can be used as indicators of where actual or potential sustainability can exist in a particular system. These are grouped into resources, economic environment, attitudes, and complex qualities. In addition, the economic consequence of off-site effects, such as siltation of reservoirs and flooding, and any negative effects of agrochemicals are increasingly being scrutinized. Factors of the social environment must also be considered in evaluating SLM using the Framework. Spendjian (1993) has outlined several categories of characteristics which require assessment. Some are at best qualitative and to biophysicists, at least, somewhat subjective. If the social dimension is to receive the prominence required in applying the Framework for evaluating SLM it appears that there is much work to be done in developing appropriate indicators.

Finally, in relation to indicators, the point should be made that it is highly unlikely that the use of a single indicator can provide for a reliable assessment of sustainability or unsustainability, unless the unsustainability of a particular land-use system is clear-cut. It is more likely that a range of indicators, covering all potentially unstable aspects of the system, will provide for a reliable assessment (Smyth and Dumanski, 1993).

**Establishing thresholds.** As emphasized earlier, a threshold provides a baseline figure for an indicator against which sustainability can be assessed. It would be expecting too much for a single threshold value to represent the boundary or cut-off between sustainable and unsustainable; what is required is a range of threshold values and trends for particular indicators. This would be consistent with the rating of diagnostic factors in the *FAO Guidelines for Land Evaluation* (1983), where a range of values is used to describe ratings of highly, moderately, marginally, and not suitable.

Our understanding of likely thresholds is poor, except for a very limited number of environmental indicators. For example, it is well-established that soil acidity influences the toxicity and availability of certain elements in soils. Below a soil pH of approximately 4.5, aluminium toxicity to plants and microorganisms can be a serious growth-limiting factor, as can a deficiency of soil phosphorus because of reduced availability under strongly acid conditions. A narrow range of soil pH values can be regarded as an approximate threshold for the primary indicator, -- soil acidity. Changes in nutrient availability with variations in soil acidity then become secondary indicators and for a given soil type, threshold values are sometimes known reasonably well, at least for the major nutrients (phosphorus and potassium).

For other soil factors, the information base on thresholds is much less well-developed. What also must be realized is that a threshold for a particular indicator is often soil-type dependent and even more likely to be determined by the resource management domain in question. This again emphasizes the need to consider a range of threshold values for a particular indicator.
A consistent and reproducible system of threshold values is required for use with the Framework and this is arguably one of the greatest challenges facing its further development and application. In a simplistic way, critical values of diagnostic factors which separate “not suitable” land from “marginally suitable” land in the 1983 FAO Guidelines for Land Evaluation could be regarded as thresholds of sustainability. As emphasized by Smyth and Dumanski (1993), however, such a simple application of the concept of sustainability thresholds ignores the concept of time and as emphasized earlier, trends in critical indicators are likely to prove more useful than a one-point-in-time-observation.

The authors are not aware of any substantial body of information on threshold values for biophysical indicators which can be used to assess sustainable land use for agriculture. However qualitative and quantitative indices, with same values for thresholds, have been combined to assess the suitability of soils and land for certain crops, e.g., *Hevea brasiliensis*, or rubber, discussed in the next section.

The values for a number of biophysical indicators can be altered by management or mismanagement, e.g., for soils, depth due to erosion, available water, pH, soil organic matter, and available nutrient levels. Deviations from a threshold value can affect productivity, negatively or positively, and hence sustainability. Consequently, it is possible to consider such indicators and thresholds for use in assessing sustainability.

It may be concluded that there is limited information on thresholds for key indicators which can be used to assess SLM. Although it is not easy work, the development of thresholds is of high priority for using the FESLM. It is certainly necessary to provide a more quantitative basis for assessment which will decrease subjectivity and increase the reliability of the analysis.

**Case Studies Involving Indicators and Thresholds.** Two case studies will be used to illustrate the use of indicators and thresholds in the evaluation of sustainability. The first relates to the suitability of soils and land for the production of rubber (*Hevea brasiliensis*) and the second relates to the sustainable management of sloping lands for agriculture in the Philippines.

Several biophysical indicators have been identified which when combined allow for the assessment of suitability status for rubber (Table 2). The initial study of Chan and Pushparajah (1972) involved soil physical properties. Subsequently, Chan et al., (1975) attempted to quantify the various soil and physiographic parameters involved. The desired characteristics were soil depth (> 100 cm), good drainage (USDA-Class D), good aeration, good structure, absence of peat or acid sulphate, a clay content of 35-50%, a sand content of 35-50%, and a slope of <8°. Each character was given equal weighting. This was later modified (Pushparajah, 1977) by including available soil water, chemical properties, and several external factors. Subsequently, Yew (1982) made further refinements and included climatic indices using a parameter approach to assess the suitability of land and soil for *Hevea* cultivation. The relationship between the yield of dry rubber and the combined indices gave the following equation:

\[ y = 0.586x + 44.54 \quad (r = 0.95^{***}) \]

Where \( y \) = yield and \( x \) = soil index value
Table 2 — Selected climate and soil physical criteria for grading soil suitability for rubber — from Pushparajah (1977) and Yew (1982)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Degree of limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nil</td>
</tr>
<tr>
<td>A. Climate</td>
<td></td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td></td>
</tr>
<tr>
<td>- Mean</td>
<td>25.0-28.0</td>
</tr>
<tr>
<td>- Daily maximum</td>
<td>29.0-34.0</td>
</tr>
<tr>
<td>- Daily minimum</td>
<td>&gt; 20.0</td>
</tr>
<tr>
<td>Mean rainfall (mm y⁻¹)</td>
<td>&gt; 2000</td>
</tr>
<tr>
<td>Dry season (months)</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>Rain interference (days)</td>
<td>&lt; 30</td>
</tr>
<tr>
<td>Sunshine (h y⁻¹)</td>
<td>&gt; 2100</td>
</tr>
<tr>
<td>B. Soil physical factors</td>
<td></td>
</tr>
<tr>
<td>Texture</td>
<td></td>
</tr>
<tr>
<td>Equal proportions of silt, clay, and sand</td>
<td></td>
</tr>
<tr>
<td>Loam (&lt; 50-70% sand)</td>
<td></td>
</tr>
<tr>
<td>Clay (&lt; 50-70% clay)</td>
<td></td>
</tr>
<tr>
<td>Silty clay (&lt; 50-70% silt + clay)</td>
<td></td>
</tr>
<tr>
<td>Very sandy (&lt; 70-90% sand)</td>
<td></td>
</tr>
<tr>
<td>Very clayey (&lt; 70-90% clay)</td>
<td></td>
</tr>
<tr>
<td>Very silty clay (&gt; 70-90% silt + clay)</td>
<td></td>
</tr>
<tr>
<td>Sand (&gt; 90% sand)</td>
<td></td>
</tr>
<tr>
<td>Very clayey (&lt; 70-90% clay)</td>
<td></td>
</tr>
<tr>
<td>Very silty clay (&gt; 70-90% silt + clay)</td>
<td></td>
</tr>
<tr>
<td>Very sandy (&gt; 70-90% sand)</td>
<td></td>
</tr>
<tr>
<td>Clay (&lt; 90% clay)</td>
<td></td>
</tr>
<tr>
<td>Silt clay (&gt; 90% silt + clay)</td>
<td></td>
</tr>
<tr>
<td>Effective depth</td>
<td>&gt; 150 cm</td>
</tr>
<tr>
<td>Stoniness of subsoil</td>
<td>Almost absent</td>
</tr>
<tr>
<td>Internal drainage (USDA)</td>
<td>Well drained</td>
</tr>
<tr>
<td>Available water (cm m⁻³)</td>
<td>&gt; 150</td>
</tr>
<tr>
<td>Permeability</td>
<td>Moderate</td>
</tr>
<tr>
<td>Erodibility (USDA Class)</td>
<td>Slightly erodible</td>
</tr>
<tr>
<td></td>
<td>(1)</td>
</tr>
</tbody>
</table>
Table 3—Assessment of sustainability at Mabini, Philippines using yield data (kg ha\(^{-1}\)) -- data from Paningbatan et al. (1992, 1993)

<table>
<thead>
<tr>
<th>Crop*</th>
<th>Year</th>
<th>Treatment*</th>
<th>(T_1)</th>
<th>(T_2)</th>
<th>(T_3)</th>
<th>(T_4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Maize</td>
<td>1989</td>
<td></td>
<td>100</td>
<td>320</td>
<td>1200</td>
<td>1740</td>
</tr>
<tr>
<td>2nd Peanuts</td>
<td></td>
<td></td>
<td>320</td>
<td>210</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>3rd Maize</td>
<td>1990</td>
<td></td>
<td>2100</td>
<td>3060</td>
<td>4540</td>
<td>4730</td>
</tr>
<tr>
<td>4th Peanuts</td>
<td></td>
<td></td>
<td>1420</td>
<td>1330</td>
<td>1460</td>
<td>1280</td>
</tr>
<tr>
<td>5th Maize</td>
<td>1991</td>
<td></td>
<td>340</td>
<td>980</td>
<td>1340</td>
<td>1040</td>
</tr>
<tr>
<td>6th Peanuts</td>
<td></td>
<td></td>
<td>630</td>
<td>510</td>
<td>550</td>
<td>690</td>
</tr>
<tr>
<td>7th Maize</td>
<td>1992</td>
<td></td>
<td>860</td>
<td>1510</td>
<td>2450</td>
<td>2790</td>
</tr>
</tbody>
</table>

Total yield
- Maize: 4 crops: 3400, 5870, 9530, 10300
- Peanuts: 3 crops: 2370, 2050, 2130, 2070

*Maize yield = Fresh marketable ear yield; peanuts yield = weight of seeds
+\(T_1\) = Farmers practice of up-and-down the slope
\(T_2\) = Hedgerows of *Gliricidia* and napier grass
\(T_3\) = As for \(T_2\), but with fertilizer inputs to maize
\(T_4\) = Hedgerows of banana + sapodilla with fertilizers to maize
Table 4 -- Benefit-cost ratios at Mabini, Philippines -- data from Paningbatan et al. (1992, 1993)

<table>
<thead>
<tr>
<th>Crop number *</th>
<th>T₁</th>
<th>T₂</th>
<th>T₃</th>
<th>T₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st crop</td>
<td>-0.88</td>
<td>-0.72</td>
<td>-0.19</td>
<td>-0.66</td>
</tr>
<tr>
<td>2nd</td>
<td>-0.77</td>
<td>-0.41</td>
<td>-0.72</td>
<td>-0.74</td>
</tr>
<tr>
<td>3rd</td>
<td>-0.95</td>
<td>1.67</td>
<td>2.30</td>
<td>2.84</td>
</tr>
<tr>
<td>Cumulative 3 crops</td>
<td>0.12</td>
<td>0.27</td>
<td>0.57</td>
<td>-0.03</td>
</tr>
<tr>
<td>4th crop</td>
<td>4.28</td>
<td>30.73</td>
<td>3.29</td>
<td>3.74</td>
</tr>
<tr>
<td>Cumulative 4 crops</td>
<td>1.14</td>
<td>1.07</td>
<td>1.20</td>
<td>0.48</td>
</tr>
<tr>
<td>5th crop</td>
<td>-0.42</td>
<td>+0.41</td>
<td>0.87</td>
<td>7.67</td>
</tr>
<tr>
<td>Cumulative 5 crops</td>
<td>+0.90</td>
<td>0.96</td>
<td>1.15</td>
<td>1.11</td>
</tr>
<tr>
<td>6th crop</td>
<td>+1.91</td>
<td>+1.15</td>
<td>1.01</td>
<td>2.44</td>
</tr>
<tr>
<td>Cumulative 6 crops</td>
<td>1.13</td>
<td>1.00</td>
<td>1.07</td>
<td>1.33</td>
</tr>
<tr>
<td>7th crop</td>
<td>-0.04</td>
<td>0.52</td>
<td>1.07</td>
<td>1.29</td>
</tr>
<tr>
<td>Cumulative 7 crops</td>
<td>0.94</td>
<td>0.93</td>
<td>1.11</td>
<td>1.32</td>
</tr>
</tbody>
</table>

* See Table 3 for the crops

+ T₁ = Farmers practice of up-and-down the slope.
+ T₂ = Hedgerows of *Gliricidia* and napier grass.
+ T₃ = As for T₂, but with fertilizer inputs to maize.
+ T₄ = Hedgerows of banana + sapodilla with fertilizers to maize.
The criteria indicated can be used to assess sustainability. However, in the case of rubber, the fact that a 25-year planting cycle is used and that clearing and tillage are done only once every 25 years, at the time of planting ensures that, together with the “closed” system of the rubber crop, any loss in sustainability is slow to develop.

In contrast, land degradation and loss of sustainability with food crop production on sloping lands can be more rapid. This is well-illustrated by results from IBSRAM’s ASIALAND Management of Sloping Lands network in which, since 1989, several countries have evaluated sustainable management of sloping lands for agriculture. Early results from a trial at Mabini in the Philippines for the period 1989 to 1992 have been reported by Paningbatan et al. (1992) and (1993). There were no discernible trends in the chemical parameters assessed, despite a soil loss of 170 t ha\(^{-1}\) with the farmer’s practice and about 2 t ha\(^{-1}\) with the improved practices during erosive events in 1990, 1991, and 1992. An assessment of yield (Table 3) also does not provide any clear trends in sustainability. On the other hand, an evaluation of the benefit-cost ratio (Table 4) provides a better indication of stability. The improved treatment (T\(_3\)) which involves hedgerows and nutrient inputs) gives a benefit-cost ratio in excess of 1.0 from the third crop whereas T\(_2\) (similar to T\(_3\) but without fertilizers) does not always provide a high benefit-cost ratio, as for the farmer’s practice.

Measurement of soil erosion by estimating sediment bed load and suspended solids leaving the experimental plot often does not provide a true picture of soil loss. Paningbatan et al. (1993) showed that even with the improved treatment, soil movement was large, but soil accumulated along the hedgerow barriers and formed terraces. The interaction between on-site and off-site effects requires further investigation.

Thus it appears that, in this case, economic indicators tend to give a clearer picture of trends and hence sustainability. However, there is a need to bring together information on economic, environmental, social, and production indicators to achieve a more meaningful evaluation of SLM using the Framework.

Conclusions. Evaluation of SLM can potentially be achieved using a Framework approach. The FESLM developed and currently under evaluation, requires reliable information on indicators and thresholds of sustainability for its successful implementation. Whereas there is a reasonable amount of information available on a range of indicators for assessing sustainability, much less is known about threshold values and this is arguably one of the highest priorities for future work. It seems likely that a range of threshold values is required for a particular indication and that the variation around this range over time requires evaluation. Case studies, using different resource management domains, are seen to be the most useful way of further developing thinking and establishing indicators and thresholds for the evaluation of SLM.

Literature Cited


Framework for Evaluation of Sustainable Land Management: Case Studies of Two Rainfed Cereal-Livestock Land Use Systems in Canada

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Abstract. The Framework for Evaluation of Sustainable Land Management (FESLM) was used to assess the sustainability of two land use systems in the Canadian Prairies. The FESLM provided a means whereby identification could be made of the factors impacting on sustainability, the processes by which these factors operate and interact, as well as the indicators and thresholds by which they could be measured in order to attain an assessment end point. On the basis of the framework, a conventional land use system was assessed as unsustainable, whereas a conservation based land use system was found sustainable.

Introduction. Global population growth exerts ever increasing demands for food resources. With most land suitable for agriculture currently in production, productivity levels on existing agricultural land must not only be maintained but increased in a sustainable manner (Dumanski et al., 1991; Ruttan, 1991). Conversely, there is evidence that agricultural land is degrading at an alarming rate (WRI 1992). In order to address such issues, the forces influencing agriculture, particularly the complex interaction of environmental, economic and social factors affecting it must be understood. Specifically, there is need for methods to evaluate i) the agricultural capability of a given parcel of land; and ii) the sustainability of agricultural production practices on that land based on criteria that reflect the interplay of all pertinent factors.

Aspects of these were addressed through the FAO criteria for land evaluation (FAO, 1976), which consisted of a framework for assessing land suitability (identification of the best land for a particular use) and capability (identification of the best use for a particular land). In a more recent initiative, an International Working Group headed by the International Board for Soil Research and Management (IBSRAM) and Centre for Land and Biological Resources Research (CLBRR), in collaboration with FAO and others, has developed a "Framework for Evaluation of Sustainable Land Management" (FESLM). The FESLM consists of criteria for assessing the sustainability of land use systems based on principles of sustainable land management (SLM). SLM is defined as a system that combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously: maintain or enhance production/services; reduce the level of production risk; protect the potential of natural resources; be economically viable; and be socially acceptable (Dumanski and Smyth, 1994). These objectives constitute the five basic pillars of SLM, respectively, productivity, security, protection, viability and acceptability. The FESLM consists of a pathway to guide the analysis of land use sustainability, through a series of scientifically sound, logical steps (FAO, 1994). It is comprised of two main stages: i) identification of the purpose of evaluation, specifically land use systems and management practices; and ii) definition of the process of analysis, consisting of the evaluation factors, diagnostic criteria, indicators and thresholds to be utilized.

The case studies make use of the FESLM to assess the sustainability of conventional and conservation based rain-fed cereal systems in Alberta, Canada. The studies also serve as a means
of assessing the efficacy of the FESLM as a sustainability evaluation tool. The studies were carried out by evaluating the agricultural practices of Mr. Lance Wheeler, a farmer in southern Alberta. Lance practiced conventional agricultural production until 1986 at which time he began a transition to conservation farming. Since 1989, Lance's production was wholly based on conservation methods.

Materials and Methods. The FESLM consists of five levels within two stages (Table 1). Implementing the FESLM through the five levels provides the necessary criteria, indicators and thresholds to predict the status of identified evaluation factors over a defined period for sustainability assessment.

Table 1. The stages, levels and aims of FESLM.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Level</th>
<th>Aim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose</td>
<td>1. Objective</td>
<td>• Identification of purpose and location of land use system; time period for evaluation</td>
</tr>
<tr>
<td></td>
<td>2. Means</td>
<td>• Definition of management practices employed to attain Objective</td>
</tr>
<tr>
<td>Analysis</td>
<td>3. Evaluation Factors</td>
<td>• Identification of environmental, economic and social factors pertinent to the evaluation</td>
</tr>
<tr>
<td></td>
<td>4. Diagnostic Criteria</td>
<td>• Identification of impact of identified factors on sustainability</td>
</tr>
<tr>
<td></td>
<td>5. Indicators and Thresholds</td>
<td>• Identification of attributes which provide a measure of sustainability</td>
</tr>
</tbody>
</table>

Source: FAO (1994).

Information for the case studies was obtained by conducting interviews with Lance and visiting his farm operation. The type of information sought is outlined in Table 2.

Table 2. Outline of the information obtained for the case study.

| Type of Operation (corporation, private) |
| Farmer's Age Group                        |
| Land Holding (total area; percent owned, rented) |
| Commodities (crops grown; livestock production) |
| Field Information (soil type, texture; occurrence of degradation) |
| Conservation Practices (tillage types; residue management schemes; fallowing methods; crop rotations) |
| Decision Making Signals (crop productivity; production risk; resource base protection; economic viability; social acceptability) |

Additional information pertaining to economic factors was obtained from reports prepared by the Canada/Alberta Research and Technology Transfer (CARTT) initiative and from Cost of Production tables prepared by Alberta Agriculture (Woloshyn and Machielse, 1992).

Results and Discussion. The type of crops grown and cultural practices utilized are determined primarily by the agroecological conditions prevailing in a given region. The agroecological regions of the Canadian Prairies experience heat and moisture limitations with a maximum agricultural growing season of three to four months, annual precipitation of 300 to 400 mm, of which 150-250
mm occurs during the growing season. Consequently, a majority of the agricultural systems are comprised of the production of small grains and oilseeds in rotation with forages, with some farms incorporating animal production. Moisture conservation and management schemes are predominant in all crop production schemes. Farm products are targeted to national and international markets.

The FESLM was applied in these case studies in the following manner:

Case Study 1: Conventional farming

PURPOSE
1. Objective. This study evaluated the sustainability of an agricultural production system based on conventional farming practiced until 1986 by Lance Wheeler on a 350-425 ha farm in southern Alberta. The mode of production was fully mechanized, capital intensive and consisted of mixed cropping with a 600-700 head hog and a 40 head cattle operation. Crop production made use of commercial seeds, fertilizers and pesticides.

2. Means. The land management practices included a three year crop rotation of canola, barley, and summerfallow. Conventional tillage was used for soil preparation, and consisted of one to two passes in the fall, and one to two pre-seeding passes with a wide-blade cultivator, as well as one pass with a rod-weeder, and one herbicide application with a sprayer at post-emergence. Summerfallowing, the practice of leaving a field fallow and devoid of growth during an entire crop growing season, was utilized for moisture conservation. In order to control weeds on summerfallow fields, there were at least four cultivation passes. Fertilizer in the form of N-P-K (11-55-0) was applied annually at rates of 45-55 kg/ha. During production after a non-fallow year, an additional 55 kg/ha of fertilizer was applied in the form of nitrogen (NH₃) by banding.

ANALYSIS
3. Evaluation Factors. The principal evaluation factors, diagnostic criteria and indicators used for evaluation of the sustainability of the conventional rainfed crop production system are shown in Table 3. The significance of each parameter is discussed below.

Physical. Lance’s farm is on a sandy loam soil in the Black Chernozemic zone of southern Alberta. The region is susceptible to moisture and heat limitations, wind erosion, and salinity. The Black Chernozemic soil zone is the most fertile in the Prairies with relatively high crop yields. The sandy loam soils in the region are susceptible to erosion, and require adequate crop cover and organic matter management for reducing erosion risks and maintaining fertility. Low annual rainfall requires that sufficient moisture be present in the soil profile at the beginning of the crop growing season to ensure germination. Under conventional tillage, this is normally achieved by keeping the land in fallow for one growing season, and restricting weed growth through tillage. The crop growing season is 100-110 days and ranges from early May to mid August. Factors such as risk of early or late frost and excessive precipitation during seeding or harvesting periods can significantly affect the length of the crop growing season. Farmers in the region indicate that frequent adverse weather conditions such as intense rain storms, hail storms and periods of strong wind storms can occur during the crop growing season.

*Numbered headings represent FESLM levels as outlined in Table 1.
**Table 3. Evaluation factors, diagnostic criteria and indicators for evaluating the sustainability of a rainfed crop production system.**

<table>
<thead>
<tr>
<th>Evaluation Factors</th>
<th>Diagnostic Criteria</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• moisture availability (low seasonal precipitation)</td>
<td>• soil moisture conservation</td>
<td>• percent land in fallow</td>
</tr>
<tr>
<td>• short growing season length</td>
<td>• soil cover maintenance for erosion control</td>
<td>• method of fallow</td>
</tr>
<tr>
<td>• hail storm hazards</td>
<td>• depth of soil moisture at seeding</td>
<td>• percent &amp; trends of degradation</td>
</tr>
<tr>
<td>• erosion hazards</td>
<td>• type of tillage practice</td>
<td></td>
</tr>
<tr>
<td>• salinization hazards</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• soil moisture conservation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• soil cover maintenance for erosion control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• percent land in fallow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• method of fallow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• depth of soil moisture at seeding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• percent &amp; trends of degradation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• type of tillage practice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biological</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• soil fertility management</td>
<td>• maintenance of adequate nutrients</td>
<td>• changes in fertilizer and pesticide use</td>
</tr>
<tr>
<td>• weed control in fallow</td>
<td></td>
<td>• length &amp; diversity of rotations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• crop yield trends</td>
</tr>
<tr>
<td>Economic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• operating costs</td>
<td>• production cost reductions</td>
<td>• trends in cost of production</td>
</tr>
<tr>
<td>• revenues</td>
<td>• risk minimization</td>
<td>• gross margin</td>
</tr>
<tr>
<td>• government subsidies</td>
<td></td>
<td>• number and types of government programs</td>
</tr>
<tr>
<td>• management objectives (profit/utility maximization; risk reduction, etc.)</td>
<td></td>
<td>• farmer’s management objectives</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Social</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• viability of rural communities</td>
<td>• proximity to available services</td>
<td>• distance to services</td>
</tr>
<tr>
<td>• acceptability of farming practices</td>
<td></td>
<td>• social perceptions of conservation practices</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• reasons for participation in government programs</td>
</tr>
</tbody>
</table>

**Biological.** In addition to its role as a moisture conserving strategy, summerfallowing is used as a management strategy for soil nutrient build-up. Stubble and residue left at harvest serve to increase soil moisture reserves by snow entrapment, but they also increase organic matter, build up soil nutrients and control erosion. In systems that include animal production, spreading manure on soils serves as additional fertilizer and organic matter input.

**Economic.** Prairie agriculture has functioned under falling commodity prices, increased competition from international producers and increased equipment and input costs. Income from small-grain cereal production has declined over the years, with barley prices dropping to $79/t in 1992 from $115/t in 1988.

The government policies and programs that predominate are: (i) risk management strategies: Crop Insurance (against crop failure or damage); income stabilization against fluctuating commodity prices: Gross Revenue Insurance Program (GRIP); (ii) Strategies to protect marginal land: PFRA permanent cover program which excludes marginal land from insurance and program coverage; (iii) subsidies: the Alberta agricultural fuel subsidy program commits 20% of the provincial agricultural budget to subsidize farmer’s fuel costs.

The management strategies and preferences of farmers (e.g. profit/utility maximization; risk reduction; planning horizon) play an important role in the relative effect of different economic signals.
Social. With the role of agriculture declining relative to other sectors, there are continued reductions in rural population. This has been accompanied with loss of services (schools, hospitals, banks, businesses, etc.) which in turn contributes to further declines in rural population.

The social acceptability of farming practices is an issue with some farmers in the region. Conservation practices such as reduced or zero tillage are not socially accepted because they are considered "sloppy". Often, the immaculate look of heavily tilled summerfallow fields are preferred to the "unkempt" appearance of fields under conservation farming. Some farmers avoid sustainable field practices due to such perceptions.

4. Diagnostic Criteria

Physical. Because rainfall during the growing season is limited to 150-250 mm, attaining sufficient moisture for crop growth has been critical in Lance's management decisions. Farmers' opinions are that reliable yields can be obtained only one year in two on a given field due to moisture limitations. Consequently, they practice summerfallowing to conserve soil moisture on uncropped fields. Under such a practice, Lance annually kept a third of his farm in summerfallow to maintain soil moisture. Summerfallowing typically required four or more tillage operations to ensure that weeds did not deplete limited soil moisture reserves, making such fields highly susceptible to wind erosion. Degradation due to wind erosion affected the entire area of Lance's farm committed to summerfallow (Table 4). Considering that the area under fallow was rotated, the entire farm under crop production experienced erosion during a three year period. Farmers' experience is that a single-season incidence of moderate erosion can reduce cereal crop yields by 10-25%.

Table 4. Data on land management parameters in the rainfed crop production system for the period 1980-84 up to 1993.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>80-84</th>
<th>85</th>
<th>86</th>
<th>87</th>
<th>88</th>
<th>89</th>
<th>90</th>
<th>91</th>
<th>92</th>
<th>93</th>
</tr>
</thead>
<tbody>
<tr>
<td>land under fallow (%)</td>
<td>30</td>
<td>20</td>
<td>18</td>
<td>20</td>
<td>15</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fallow method</td>
<td>tillage</td>
<td>chemical &amp; tillage</td>
<td>chemical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>area affected by erosion (%)</td>
<td>30</td>
<td>20</td>
<td>15</td>
<td>6</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>tillage practice (conventional; conservation/reduced; zero)</td>
<td>conventional</td>
<td>reduced</td>
<td>zero*</td>
<td>zero</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fertilizer use: on fallow (per ha)</td>
<td>45 kg 11-55-0 N-P-K</td>
<td></td>
<td>55 kg N(NH₃) &amp; 45 kg 11-55-0 N-P-K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>on stubble</td>
<td>55 kg N(NH₃) &amp; 45 kg 11-55-0 N-P-K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*One cultivation required for managing excess residue prior to seeding.
Source: producer.

Biological. Benefits obtained in nutrient build-up due to fallowing were counterbalanced by loss of soil fertility due to eroded topsoil, resulting in crop yield losses or increased fertilizer use to maintain yields. Furthermore, there was increased risk of sediment loading of ditches and streams. Manure addition supplemented the soil with nutrients, but there was potential for surface and groundwater contamination.
Economic. Topsoil loss due to wind erosion on summerfallow decreased soil fertility, leading to increases in the use of fertilizers. Concurrently, fertilizer prices have risen relative to grain prices, as have other input prices (Table 6), adding to escalating costs of production. Census data for 1986 showed that fuel and fertilizer costs were 13% and 12%, respectively, of total operating costs (Kirkwood et al., 1993). Falling prices for small-grain cereals due to increased competition from international producers have added to the debt loads and cash flow constraints experienced by most Prairie farmers. Crop Insurance was seen by Lance and other farmers in the region as necessary and beneficial in areas that experience droughts and hail damage.

The main management strategy under conventional farming was risk management. Since financial constraint was a critical factor, maintaining reliable yields was of primary importance. Such factors entailed increased use of fertilizers and fostered the continuation of summerfallow. Lance's long-term animal production operation provided a buffer against falling grain prices and served as an added risk-management strategy.

Social. Lance lives about 50 km from a major urban centre, and as such sees himself within an acceptable distance for access to services. He has indicated, however, that towns and communities further than 50 km away are dying due to dwindling populations resulting from lack of services, or opportunities for off-farm labour.

5. Indicators and Thresholds. The indicators used for assessing the sustainability of conventional crop production and the characteristics that they signify are given in Table 5.

Table 5. Indicators and their significance in sustainability evaluation.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Indicated Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td>potential for erosion</td>
</tr>
<tr>
<td>percent land in fallow</td>
<td>susceptibility to erosion</td>
</tr>
<tr>
<td>method of fallow</td>
<td>rates of germination</td>
</tr>
<tr>
<td>depth of soil moisture at seeding</td>
<td>severity of degradation</td>
</tr>
<tr>
<td>percent &amp; trends of degradation</td>
<td>potential for soil resource conservation</td>
</tr>
<tr>
<td>type of tillage practice</td>
<td></td>
</tr>
<tr>
<td>Biological</td>
<td>soil nutrient and pest status; risk of pollution</td>
</tr>
<tr>
<td>changes in fertilizer and pesticide use</td>
<td>potential for natural fertility and pest control</td>
</tr>
<tr>
<td>length &amp; diversity of rotations</td>
<td>stability of production</td>
</tr>
<tr>
<td>crop yield trends</td>
<td></td>
</tr>
<tr>
<td>Economic</td>
<td>changes in relative costs and returns</td>
</tr>
<tr>
<td>trends in cost of production</td>
<td>operating cash flow</td>
</tr>
<tr>
<td>gross margin</td>
<td>amount of support required for production</td>
</tr>
<tr>
<td>number and types of government programs</td>
<td>type of planning strategy</td>
</tr>
<tr>
<td>farmer’s management objectives</td>
<td></td>
</tr>
<tr>
<td>Social</td>
<td>susceptibility of community attrition</td>
</tr>
<tr>
<td>distance to services</td>
<td>facility for adoption of conservation practices</td>
</tr>
<tr>
<td>social perceptions of conservation practices</td>
<td>flexibility of farmer’s operation</td>
</tr>
<tr>
<td>reasons for participation in government programs</td>
<td></td>
</tr>
</tbody>
</table>

ASSESSMENT
Trends for most of the indicators identified above clearly indicate that agricultural production in the Canadian Prairies using conventional farming practices was not sustainable on the basis of the pillars of SLM (Tables 4 and 6). Physical indicators showed that although fallowing ensured sufficient soil moisture for crop production, the extent and method of fallow contributed to
continued topsoil loss and yield reductions. The use of conventional tillage for seedbed preparation increased susceptibility to soil erosion. Biological indicators showed that fertilizer and pesticide use increased to maintain crop yields and counteract weed and disease resistance to pesticides. Growing season precipitation and crop yields showed substantial variability, indicating a lack of stability. Economic indicators of costs of production and gross margin showed downward trends in commodity prices, coupled with increases in input costs. The only indicators that showed sustainable trends were the farmer’s management objectives and distance to services. This analysis indicated that acceptability was the only SLM pillar that was satisfied, whereas the status of all other pillars demonstrated that conventional land management practices in this environment were unsustainable.

Table 6. Growing season precipitation, crop yields, relative costs and returns for inputs under rainfed agriculture.

<table>
<thead>
<tr>
<th>Year</th>
<th>Precipitation* (mm)</th>
<th>Yields (t/ha)**</th>
<th>Relative Costs/Returns*</th>
<th>Grain*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Barley</td>
<td>Canola</td>
<td>Fuel</td>
<td>Fertilizer</td>
</tr>
<tr>
<td>1980</td>
<td>280.0</td>
<td>4.86</td>
<td>72.2</td>
<td>82.8</td>
</tr>
<tr>
<td>1981</td>
<td>366.4</td>
<td>3.51</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>1982</td>
<td>267.7</td>
<td></td>
<td>117.2</td>
<td>92.0</td>
</tr>
<tr>
<td>1983</td>
<td>158.4</td>
<td></td>
<td>123.6</td>
<td>86.5</td>
</tr>
<tr>
<td>1984</td>
<td>179.8</td>
<td>3.78</td>
<td>128.8</td>
<td>90.1</td>
</tr>
<tr>
<td>1985</td>
<td>182.2</td>
<td>2.97</td>
<td>135.7</td>
<td>89.9</td>
</tr>
<tr>
<td>1986</td>
<td>264.0</td>
<td>5.13</td>
<td>115.7</td>
<td>85.8</td>
</tr>
<tr>
<td>1987</td>
<td>263.7</td>
<td>2.97</td>
<td>109.1</td>
<td>80.9</td>
</tr>
<tr>
<td>1988</td>
<td>311.3</td>
<td>3.24</td>
<td>107.7</td>
<td>81.2</td>
</tr>
<tr>
<td>1989</td>
<td>234.1</td>
<td>3.51</td>
<td>107.7</td>
<td>80.3</td>
</tr>
<tr>
<td>1990</td>
<td>303.5</td>
<td>2.70</td>
<td>139.7</td>
<td>77.8</td>
</tr>
<tr>
<td>1991</td>
<td>303.1</td>
<td>2.43</td>
<td>152.3</td>
<td>77.1</td>
</tr>
<tr>
<td>1992</td>
<td>432</td>
<td>4.32</td>
<td>155.3</td>
<td>76.0</td>
</tr>
</tbody>
</table>

*Growing season precipitation (May 1 to August 31).
**Source: Producer. Yields records for 1982 and 1983 not available.
*Relative costs and returns for rainfed agricultural production in Alberta; 1981 = 100
*Based primarily on feed barley.
*Source: F. Jetter, Alberta Agriculture. Personal communication.

Case Study 2: Conservation farming

On the basis of the evidence, Lance concluded that conventional farming was not sustainable and began a transition to conservation cropping practices in 1986 with full conversion to minimum tillage by 1989, and zero tillage in 1993. The overall objectives of the operation were the same, with modifications made to the means of achieving those objectives. The use of the framework in evaluating the new means is presented below.

PURPOSE

1. Objective. The objectives of the crop production operation were identical to those described under conventional farming systems, with two changes: i) the operation was increased from 425 to 480 ha and the hog operation increased to 1100 head; and ii) the 40 head cattle operation, which was previously in place, was discontinued in 1990.
2. Means. Production under conservation farming consisted of a cereal, oilseed, legume cropping rotation with barley as the major crop. Specialty crops, such as flax, were also included for added revenue when warranted by the market. The type and proportion of crops grown were: barley 30%, canola 15%, feed wheat 10% and field peas 10%. Lance reduced his summerfallow area to 8% of cropped land and also kept 20% of his land in pasture. The land management practices consisted of zero tillage, one herbicide application at pre-seeding and two applications at post-emergence. Fertilizer in the form of nitrogen was applied by banding at a rate of 45-67 kg/ha while 45-50 kg/ha of phosphorus (N-P-K 11-55-0) was applied at seeding.

ANALYSIS
3. Evaluation Factors. Evaluation factors are primarily associated with agricultural systems rather than actual practices. Thus, factors identified under conventional farming hold for conservation farming as well.

4. Diagnostic Criteria
Physical. Lance’s decisions under conservation farming were aimed at reducing erosion while ensuring moisture availability. To this end, he reduced his fallow fields to 8% of farm land, thereby significantly reducing wind erosion. Furthermore, Lance relied on chemical fallowing to control weeds. In effect, Lance eliminated fallowing from his crop rotation since he maintained the area in fallow for spreading manure from his hog operation. Lance indicated that a 12 ha area was affected by salinity, which he seeded to forages and rented out as pasture.

Lance addressed moisture availability concerns by leaving standing stubble for snow capture. In compensating for reduced fallow, he left a higher standing stubble (250 to 400 mm) to entrap more snow for greater moisture build-up. In addition, he monitored soil moisture at seeding with a moisture probe and if the depth of moist soil was less than 200 mm, and long-range forecasts were for low precipitation, Lance put that field into fallow rather than risk crop failure.

The elimination of swathing in 1991 and tillage in 1993 have allowed Lance to make greater use of the crop growing season by giving him more flexibility at seeding and harvest. A swathed crop requires a minimum of 4-5 dry days in sequence prior to combining. Conversely, straight combining can be conducted within one to two days after adverse weather conditions.

Biological. Lance’s residue management strategy consisted of leaving standing stubble at harvest. The stubble was later chopped and spread with a rotary cutter to provide some protection against erosion as well as serve as organic matter amendment. Manure application from his hog production operation served as a soil nutrient and organic matter supplement. Lance incorporated legumes in his rotation to provide additional feed for his livestock operation, improve soil fertility and reduce chemical fertilizer inputs. In spite of these improvements, Lance has seen crop yield response to chemical fertilizers levelling off and indicated that yield increases will have to come from improved varieties.

Economic. Under conservation farming, fuel costs were reduced by 40-50% by practicing initially minimum and subsequently zero tillage. Moreover, the addition of legumes to the rotation reduced feed costs for the hog operation. Animal production continued to provide a buffer against falling grain prices and served as an added risk management strategy.
Lance realized the importance of increasing farm size to increase gross margin. On the basis of the length of the crop production season and the capability of his agricultural machinery, Lance identified the upper limit on the farm that he could sustainably operate at 480-600 ha. He increased his own holdings from 365 to 480 ha between 1983 and 1988.

The PFRA permanent cover program is viewed positively by Lance and area farmers as it has taken marginal land out of annual production and converted it to permanent forage. The Gross Revenue Insurance Program (GRIP) was not always seen to be in the best interest of soil conservation or farmers’ production goals. It was also perceived as too costly to justify the benefits that might accrue. The Alberta agricultural fuel subsidy program was also not seen as conducive to sustainable land management as it encouraged excessive tillage, particularly in fallow fields, and lead to soil degradation problems. Lance did not participate in GRIP or other government programs. However, he maintained crop insurance against hail damage.

Lance’s management strategy in switching to conservation farming was one of gradual shifts in the practices involved. For example, in switching to chemical fallowing, Lance began by combining both tillage and pesticide applications for weed control, with eventual elimination of tillage. Similarly, there was a gradual reduction to minimum tillage for seedbed preparation with a complete shift to zero tillage in the 1993 production season. Instead of purchasing new equipment for seeding into stubble, Lance modified his seeder from a row-spacing of 200 mm to 250 mm, with corresponding changes to the rate of seeding such that plant population densities remained the same. In addition, Lance diversified his crop production to include specialty crops to increase his gross margin. In 1993 he grew flax for the first time in many years based on market trends (which he follows). Because price trends for flax were downward, he committed a small acreage, 32 ha, to flax production and presold the whole crop prior to seeding, realizing a profit of $20-25/t over current market prices.

5. Indicators and Thresholds. The key indicators identified under conventional farming apply under conservation farming as well. A comparison of their status under the two production systems is given in Table 7.

Clear cut thresholds have been difficult to identify in Lance’s decision process. His mode of operation suggested that any change in the status of indicators triggered a response. For example, each increase in fertilizer prices initiated alternate strategies for enhancing or maintaining soil fertility. Similarly, Lance followed market trends for regional commodities in order to decide on strategies that would enhance his gross margin.

ASSESSMENT

The conservation-based production system compared favourably to most of the pillars of SLM. Lance’s transition to chemical fallowing eliminated erosion, which addressed the SLM pillars pertaining to productivity and protection of natural resources. The maintenance of his hog operation minimized the level of production risk. The reduction in overall costs of production (Table 8) indicated that the economic viability of the enterprise was sustainable. His participation in soil conservation clubs and the overall impact of such clubs insured social acceptability. The only area of concern that needed monitoring was the effect of increased fertilizer and pesticide use on soil water quality.
Table 7. The status of indicators used in the case studies under conventional and conservation production systems.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Physical</th>
<th>Status</th>
<th>Conventional</th>
<th>Conservation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- percent land in fallow</td>
<td>- 20 - 30%</td>
<td>- &lt; 10%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- method of fallow</td>
<td>- tillage</td>
<td>- tillage + chemical; chemical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- depth of soil moisture at seeding</td>
<td>- weather dependent</td>
<td>- improved with increased stubble height</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- percent &amp; trends of degradation</td>
<td>- entire farm experienced erosion over 3 yr period</td>
<td>- erosion eliminated; salinity stable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- type of tillage practice</td>
<td>- conventional</td>
<td>- minimum; zero</td>
<td></td>
</tr>
<tr>
<td>Biological</td>
<td>- changes in fertilizer &amp; pesticide use</td>
<td>- according to standard rates for region</td>
<td>- increased over conventional</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- length &amp; diversity of rotations</td>
<td>- 3 yr; low diversity</td>
<td>- 3 yr; more legumes and forages</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- crop yield trends</td>
<td>- variable</td>
<td>- variable</td>
<td></td>
</tr>
<tr>
<td>Economic</td>
<td>- trends in cost of production</td>
<td>- increasing costs, reduced returns</td>
<td>- reduced fuel costs, increasing returns with production of specialty crops</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- gross margin</td>
<td>- decreasing ($30/ha in 1991)</td>
<td>- improving ($41/ha in 1991)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- number and types of government programs</td>
<td>- crop insurance</td>
<td>- crop insurance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- farmer's management objectives</td>
<td>- risk reduction, profit maximization</td>
<td>- risk reduction, profit stabilization</td>
<td></td>
</tr>
<tr>
<td>Social</td>
<td>- distance to services</td>
<td>- 50 km</td>
<td>- 50 km</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- social perceptions of conservation practices</td>
<td>- favoured conventional tillage</td>
<td>- increased acceptance of conservation practices</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- reasons for participation in government programs</td>
<td>- risk reduction, income stabilization</td>
<td>- risk reduction</td>
<td></td>
</tr>
</tbody>
</table>

Overall, Lance clearly addressed sustainability issues pertaining to each of the SLM pillars, and this evaluation indicated that his current practices are sustainable. Moreover, Lance was continuously responding intuitively to sustainability indicators. His experimentation with different types of animal production indicated that it was quite likely that his current practices would continue to shift as he obtained feedback. It can be said that the key component to the sustainability of Lance’s production system is his management strategy. Thus, even if future developments make his current practices unsustainable, the flexibility of Lance’s decision making process clearly indicated that his management techniques are sustainable.

Conclusions. The FESLM based analysis indicated that crop production using conventional tillage methods was not sustainable in a rainfed agricultural system in southern Alberta. It also demonstrated the sustainability of a conservation-based production system within the same environment.

The FESLM was a valuable tool for structuring the analysis, identifying key factors and providing a framework for carrying through an assessment of land use systems in terms of their sustainability. It was also useful in identifying areas that endangered sustainability and thus required closer
monitoring. It provided, in particular, an important process for the identification of key indicators essential for assessing sustainability within a given environmental envelope.

Table 8. Comparisons of some key factors in costs of production and gross margin for conventional and conservation based land use systems.

<table>
<thead>
<tr>
<th>Barley Parameter</th>
<th>Conventional</th>
<th>Conservation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield t/ha</td>
<td>2.92</td>
<td>2.89</td>
</tr>
<tr>
<td>Total Revenue</td>
<td>226.95</td>
<td>224.65</td>
</tr>
<tr>
<td>Seed</td>
<td>10.15</td>
<td>10.50</td>
</tr>
<tr>
<td>Fertilizer</td>
<td>11.58</td>
<td>38.04</td>
</tr>
<tr>
<td>Pesticide</td>
<td>41.22</td>
<td>30.97</td>
</tr>
<tr>
<td>Insurance</td>
<td>12.87</td>
<td>19.76</td>
</tr>
<tr>
<td>Fuel</td>
<td>14.82</td>
<td>9.81</td>
</tr>
<tr>
<td>Repairs</td>
<td>18.45</td>
<td>13.49</td>
</tr>
<tr>
<td>Machine &amp; custom</td>
<td>--</td>
<td>12.97</td>
</tr>
<tr>
<td>Operating interest</td>
<td>2.84</td>
<td>5.66</td>
</tr>
<tr>
<td>Total Variable Costs</td>
<td>142.69</td>
<td>145.29</td>
</tr>
<tr>
<td>(includes items not listed above)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insurance</td>
<td>7.11</td>
<td>3.51</td>
</tr>
<tr>
<td>Depreciation</td>
<td>34.63</td>
<td>24.45</td>
</tr>
<tr>
<td>Opportunity cost</td>
<td>12.84</td>
<td>10.08</td>
</tr>
<tr>
<td>Total Fixed Costs</td>
<td>54.59</td>
<td>38.04</td>
</tr>
<tr>
<td>Cost of Production</td>
<td>197.28</td>
<td>183.32</td>
</tr>
<tr>
<td>Gross Margin</td>
<td>29.66</td>
<td>41.32</td>
</tr>
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</table>


Acknowledgements. The extensive and enthusiastic cooperation of Lance Wheeler and his family in this study are gratefully acknowledged. The authors extend their appreciation to Frank Jetter and Terry Appleby of the Production Economics Branch of Alberta Agriculture for their assistance in determining production costs and returns. The work of Bernard Vigier in preparing the questionnaire and collecting the initial data are also sincerely acknowledged.

References
Application of the Framework for Evaluating Sustainable Land Management and Further Developments

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Abstract

Applications and further development of the Framework for Evaluating Sustainable Land Management (FESLM) will depend on the completion of a series of case studies and on the development of a recognized list of indicators. Yet the FESLM gives great hope to developers, land-use planners, scientists, and even farmers. In contrast with the present post evaluation situations, the FESLM enables them to develop predictions of what can be sustainable or unsustainable before land-use systems reach a point of no return in terms of degradation.

To do so, it appears that land-use systems are the most convenient basic unit. In terms of evaluation, long-term sustainability (more than 25 years) may be an unrealistic aim but short-term sustainability (from 7-14 years) and unsustainability which can be assessed in less than seven years are certainly more practical objectives. This evaluation should be possible through simple indicators, criteria, and thresholds which should also be common to many land-use systems.

The applications of the FESLM can concern the evaluation of land-use systems which interest not only scientists, but also developers and land-use planners. This evaluation can lead to the development of computerized decision-making systems and can be linked to geographical information systems (GIS). The FESLM, through its analysis, helps to identify elements of unsustainability in the system and to develop corrective measures. Moreover it can be a basis for the development of simulation models which can integrate new management practices for correcting or reducing unsustainability.

However, one should not forget that farmers, developers, and planners are the end users who will ultimately implement the sustainable management of their land and that they need to understand the FESLM process to be involved.

Introduction

The Framework for Evaluating Sustainable Land Management (FESLM) (Smyth and Dumanski, 1993) is an attempt to quantify the sustainability of land management systems in a hierarchial and orderly manner by using diagnostic factors, criteria, indicators, and thresholds. It is designed to help researchers, policy makers, developers, farmers or other users to assess the sustainability of the land uses they are working on and eventually to improve them. It offers a predictive means to evaluate sustainability, which differs from the present system where most evaluation is done when the project is finished and often when damages have already occurred. Ruttan (1991) contends that sustainability is essentially viewed as "a guide to agricultural research rather than a guide to
practice". If this was the case the FESLM would probably not generate much interest, except in some academic circles. The interest shown by the World Bank in developing sustainability indicators and by other development agencies seems to indicate that there is a wider possibility of application than just a guideline for agricultural research. Yet, the FESLM is still at a conceptual stage of development and needs to involve case studies, evaluations, and the selection of appropriate and sound parameters. It is a tool in the process of evaluation and one can probably only see a few of its uses at present. Essentially, the two major questions are: (i) How to develop a sufficiently simple FESLM which can be flexible enough to answer the questions of different types of users (but remains open for new developments)? (ii) What kinds of applications can be foreseen?

The FESLM

"Sustainability, within the context of the FESLM, is a measure of the extent to which the overall objective of sustainable land management can be met by a defined land use on a specific area of land over a stated period of time (Smyth and Dumanski, 1993).

Smyth and Dumanski (1993) also state that "sustainable land management technologies, policies, and activities need to simultaneously:

- maintain or enhance production/services (productivity);
- reduce the level of production risk (security);
- protect the potential of natural resources and prevent degradation of soil and water quality (protection);
- be economically viable (viability); and
- be socially acceptable (acceptability)."

The premises in these principles are that one can find sufficiently stable land-use systems over a sufficient length of time to evaluate them according to the abovementioned objectives.

The definition of the system to be measured is an essential component of the FESLM. Smyth and Dumanski (1993) contend that land-use systems and the way they are managed are the main purpose of the evaluation. The systems can be physically based on certain land-use units and identified through field surveys or by remote sensing for example. There is no major problem in areas where a well-identified cropping system dominates - cereal-based systems in North America or Northern Europe, rubber estates in Malaysia. Yet, especially in the tropics, the identification of land-use systems is often more complicated as land can be used for multipurpose objectives. The farmer manages his farm to function according to his needs and not necessarily according to the suitability of the land. In this case the land use may be subordinated to other components of the farming system and the evaluation of the sustainability of individual land-use units, especially in socioeconomic terms may become difficult. Therefore, following Blaikie and Brookfield (1987), the Population Growth, Land Transformation and Environmental Change (PLEC) project of the United Nations University, contends that farming systems, with their historical perspectives, should be the basis for the evaluation. The difficulty here is that farming systems cover a full range of exploitation, which may include many land-use units. One can always add
the evaluation of each unit but the sum may be economically sustainable and socially acceptable for the farmers whereas some elements may not meet the security or protection criteria. A pig farm installed close to a creek where all the sewage is dumped may be economically viable and acceptable to the farmers but it will not meet the protective objective. The farmer in this case is not the only land user. In addition, many farms are sustainable due to off-farm revenues which are difficult to integrate. The farm level appears then to be difficult to accept as a unit for the evaluation and one may prefer the individual land-use unit. Similar arguments may be advanced for watersheds or regions unless one considers only a dominant land-use. In theory, systems will only be sustainable if all the components of sustainable land management are met.

The second part of the FESLM premise is that a land-use type is sufficiently stable to be evaluated, since a system of continuous evaluation would be difficult to assess. Yet farming systems and land use are changing rapidly due to environmental (consequence of pollution of water tables), economic (prices and subsidies), demographic (population pressure), and policy (regulations on inputs or immigration) issues. This situation is especially acute for annual crops but is also true for perennial crops and livestock. Smyth and Dumanski (1993) suggest that twenty-five years is a minimum for evaluating long-term sustainability and that below seven years one can only measure unsustainability. As a result of the current rapid changes in land uses, the evaluation of long-term sustainability may seem to be an academic exercise, even if simulation models are used. In terms of application, one may prefer to assess short-term sustainability (7 to 14 years) or even unsustainability through development of trends. These time spans are often the most useful for developers and farmers.

Once the object for assessment is known, the next question concerns the number of parameters to be used, and the relevance and commonality of these parameters for different land-use systems. Smyth and Dumanski (1993) offer an open-ended hierarchied list of diagnostic criteria (causes, effects, and observations), indicators (measurable or observable attributes), and thresholds. The possible application of the FESLM suggests that the parameters to be used should be discriminate, but also common to different land-use systems and limited in number. Participants of the International Workshop on Sustainable Land Management for the 21st Century held in Lethbridge, Canada from June 20-26, 1993 were able to select a limited number of sustainable land management indicators for the major climatic regions of the world (Dumanski, 1993). When one examines the list these indicators are obviously meaningful. However, the determination of these few, discriminate, and common indicators will only be possible when a sufficient number of case studies have been analyzed. Identification of case studies is underway in different projects, particularly on sloping lands and Vertisols in an IBSRAM/ACIAR (Australian Centre for International Agriculture Research) project. Ultimately, precision/discrimination of the indicators and thresholds may have to be balanced with their degree of commonality and simplicity and the accuracy of the evaluation requested. Scientists will insist on precision, whereas developers and farmers will prefer simplicity and/or commonality.

At this stage it is assumed that the FESLM is a tool to evaluate trends of sustainability or unsustainability of land-use systems, according to a set of objectives, and a number of indicators/thresholds. It is further assumed that somehow the required level of accuracy will be achieved.
Application and Further Developments

Some of the applications and further developments of the FESLM are summarized in Table 1. The first use of the FESLM is to evaluate current land-use systems. Researchers, developers, planners, farmers, bankers or others need to evaluate existing situations and take corrective action if potential problems are foreseen. The FESLM provides a mechanism for such analysis and diagnosis. It is a great step forward in regard to the present situation where most of the evaluations of development projects are done afterwards and are only based on the final productivity. For example, the rice-wheat system in South Asia is tending to decline but one has few ideas why, although suggested causes have been attributed to soil quality, pests, inadequate varieties, or a range of socioeconomic criteria (Fujisaka et al., 1994). The FESLM could help researchers to make the diagnosis and to complete the promises to effect improvement.

Table 1: Potential application of the FESLM

<table>
<thead>
<tr>
<th>USERS</th>
<th>APPLICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scientists</td>
<td>• Evaluation of research results.</td>
</tr>
<tr>
<td></td>
<td>• Evaluation of hypothesis on future land uses through simulation models.</td>
</tr>
<tr>
<td></td>
<td>• Development of decision-support systems.</td>
</tr>
<tr>
<td></td>
<td>• Linkage with GIS to assess, on a geographical basis, agronomic, environmental, or economic risks.</td>
</tr>
<tr>
<td>Farmers/extensionists</td>
<td>• Analysis of a situation and identification of improvement of alternatives through decision-support systems.</td>
</tr>
<tr>
<td>Developers</td>
<td>• Long-term benefits of a project.</td>
</tr>
<tr>
<td></td>
<td>• Social and environmental impact of a project.</td>
</tr>
<tr>
<td>Planners</td>
<td>• Land-use plans at local, regional, or national scale.</td>
</tr>
<tr>
<td></td>
<td>• Alternative plans in case of unforeseen changes in the conditions of the land use (change in economic conditions).</td>
</tr>
<tr>
<td>Insurers/bankers</td>
<td>• Evaluation of economic risks if sustainable land management is not met.</td>
</tr>
<tr>
<td>Governments</td>
<td>• Effectiveness of land-use policies and eventually their improvement.</td>
</tr>
</tbody>
</table>

Another example may be an irrigation project which does not produce all the expected benefits. An analysis with the FESLM may help developers to stratify the reasons for failure. Similarly, a plan or a development project requires a loan and bankers and insurers will require the FESLM to evaluate their risks. Governments for their part are interested in the effectiveness of land-use policies and eventually in their improvement and the FESLM can be an analytical tool for this purchase. It is not by chance that the World Bank and other development agencies are
interested in indicators and thresholds. However, these indicators and thresholds will only be valuable if they are organized in such a way that they can cover the five major objectives of the FESLM: productivity, security, protection, viability, and acceptability.

The computerization of the FESLM can lead to a decision-support system which will help planners, developers, and scientists to analyze their results. Examples of such systems were provided in the abovementioned Lethbridge International Workshop (Dumanski, 1993). Furthermore, linking the FESLM to appropriate GIS could provide geographical expansion of the system. At Lethbridge, Bouma (1993) gave examples of wheat constraints in Europe as analyzed through a GIS. Maps of sustainable land management could be produced to fruitfully complement the UNEP Soil Degradation Map (Oldeman et al., 1990). A new generation of intelligent geographical information systems would be able to help spot and correct inaccuracies in data (Burrough, 1992).

The FESLM can provide more than a 'yes-no-perhaps' type of answer to the sustainability question. By analyzing the reasons for the unsustainability of a system through criteria, indicators, and thresholds information is provided on where to focus the effort to change the situation. The FESLM can then become a tool for improving sustainable land management. In this regard it interests farmers, developers, and land researchers. Farmers are already organizing their land management decisions according to their observations of visible parameters - erosion features, type of crusting, occurrence of weeds, leaf symptoms - or on simple analytical tests. These observations and tests could be organized in a decision-support system to better serve sustainable land management. Researchers for their part would have to develop simulation models and other prediction tools to integrate management changes.

Planners will improve their plans and be able to develop alternatives in case of unforeseen changes in the economic conditions of the land use. In this sense the FESLM could help to correct and reduce unsustainable elements in land-use systems.

Conclusion

FESLM can have multiple applications which are now urgently needed. The work to be done to achieve a simple, but sufficiently discriminate FESLM should not be underestimated. The accuracy obtained will determine the possibility of success of its application. The prospect of developing an evaluation and prediction tool to assess sustainable land management is such an exciting challenge that computer specialists, modeles, and specialists in intelligent geographical information systems are eager to use (and maybe abuse) a system which has not yet been fully developed. However, one must not forget while embarking on the FESLM, that land users have practical needs and should be provided with simple answers. They often have better information than researchers particularly on socioeconomic aspects of decision making. Many land users have already taken the right decisions and entered into the sustainable land management era. Scientists must resist the temptation to be too directive and they should provide land users with what Röling (1993) calls a platform for decision making which will involve them in the implementation of the FESLM. This will give land users a sense of ownership rather than a set of
ready-made plans and instructions. The future of sustainable land management comes at this price.

Acknowledgements

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Symposium ID-13

Thursday, July 14
afternoon session

Indurated Volcanic Soils, Uses and Management

Convener: Paul Quantin. (France)
Co-conveners: Christian Prat. (Mexico)
Héctor M. Arias R. (Mexico)

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<th>Page</th>
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<td>436</td>
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P. Quantin. ORSTOM, 72 Route d'Aulnay 93143 Bondy Cedex, France.

Résumé.

Quand les sols volcaniques indurés apparaissent en surface suite à une érosion anthropique ou pluviale, ils provoquent la désertification d'immenses régions d'Amérique Latine et posent de graves problèmes de gestion agricole. Cet exposé traite de deux principaux thèmes: premièrement, la caractérisation, la classification et les processus de formation de ces horizons indurés; deuxièmement, la réhabilitation agricole et forestière des sols volcaniques indurés, leur productivité et leur conservation dans le monde.

Dans la première partie, nous ferons une revue des différents types d'horizons indurés en Amérique Latine (tepetate, talpetate, cangahua, fierrillo, etc...) et au Japon (masa, koro, nigatsuchi). Plusieurs processus de cimentation par les argiles, la silice, le carbonate de calcium, les oxydes de fer et d'autres minéraux sont décrits en détails. Ensuite, une meilleure caractérisation et classification des hardpans volcaniques seront proposées. Enfin, on étudiera à travers l'histoire préhispanique et moderne du Mexique, l'impact anthropique sur l'induration et la désertification de ces sols.

La seconde partie concerne principalement les résultats d'observations et d'essais réalisés sur des fragipans et des matériaux pétrocalciques, appelés "tepetates" au Mexique et "cangahua" en Equateur. Ils montrent que leur érodibilité sous l'action de la pluie est limitée à quelques événements pluvieux. Mais, sous cultures, les horizons indurés deviennent très érodibles. Heureusement, le ruissellement et les pertes de terre sont particulièrement réduits par un couvert végétal adéquat et des travaux de conservation des sols. Les processus érosifs peuvent ainsi être bien contrôlés. La fertilité potentielle peut devenir assez élevée après un aménagement approprié du hardpan conduisant à la formation d'agrégats de taille optimale, ainsi que par une fertilisation minérale modérée d'azote et de phosphore ou d'apport de fumier. A partir de la première année de culture, la productivité est correcte en ce qui concerne le blé, l’orge, la vesce, le haricot alors que les rendements sont mauvais pour le maïs et dans une moindre mesure pour la fève. Heureusement, les rendements de ces dernières cultures augmentent très rapidement après 2 ou 3 ans (bénéficiant probablement du développement de micro-organismes spécifiques symbiotiques). Finalement, la productivité de l'ensemble des cultures devient excellente après quelques années de gestion agricole adéquat. Par conséquent, la réhabilitation agricole de fragipans et de sols pétrocalciques en Equateur et au Mexique peut être bénéfique aux petits paysans, malgré l'importance des travaux et le coût de la restauration. Des résultats sont également donnés afin de montrer l'intérêt et la productivité des hardpans dans le cas de reforestation au Mexique. Enfin, d'autres usages des hardpans au Nicaragua et au Japon sont brièvement décrits.

Introduction.


Les sols volcaniques présentent souvent des horizons indurés que l'érosion anthropique fait affleurer, laissant à nu des surfaces stériles. Malheureusement il s'agit de régions très peuplées et cela restreint sérieusement le développement agricole. Des travaux ont été entrepris dans plusieurs pays,
surtout au Mexique, en Équateur, au Japon et aux Canaries, pour une réhabilitation agricole des sols indurés ou des travaux de reforestation et de conservation des sols.

L’intérêt de cette restauration au Mexique a conduit à organiser à Mexico (20-26 octobre 1991) un premier symposium international intitulé “Suelos volcánicos endurecidos”. Il a permis de frôler les premières études et données expérimentales obtenues en Amérique latine, surtout au Mexique et en Équateur. Ce deuxième symposium, dans le cadre du 15ème Congrès Mondial de la Science du Sol à Acapulco, a pour but de faire le point des connaissances acquises et des problèmes qui demeurent à étudier. Le terrain est élargi de l América Latine à d autres pays, notamment au Japon.


I. Caractérisation, classification et processus de formation des horizons indurés.


Ce symposium sur les sols volcaniques indurés rassemble une série d’exposés oraux, d’articles et de posters qui illustrent tout d’abord certains processus de cimentation, puis posent le problème des critères de classification, enfin montrent l’impact anthropique sur leur apparition sur surface.

Le problème de la silicification qui conduit à une cimentation et induction en duripan est analysé en détail dans un sol volcanique argileux du Mexique; la comparaison avec l’étude de silicites anciens permet d’éclairer la connaissance de ce processus (Dubroeucq et Thiry, 1994). La formation du fragipan à partir de dépôts pyroclastiques récents près de Mexico, par un processus d’argilification et de silicification discrète, est illustrée par des études détaillées de l’échelle du terrain à celle du microscope électronique à haute résolution (Bertaux et Quantin 1994; Hidalgo, Elsasser et Quantin, 1994). Un processus d’encroûtement calcaire, formant un horizon pétrocalcique est décrit près de Mexico (Fedoroff et al., 1994) et aux îles Canaries (Jahn et Stahr, 1994). Un encroûtement ferrugineux, dit "fierrillo", est étudié dans les sols "ñadis" du Chili (Luzio, 1994) et les andosols des Açores (Pinheiro, 1994); il est dû à un processus de redoximorphie à la base d’un andosol; il semble
être le stade initial de formation de l’horizon placique. Au Japon Yamada et al. (1994) montrent que l’horizon placique est la conséquence d’un processus de podzolisation.


Flach et al. (1994) posent le problème de la caractérisation des sols indurés, en face de la variété des matériaux et de l’imprécision des appellations locales. Ils rappellent les définitions et critères utilisés en classification des sols concernant : fragipan, duripan, horizons pétrolcalcique, pétrogypseique, placique et orstein. Ils constatent la difficulté de classer les tepetates en taxonomie des sols. Ils proposent des critères pour caractériser la cimentation, l’induration et la morphologie des horizons indurés. Ils concluent que le système de classification des "pans" (horizons indurés) peut être amélioré; mais il est important pour une utilisation pratique de faire une description et caractérisation détaillée par des méthodes standard de chaque type de matériau à aménager.

Finalement le processus d’érosion anthropique est évoqué comme facteur d’apparition en surface des horizons indurés, notamment les "tepetates" du Mexique. Selon Miehlich (1992) les tepetates s’indurent après érosion du sol superficial par solidification des revêtements de silice non cristalline, de même que s’indurent les sols "nigatsuchi" du Japon (Yamada et al.1994); ils forment alors un fragipan ou un duripan. Aliphat et Werner (1994) évaluent l’impact anthropique au Mexique, aux époques préhispanique et moderne. Ils montrent une relation entre les affleurements de tepetates et les régions de forte occupation humaine à l’époque préhispanique. Cependant la civilisation indienne préhispanique était parvenue à aménager d’une manière durable et très productive les aires de sols à tepetate. Ce serait l’impact de la colonisation européenne, qui en provoquant la dépopulation de ces régions et l’abandon des aménagements agricoles adaptés, aurait conduit à une reprise et à une accélération du processus d’érosion, laissant à nu de vastes surfaces de sols indurés et stériles. Nous verrons dans la deuxième partie de cet exposé que ce processus de dégradation des sols et de désertification n’est pas irréversible, mais qu’une réhabilitation agricole et forestière est possible.

II. Réhabilitation agricole et forestière des sols indurés, conservation et productivité.

Les horizons indurés de sols volcaniques ont des propriétés physiques et chimiques qui limitent le développement des plantes. Ils sont stériles à l’état naturel, ou peu productifs quand ils sont cultivés avec seulement un labour profond, sans apport de fertilisants. De plus le labour les rend très érodibles. Cependant ils ont des propriétés favorables à la réhabilitation d’un sol agricole productif et stable, si l’on utilise des méthodes appropriées.

1. Contrainstances et propriétés favorables.

Le premier facteur limitant des sols indurés est la compacité. Leur densité apparente et leur dureté sont variables. Les horizons à consistance de fragipan, tepetate, talpetate, cangahua, masa, fiierrillo ou placic, s’ils ne sont pas fortement cimentés par de la silice ou du calcaire, ont une densité modérée (1 à 1,6) et une microporosité importante (40 à 60%). C’est leur macroporosité trop réduite (< 5%) qui empêche la pénétration de l’eau et de l’air, et en conséquence des racines; leur conductivité hydraulique est très lente (< 5 mm/h). Mais ils contiennent assez d’argile (> 20%), douée d’une forte capacité d’échange de base (> 15 cmol kg⁻¹ sol total), pour permettre une bonne rétention de l’eau et des
nutriments (Quantin, 1992). Après une fragmentation appropriée (rippage et labour profond, puis pulvérisage) les fragipans acquièrent des propriétés physiques favorables. La taille de l'agrégat optimum se situe vers 3 mm (Oleschko, in Quantin, 1992). Les horizons fortement cimentés et indurés, de type duripan ou pétrocalcique, sont plus durs à fragmenter à la dimension optimum, plus denses et moins aptes à la restauration d'un sol agricole.

Le deuxième facteur limitant est chimique. Ces matériaux, notamment duripans et fragipans, sont quasi dépourvus de matière organique et donc carencés en azote. En outre ils manifestent une déficience sèvre en phosphore disponible pour la plante (Etchevers, Cruz et al.1992). Ces deux carences sont la cause majeure de leur stérilité. Un troisième facteur est leur très faible activité biologique, notamment leur carence en micro-organismes symbiotes tels que rhizobium, azospirillum et endomycorhizes de certaines plantes, telles que maïs et haricots (Quantin 1992), en première année de culture. Cependant ces matériaux ont d'autres propriétés chimiques favorables, notamment un pH souvent proche de la neutralité et une certaine richesse en éléments Ca, Mg et K échangeables. Il est facile de remédier à la carence en N et P par une fertilisation minérale ou organique, voire biologique pour certaines plantes. Donc les fragipans ont une bonne fertilité potentielle après correction de leurs facteurs limitants. Ce n'est pas le cas des horizons de duripan, pétrocalcique ou plaquique, dont les contraintes physiques et chimiques sont beaucoup plus sévères.

2. Hydrodynamique, érodibilité et conservation.


La plupart des horizons indurés de sols de type duripan, fragipan ou pétrocalcique sont situés en climat de régime "ustic", marqué par une longue saison sèche. Il y a une grande variabilité des pluies, interannuelle et stationnelle. La valeur moyenne de l'indice d'érosivité (de Wischmeier) des pluies est plutôt faible ou modérée. Mais les rares pluies (0 à 3) de forte intensité (I30 > 50 mm/h - E.I30 > 1000 MJ/ha/mm/h) sont responsables de la majeure partie de l'érosion. Le reste provient de quelques pluies modérément érosives (I30 entre 30 et 50 mm/h). Les tepetates ou la cangahua à nu dans leur état naturel ont un très fort coefficient de ruissellement (> 70%), mais s'érodent très peu (0 à 10 t/ha/an). Après "roturation" ces matériaux infiltrent mieux, mais sont instables et l'érosion peut dépasser 100 t/ha/an. Une agriculture bien conduite de maïs avec billonnage isohypse réduit le ruissellement à 10% et supprime l'érosion si les pluies sont faiblement érosives (I30 < 30 mm/h); mais le ruissellement augmente à près de 20% et surtout l'érosion à 20-30 t/ha/an en cas de fortes pluies (I30 > 50 mm/h). Le billonnage ne suffit pas pour contrôler les fortes pluies. L'efficacité du billonnage doit être complétée par des ouvrages anti-érosifs, tels que terrasses à pente dégressive, talus enherbés, murets, etc...

L'observation de l'évolution des états de surface (Janeau et al. 1992) montre une fonte des agrégats fins (< 2 mm), qui provoque tassement, encroûtement de surface et réduction progressive des pores grossiers et de l'infiltration des eaux de pluies. Le système tepetate roturé n'est pas stable; il ne faut pas dépasser un seuil de fragmentation ni multiplier les travaux du sol. Il conviendrait d'améliorer la stabilité structurale par des amendements organiques et de développer l'activité biologique. Cependant l'amélioration de l'infiltration de l'eau est assez durable pour permettre en année normale un emmagasinement suffisant de l'eau et maintenir le sol au-dessus du point de flétrissement pendant la courte période sèche au milieu de la saison des pluies (Baumann et al. 1992; Marquez et al. 1992).

3. Fertilité naturelle et potentielle; fertilisation minérale, organique et biologique.

Il y a peu de résultats encore, sauf au Mexique, concernant les propriétés chimiques des sols volcaniques indurés et surtout l'évaluation de leur fertilité potentielle. Les données majeures concernent les formations suivantes :
- duripan de la région de Xalapa, Mexique (Rossignol et al. 1992);
- fragipans et horizons pétrocalciques de la région de Mexico (Etchevers, Cruz et al. 1992; Etchevers, Lopezet al. 1992; Etchevers, Zebrowski et al. 1992); 
- talpetate du Nicaragua (Prat, 1991; Prat et Quantin, 1992; Vogel et al. 1994); 
- horizons plaquique du Chili (Luzio et al. 1992) et du Japon (Yamada et al. 1994); 
- autres horizons indurés du Japon (Yamada et al. 1994).

Etchevers et Ferrera (1994) proposent une synthèse de ces données. Ils présentent surtout leurs travaux concernant les propriétés chimiques la microbiologie et la fertilité des fragipans et horizons pétrocalciques de la région de Mexico. Les deux facteurs limitants majeurs sont la carence en azote et une déficience sévère en phosphore facilement disponible pour les plantes (2 à 3 ppm de P, méthode Olsen). En outre les matériaux pétrocalciques ont un pH légèrement alcalin et une déficience en micro-éléments (Fe, Mn et Zn) disponibles. Mais ils ont une forte capacité de rétention des bases échangeables, et notamment des teneurs élevées de Ca, Mg et K échangeables. La fertilité potentielle est très élevée après correction des carences en azote et phosphore par une fertilisation minérale plutôt modérée (N 60 à 120 unités/ha, P 60 à 80 unités/ha), ou par une fertilisation organique. La fixation phosphore ajouté est rapide, mais cet élément demeure à 70-80% sous une forme "labile", facilement disponible pour la plante. Sur les tepetates cultivés et fertilisés les teneurs en N et P labile augmentent progressivement; mais celle de K diminue, sans atteindre cependant après plus de 10 ans le seuil de déficience. Il y a fixation sélective de K par les argiles (illites, smectites) de ces tepetates; d'autre part l'altération des verres rhyolitiques recharge le stock en cet élément. On observe aussi une diminution légère du pH.


La réhabilitation agricole a été pratiquée à l'époque préhispanique, puis abandonnée. Les premiers essais modernes, suite à une extension catastrophique de l'érosion dans les régions de fort peuplement agricole, ont commencé il y a près de 30 ans au Mexique et de 26 ans en Equateur. Il s'agissait surtout de programmes de reboisement et de travaux de remodelage et conservation en vue de réduire l'érosion. Les essais de réhabilitation agricole se sont développés ensuite, depuis une douzaine d'année, pour récupérer des terres cultivables. In Equateur, pays moins avancé, les travaux de restauration à partir de la cangahua sont surtout manuels, sur de petites parcelles cultivées par de petits paysans; sur une faible surface (165 ha) le travail a été mécanisé avec l'aide de l'Etat. Près de mille hectares ont été récupérés pour l'agriculture et 15000 ont été reboisés. Au Mexique le reboisement concerne plus de 5000 ha; mais la restauration agricole est dix fois plus développée qu'en Equateur et mécanisée sur des parcelles de plus grande taille. Le travail est fait souvent avec l'aide de l'Etat, mais aussi avec des entreprises privées. Ce sont encore les petits paysans (< 20 ha/famille) qui sont le plus intéressés pour accroître leurs ressources en terre cultivable. Ils assument une large part du coût de cet investissement, malgré leurs faibles ressources.

Des essais agronomiques ont été entrepris récemment au Mexique et en Equateur pour évaluer des systèmes de cultures appropriés et la productivité (Navarro et Zebrowski, 1994). Certaines plantes
telles que le blé, l'orge, la vesce et les haricots ont une production normale dès la première année grâce à une fertilisation minérale fractionnée ou à un amendement organique (Marquez et al. 1992; Baez et al. 1994; Chora et al. 1994). Mais le maïs, et la fève dans une moindre mesure, produisent très peu, quelle que soit la fertilisation minérale ou organique. Cependant le rendement augmente rapidement avec le temps : il devient moyen dès la deuxième ou la troisième année et bon dès la cinquième. De nouveaux essais sont entrepris pour améliorer plus vite la production grâce à l'utilisation d'engrais verts ou une insémination de micro-organismes symbiotes spécifiques.

Le coût des opérations de réhabilitation agricole est très variable suivant le type d'horizon induré, le mode de travail du sol et les conditions économiques locales. Sa rentabilité demeure controversée. Cependant dans la région de Mexico, en travail mécanisé sur un tepetate-fragipan, la rentabilité semble assurée en huit années de culture seulement (Marquez et al., in Quantin 1992). De toute manière la réhabilitation des tepetates ou de la cangahua est une ressource en sol nécessaire pour les petits paysans. Elle pourrait être rentable avec l'aide de l'État pour minimiser les coûts d'investissement et pour fournir l'information technique appropriée.

Au Chili les sols indurés de type fierrillo sont surtout aménagés en pâturages. Au Japon les sols indurés des terres hautes ont été récemment mis en valeur. Leur utilisation varie suivant les types de matériau. Une agriculture de subsistance ou la prairie sont développées avec succès sur les sols masa (duripans) et kora (tufs), le noisetier ou du sorgho fourrager sur les sols nigatsuchi (fragipans) et la forêt sur les sols kora (duripans).
Introduction to the Knowledge and Management of Indurated Volcanic Soil Horizons

Abstract.

The indurated volcanic soils, when rising to the surface after anthropic and pluvial erosion, cause the desertification of large areas in Latin America or some serious difficulties to an agricultural management in other countries. This paper deals with two main topics; first: characterization, classification and processes of indurated horizons formation; secondly: agriculture and forest rehabilitation on indurated volcanic soils, productivity and conservation.

In the first part, a review is made about various type of indurated horizons in Latin America (tepetate, talpetate, cangahua, fierrillo, etc...) and Japan (masa, koro, nigatsuchi). Several processes of cementation by clays, silica, calcium carbonate, iron oxides and other minerals are described in detail. Then a better characterization and classification of volcanic hardpans is proposed. Finally the anthropic impact, prehispanic or modern in Mexico, on hardning and desertification is questioned.

The second part concerns mostly the results of observations and trials made on some fragipans and petrocalcic materials, namely "tepetates" of Mexico and "cangahua" of Ecuador. They show that the rainfall erosivity is due only to few events. But under cultivation the indurated horizons become very erodible. Fortunately runoff and soil losses are strongly reduced by a suitable crop cover and soil conservation works. Thus the erosion process can be well controlled. The potential fertility becomes rather high after an appropriate hardpan breaking to optimum sized aggregates, as well as by a fairly moderate N and P mineral fertilization or manure addition. Since the first year of cultivation the productivity is rather good for wheat, barley, vetch and beans crops, while maize and in some way broad beans give poor yields. Fortunately for these latter crops yields increase quickly, after 2 or 3 years (owing probably to a specific symbiotic microorganism development). Finally the productivity of all crops have become optimum since few years of good cultivation. Therefore the agricultural rehabilitation of fragipans and petrocalcic soils in Ecuador and Mexico can be profitable for small farmers, despite the expensive works and inputs for soil restoration. Some results are given about the interest and the productivity of hardpan reforestation in Mexico. Finally other land use managements of hardpans are briefly tackled in Nicaragua and Japan.

Introduction.

The soils from volcanic origin cover near a quarter of the land surface in the Andean countries of Latin America (Chile, Peru, Ecuador, Colombia), as well as in Central America and Mexico (Zébrowski, 1992). Their extension is also important in the countries around the Western Pacific shore line, namely Japan, the Philippines, Indonesia, New Guinea and New Zealand, as well as some archipelagos in the Atlantic (Azores, Canary, Cape Verde or Caribbeans islands), in the Indian Ocean (Comoros, Reunion, Mauritius), the Pacific (Hawaii, Fiji, Vanuatu, Polynesia) and the Mediterranean sea (Eolian islands).

The volcanic soils often have some indurated horizons which can rise to the surface after erosion, leaving barren and sterile area. Unfortunately it concerns densely populated countries, and hinders seriously the agricultural development. Some works have been undertaken mostly in Mexico, Ecuador, Japan and Canary Islands with a view to an agricultural rehabilitation of the indurated soils or of reaforestation works and soil conservation.

The aim of this soil restoration in Mexico led to organize a first international symposium on the "indurated volcanic soils" in Mexico (October 20-26th, 1991). It allowed to compare the first studies and experimental data already obtained in Latin America, mostly in Mexico and Ecuador. This second symposium, within the framework of the 15th World Soil Science Congress in Acapulco, aimed at
summing up the state of the present knowledge and the problems which remain to study. The fieldwork is now enlarged from Latin America to other countries, namely Japan.

The works presented here are gathered into two main parts. First: characterization, classification and forming processes of the indurated horizons. Second: agricultural rehabilitation, conservation and productivity of indurated soils restored to agriculture or forestry.

I. Characterization, classification and forming processes of indurated horizons.

The indurated volcanic soils have various local names as: “tepetate” in Mexico or “talpetate” in Nicaragua, “cangahua” in Ecuador, “sillar” in Peru, “cancacua” or “ñadís” in Chile, “masa”, “kora” or “nigatsuchi” in Japan. These names correspond with a large variety of indurated materials.

Some indurated soils have inherited their cement or induration from a former geological process, either volcano-sedimentary or hydrothermal in a pyroclastic flow, as in the case of volcanic tuffs or breccias. They are namely known in Peru (Nimlos et Zamora, 1992), Ecuador (Colmet-Daage et al., 1969), Colombia (Faivre et Gaviria, 1992), Nicaragua (Prat, 1991; Prat et al., 1992), Mexico (Quantin et al., 1992), Italy (Lulli et al., 1990), and Japan (Yamada et al., 1994). Then these materials have been submitted to weathering and biological alteration through a soil. The more arid the climate the lesser the alteration; thus this material can keep its former consolidated structure. The latter pedological process can even reinforce it by deposits of clay, silica, iron oxide or lime in coarse pores, even sometimes as impregnation of micropores in the matrix.

The coincidence of a climate with a well distinct arid season and of pedological accumulations (viz clay, silica, lime, etc...) has generally led the pedologists to be unaware of the incident of a former consolidated geological structure. Therefore this matter remains debatable. However in numerous cases the pedogenesis is directly responsible for the soil horizon induration. There is especially the case of silicification in red halloysite clay soils in Mexico (Rossignol et al., 1992), Dubroeucq, 1992, Dubroeucq et Thiry, 1994); or of lime encrusting in mollisols or vertic soils in Ecuador (Winckell et Zebrowski, 1992); or of ferruginous encrusting as in the “fierrillo” horizon of the “ñadís” soils in Chile (Luzio et al., 1992, Luzio et Palma, 1994); or of placic horizons of podzolic soils in Japan (Yamada et al., 1994); or of various accumulations under a subarid climate in Peru (Nimlos et Zamora, 1992) viz silica (duripan), lime (petrocalcic), gypsum (petrogypsic), even soluble salts (petrosalic).

This symposium on the indurated volcanic soils will gather series of oral presentations, papers and posters which enlighten firstly some processes of cementation, then raise the question of classification criteria, finally show the anthropic relationship with the rising e of indurated horizons to the surface.

The problem of a silicification which leads to a cementation and induration to duripan is analysed in detail in a clayey volcanic soil of Mexico; the comparison with the study of old silcretes allows to enlighten the knowledge of this process (Dubroeucq et Thiry, 1994). The fragipan formation from recent pyroclastic deposits near Mexico by a process of argilification and unobtrusive silicification is showed by detailed observations from the field scale to the high resolution electronic microscopy (Bertaux et Quantin, 1994, Hidalgo, Elsass et Quantin, 1994). A process of lime encrusting to form a petrocalcic horizon is described near Mexico (Fedoroff et al., 1994) and in the Canary Islands (Jahn et Stahr, 1994). A ferruginous encrusting, named “fierrillo”, is studied in “ñadís” soils of Chile (Luzio et al., 1992, Luzio et Palma, 1994) or of placic horizons of podzolic soils in Japan (Yamada et al., 1994); or of various accumulations under a subarid climate in Peru (Nimlos et Zamora, 1992) viz silica (duripan), lime (petrocalcic), gypsum (petrogypsic), even soluble salts (petrosalic).

In Japan too, Yamada et al. (1994) think that the “masa” soils are cemented by a non-crystalline and silica-rich material, while the air-desiccation could indurate an aluminium-rich allophane in the “nigatsuchi” soils, or in the “Kora” soils the cementation could be due to a hot solidification of volcanic ash before pedogenesis. In Nicaragua, Vogel et al. (1994) also mention the role of non crystalline silicates such as allophane in the cementation of the “talpetate”; but in this case it could be due to palagonite from a former hydrothermal alteration in a pyroclastic tuff (Prat, 1991; Prat and Quantin, 1992). In Colombia, as in the case of the “cangahua” in Ecuador (Winckell et Zebrowski, 1992), Faivre and...
Gaviria (1992, 1994) show the relationship between the cementation of pyroclastic materials in soils and their location on piedmonts under a fairly arid climate. Such a situation is favourable to the accumulation of clay, iron oxides, silica and lime. Although the characterization of these indurated soils still remains imprecise and a more accurate determination of the cementing agent is to be made.

Flach et al. (1994) raises the question of the indurated soil characterization, as related to the large variety of materials and the imprecision of local names. They recall the definitions and criteria used in soil taxonomy concerning: fragipan, duripan, petrocalcic, petrogypse, placic or orstein horizons. They note the difficulty to class “tepetates”. They propose some criteria for characterizing cementation, induration and morphology of indurated horizons. They come to the conclusion that a classification system of the “pans” (indurated horizons) should be improved. But they emphasize that it is important to make a detailed description and characterization of each type of indurated material with a view to their effective land use.

Finally the anthropic process of erosion is mentioned as the factor of the rising of indurated horizons to the surface, especially the “tepetates” in Mexico. According to Miehlich (1992) tepetates are indurating after erosion of top soil, due to a solidification of non crystalline silica, in the same way as the “nigatsuchi” soils in Japan (Yamada et al. 1994). Thus they can form a fragipan or a duripan. Aliphat and Werner (1994) evaluate the anthropic impact in Mexico during the prehispanic and modern epochs. They show firstly a relationship between the rising of tepetates to the surface and the densely populated area during the prehispanic period. Although the Indian prehispanic people had achieved a sustainable and highly productive management of the tepetate soils owing to suitable works of soil and water conservation. The hard impact of the European colonization, leading to a severe drop of inhabitants and the abandonment of the appropriate works of soil conservation, is probably the main cause of the erosion process reactivation and acceleration, leaving at the surface the barren indurated soils. However we will show in the second part of this paper that the soil degradation process is not irreversible; an agriculture and forest rehabilitation is possible.

II. Agriculture and forest rehabilitation of indurated soils, conservation and productivity.

The indurated volcanic soils have serious physical and chemical constraints which hinder the plant growth. They are naturally sterile or of very low productivity when cultivated using only a deep tillage without fertilizers. In addition they become very erodible after ploughing. However they have some suitable properties for the rehabilitation of a stable and productive agricultural soil, when we use appropriate methods are used.

1. Constraints and suitable properties.

The first limiting factor of indurated soils is their compactness. Their bulk density and hardness are variable. The horizons of fragipan consistency such as tepetate, talpetate, cangahua, masa, fierrillo or placic horizon, have a moderate density (1.0 to 1.6) and an important microporosity (40 to 60%), if they are not hardly cemented by silica or lime. But their too small macroporosity (<5%) restrains the air and water infilling, thus rooting; their hydraulic conductivity is very slow (<5 mm/h). But they contain enough clays (>20%) of high cation exchange capacity (>15 cmol/kg-1 of whole soil) to allow a good water and nutrient retention capacity (Quantin, 1992).

By an appropriate fragmentation (subsoiling, deep tillage, and harrowing) the fragipans acquire suitable physical properties. The optimum aggregate is about 3 mm sized (Oleschko, in Quantin, 1992). The hardly cemented and indurated horizons of duripan of petrocalcic type, less easily broken to the optimum size and more compact, are less easily suitable to an agricultural soil restoration.

The second limiting factor is chemical. These materials, especially duripans and fragipans are almost lacking of organic matter and thus of nitrogen. In addition they show a severe deficiency in phosphorus available for plant growth (Etchevers, Cruz et al., 1992). Both deficiencies are a major cause of their sterility. A third limiting factor is their very low biological activity, especially their deficiency in symbiotic microorganisms such as rhizobium, azospirillum and endomycorhizae of...
certain plants, like maize and beans (Quantin, 1992) in the first year of cultivation. However these materials have other suitable chemical properties, viz an often nearly neutral pH and a certain richness in exchangeable Ca, Mg and K elements. It is easy to solve the N and P deficiency by a mineral, organic or even biological fertilization. Thus fragipans have a good potential fertility after the improvement of their limiting factors. But it is not the case of duripan, petrocalcic or placic horizons, due to their more serious physical or chemical constraints.


The studies presented here concern mostly the indurated volcanic soils from Latin America, namely the cangahua in Ecuador (Custode et al., 1992), the talpetate in Nicaragua (Prat, 1991; Prat et al., 1992) and the tepetate in Mexico (Arias et al., 1992, Baumann et al., 1992, Quantin, 1992, Marquez et al. 1994). De Noni et al. (1994) are giving a synthesis of these works.

Most indurated horizons of duripan, fragipan or petrocalcic type lie under an ustic climate regime, with a fairly long dry season. There is a great variability of rainfall, interannual and local. The average value of the rainfall erosivity index (after Wischmeier) is rather low or moderate. Only few rains (0 to 3) of high intensity (I30 > 50 mm/h, EI30 > 1000 MJ/ha/mm/h) are responsible for the major part of erosion. The rest is due to moderately erosive rainfalls (I30 # 30 to 50 mm/h). On a barren tepetate or cangahua the runoff percentage is high (> 70%), while the soil loss is very low (0 to 10 t/ha). After subsoiling and tillage of these materials the rain water infilling is better but the soil loss is increasing sharply to 100 t/ha/y and even more, due to the great instability of the finer sized aggregates. A well managed cultivation of maize, using a level contour ridging reduces the runoff rate to 10% and stops the soil loss if rainfalls are weakly erosive (I30 < 30 mm/h); although the runoff rate increases to near 20% and above all the soil loss to 20-30 t/ha/y in the case of heavy rains (I30 > 50 mm/h). Thus the ridging is not effective enough to control the highly erosive rainfalls. The ridge efficiency must be improved with other anti-erosion works like terraces with progressively reduced slope, grass covered embankments, low walls, etc...

The observation of the surface soil morphology (Janeau et al., 1992) has shown some melting of fine aggregates (< 2 mm) which produces a packing down, an encrusting to the surface and a progressive decrease of coarse pores and rain water infiltration. A cultivated tepetate is unstable. It is necessary to avoid exceeding a threshold of fragmentation and of soil cultivation works. It would be convenient to improve the soil structure stability by an organic matter enrichment and a biological activity development. Anyway the water infiltration improvement is stable enough to allow a sufficient water storage during a normal year and to maintain the soil water retention above the wilting point during the short dry period in the middle of the rainy season (Baumann et al., 1992, Marquez et al., 1992).

3. Natural and potential fertility; mineral, organic and biological fertilization.

There are still few results, except in Mexico, concerning the chemical properties of indurated volcanic soils and the evaluation of their potential fertility. The major data concern the following formations:
- duripans from the Xalapa region, Mexico (Rossignol et al. 1992);
- fragipans and petrocalcic horizons from the Mexico city area (Etchevers, Cruz et al., 1992; Etchevers, Lopez et al., 1992; Etchevers, Zebrowski et al., 1992);
- talpetate from Nicaragua (Prat, 1991; Prat et Quantin, 1992; Vogel et al., 1994);
- placic horizon from Chile (Luzio et al., 1992) and Japan (Yamada et al., 1994);
- other indurated horizons from Japan (Yamada et al., 1994)

Etchevers and Ferrera (1994) have made a synthesis of these data, although showing mostly their own work results about the chemical properties, the microbiology and the fertility of some fragipans and petrocalcic horizons near Mexico city. The two major limiting factors are a lack of nitrogen and a severe deficiency in phosphorus easily available for plant growth (2 to 3 ppm, Olsen method). In
addition the petrocalcic materials have a slightly alkaline pH and a deficiency in available Fe, Mn and Zn microelements. But all have a high cation exchange capacity and especially a high content in exchangeable Ca, Mg and K elements. The potential fertility is high after improving the deficiencies in nitrogen and phosphorus by a rather moderate mineral fertilization (N 60 to 120 units/ha and P 60 to 80 units/ha), or an organic fertilization. The phosphorus adsorption is quick, but 70 to 80% of the added element remains easily available for plant growth under a "labil" form. In cultivated and fertilized tepetates the N and labil P content increases progressively. But the exchangeable K values decrease, without reaching however a deficiency threshold after more than ten years of cultivation. There is a selective adsorption of K by the clay minerals (illite, smectites) of these tepetates. In addition the quick weathering of rhyolitic glasses is always recharging the stock in this element. We also observe a slight decrease of the pH.

The addition of organic matter under the form of manure is often used at the beginning of the agricultural restoration of tepetates in Mexico as well as of the cangahua in Ecuador (de Noni et al., 1992) or the eroded volcanic soils in El Salvador (Collinet et Mazariego, 1993). In addition to the nitrogen and phosphorus supply, it reduces the pH; this effect is especially good on the petrocalcic soils. There is also a development of the microbial activity. Ferrera (1992) has well shown the important role played by some symbiotic microorganisms for the nutrition of certain crops. Therefore we have to take into account the three ways of fertilization, viz mineral, organic and biological, in order to reach a high level of potential fertility. Some trials of green manure fertilization are made in Mexico, Ecuador and El Salvador; this practice also allows to improve the soil structure (Collinet, 1994).

4. Agriculture and forest rehabilitation: productivity and profitability.

Navarro and Zebrowski (1994) have made a synthesis on the agricultural rehabilitation of the tepetates (fragipans) in the Mexico city area and on the cangahua in Ecuador. Arias and Oropeza (1994) add some information about the reafforestation, from their program “a tepetate reclamation in the Mexico watershed”.

The agricultural restoration of tepetates has been used during the prehispanic epoch, then neglected after the European conquest. The first modern experiments on the tepetate reclamation started 30 years ago in Mexico and 26 years ago in Ecuador. The reason was the catastrophic extension of the erosion in the densely populated rural lands. The first trials mostly concerned the reafforestation and some reshaping works in order to reduce erosion. Since a dozen years numerous agricultural restoration experiments have been made in order to recover cultivable lands. In Ecuador, a less advanced country, the restoration works on the cangahua are mostly manual. They are made by small farmers on small plots. Although a mechanized reclamation has been carried out with a State assistance, but only on 165 ha. In fact near 1 000 ha have been recovered for agriculture and perhaps 15 000 ha for forestry. In Mexico the reafforestation covers more than 5 000 ha. The agricultural restoration could be more than ten times larger than in Ecuador and it is mostly mechanized on larger plots. The reclamations works are often carried out with some State assistance, but also with private firms. The small farmers (< 20 ha/family) are the most interested in increasing their cultivable land. They support a large part of investments, despite their poor resources.

Some agronomical experiments have been recently made in Mexico and Ecuador in order to evaluate suitable crop systems and their productivity (Navarro et Zebrowski, 1994). Some crops such as wheat, barley, vetch and the common beans can give normal yields as soon as the first year of cultivation, owing only to a mineral or organic fertilization (Marquez et al., 1992, Baez et al., 1994, Chora et al. 1994). Meanwhile the maize, and in someway the broad bean yield produce very little whatever the mineral or organic fertilization may be. But the yield of this crops is increasing with time: it becomes average as soon as the second or third year and good from the fifth year of cultivation. New trials are undertaken to better improve production using either green manures or a symbiotic microorganism insemination.

The cost of agricultural rehabilitation works is very variable according to the type of indurated horizon, the means of soil cultivation and the local socio-economical conditions. The profitability still remains debatable. However in Mexico the investment return and the profitability are obtained after
only eight years of cultivation, in the case of mechanized reclamation works on a tepetate of fragipan type (Marquez et al. in Quantin, 1992). Anyway the tepetate or cangahua reclamation is a soil resource absolutely vital for the small farmers. The reclamation investments could be profitable owing to a State assistance in order to minimize the investment costs and to give an appropriate technical information.

In Chile the “fierrillo” indurated soils are mostly used for grassland. In Japan the indurated soils of the highlands have been recently reclaimed. Their use varies according to the type of material. Subsistence crops or grassland are successfully used on the “masa” (duripans) and “kora” (tuffs) soils, hazelnut or fodder sorghum on the “nigatsuchi” (fragipans) soils, and forest on the “kora” (duripans) soils or the “placic” horizon soils.
Littérature Citée - Literature Cited.


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Indurations Siliceuses dans des Sols Volcaniques. Comparaison avec des Silcrètes Anciens

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Abstract: Silica indurations in quaternary volcanic soils and pedogenic silcretes in tertiary paleosols show the same disposition of superimposed prismatic layers and the same eluvial-illuvial features inside the prisms. Such profiles are due to a non-congruent dissolution process of 1/1 Si-Al parent clay with Al elimination and Si redistribution into the layers of secondary clay coatings or intercalated between the tabular crystals of the parent clay. This process develops along gentle planar slopes under contrasted seasonal tropical conditions.

Introduction

Les sols volcaniques de l’altiplano mexicain présentent fréquemment des niveaux très compacts appelés localement "tepentes". Les profils ont alors de 1 à 3 m d'épaisseur et présentent une structure en couches prismatiques superposées. Dans la région de Xalapa, Veracruz, on observe des horizons laminaires de 1 à 5 cm d'épaisseur se disposant entre les différentes couches prismatiques. Ces horizons s'indurent de manière irréversible lorsqu'ils sont exposés à l'air (duripans). L'induration est due à un enrichissement en silice résultant d'une évolution pédologique et climatique. Elle met en jeu des processus simultanés de dégradation et de néoformation d'argile au sein des prismes et un processus de remplacement des minéraux argileux par la silice. Si ce dernier phénomène est la cause pressumée de l'induration des tepentes (Hessmann, 1991; Hidalgo et al., 1991), il n'a pas été clairement démontré jusqu'à présent. Nous présenterons dans cet exposé quelques faits nouveaux contribuant à l'explication de ce processus particulier de silicification et nous les comparerons à d'autres silifications climatiques antéquaternaires connues.

Les silicifications actuelles dans les sols volcaniques

1. Description des profils

L'étude de deux coupes de la région de Xalapa (Veracruz, Mexique) permet de préciser la disposition des structures prismatiques et la localisation des traits pédologiques portant les silicifications. Une première coupe a été prise à Sumidero sur une altération d’andésite, une seconde à Limones sur une altération de cendre à blocs. Ces deux matériaux sont anciens (Pleistocène inférieur). Ils ont subi une altération climatique profonde et intense et sont rajeunis par des apports pyroclastiques du Pleistocène supérieur. Les coupes indurées ont été mises à jour à la faveur d'entailles relativement récentes.

1.1 Formations de Sumidero.

Le profil de Sumidero présente de haut en bas sur 3 m de profondeur plusieurs horizons superposés (fig. 1).

-(0 m) Epipédon organique dans un matériau cendreux de composition trachytique et attribué au Pleistocène supérieur (38 800 ans).
(0,5 m) Horizon à structure columnaire, sablo-limoneux, d'environ 0,5 m d'épaisseur. Les colonnes ont de 0,2 à 0,3 m de section, elles sont grossièrement hexagonales et couvertes par des coiffes d'éluviation centimétriques.

(1 m) Premier horizon laminaire, ocre-rouille intercalé de gris, de 0,02 à 0,10 m d'épaisseur. Il consiste en une succession de plaquettes indurées dans une matrice limoneuse.

(1,10 m) Horizon prismatique d'environ 1 m d'épaisseur. Les prismes sont brun-jaune, sablo-argileux, avec des nodules ferrugineux centimétriques. Ils sont plus argileux à leur base où s'individualisent des taches grises allongées horizontalement.

(2,10 m) Second horizon laminaire d'épaisseur 0,3 à 0,5 m. Il se compose d'alternances de niveaux argileux gris très plastiques et gorgés d'eau, séparés par des plaquettes indurées très compactes et brunes.

(2,50 m) Horizon inférieur tacheté (plinthite), argileux, brun, à structure polyédrique, avec un réseau de taches gris-clair à contours nets. Certaines s'orientent en réseau sub-horizontal. Les parois des pores, au voisinage des taches claires, sont fréquemment tapissées par des produits argileux blancs, friables, d'aspect filamentieux (pseudomycelium).

(3 m) Des boules d'andésite altérées apparaissent, elles correspondent à l'altération d'une puissante coulée de lave datée de 1,7± 0,2MA visible en place à 5 m de profondeur.

Figure 1 : Coupe et diagramme minéralogique vertical du profil de Sumidero. L'horizon supérieur cendreux s'individualise bien par sa composition minéralogique. Les horizons éluvés se distinguent par des rapports cristobalite (et quartz)/argile plus élevés, mais les rapports cristobalite/quartz varient peu.

1.2. Formations de Limones
Le profil de Limones est nettement plus épais et présente, du haut vers le bas, plusieurs couches columnaires superposées (fig. 2).

(0 m) Epipédon organique, brun grumeleux, argileux.
(0,80 m) Horizon meuble argileux d'environ 1,70 m d'épaisseur, à réseau orthogonal de taches grises allongées (plinthite). Ces matériaux supérieurs proviennent de l'altération d'une coulée de cendre à blocs du début de l'Holocène (≈ 8 000 ans).

(2,50 m) Premier niveau columnaire de 0,40 m d'épaisseur brun sombre, constitué par des colonnes juxtaposées d'environ 0,10 m de diamètre et de texture argileuse.

(2,90 m) Horizon laminaire d'environ 1 m d'épaisseur, beige, limono-argileux, composé de très nombreuses plaquettes indurées, brunes à coeur noir. A la base on observe une zone de transition très éluiviée sableuse, dans laquelle les plaquettes se moulent sur les structures en dôme de l'horizon sous-jacent.

(4 m) Puissant horizon columnaire de 1,50 m d'épaisseur constitué de colonnes compactes, sablo-limoneuses, de 0,40 m de section, dans lesquelles on distingue des figures de roches altérées en boules. Le sommet des colonnes est surmonté par d'épaisses coiffes sableuses, éluviées, emboitées verticalement les unes au-dessus des autres.

(5,50 m) Horizon à structure prismatique d'environ 0,80 m d'épaisseur, moins développée (prismes de 0,15 x 0,10 m), nettement argileux, brun.

(6,30 m) Altérite argileuse brun-jaune à restes de feldspaths argilifiés et blocs d'andésite altérés en boules. Elle correspond, sur 3 m d'épaisseur, à l'altération d'une puissante coulée de cendres à blocs attribuée au Pléistocène inférieur (≈ 1,5MA).

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<th>HORIZONS</th>
<th>STRUCTURES</th>
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<td>Columnaire argileux</td>
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<td>Plinthite et andésite altérée</td>
<td>int. cristobalite</td>
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Figure 2 : Coupe et diagramme minéralogique vertical du profil de Limones. Les minéraux accessoires soulignent les discontinuités dans les venues volcaniques. Les horizons columnaires s'individualisent au sein des plinthites à halloysite, en dehors des matériaux volcaniques récents. La cristobalite n'est pas liée aux horizons, mais au contraire augmente dans les horizons éluviés et apparaît héritée.

1.3 Traits pédologiques

Dans les deux coupes les prismes sont le siège d'éluviations et d'illuviations. Le cœur des prismes présente de nombreuses cavités millimétriques dans lesquelles les grains du squelette sont libres et dépourvus de plasma. De fins tubules tapissés d'argilanes relient certaines cavités entre elles. A ce niveau la densité du matériau peut descendre jusqu'à 1,4 (Campos & Dubroeucq, 1990). En revanche, à la base des prismes, le matériau est nettement plus compact, sans macroporosité, et montre d'épais revêtements argileux. On a dans le prisme un couple éluvation-illuviation. Le cœur est le siège de soutirages, à la base
se font des accumulations. Cette évolution modifie complètement la morphologie du prisme initial et se traduit sur l'ensemble du profil. Elle aboutit à la formation de colonnes à sommet blanchi dans lesquelles l'argile a pratiquement disparu, et de lits d'argile grise à la base des prismes qui constituent la phase d'accumulation la plus évidente.

1.4. Organisation latérale des horizons

A l'amont, des horizons ocre à taches grises (plinthites) se différencient à la base des profils. Ces taches sont allongées dans le sens du drainage et constituent la première discontinuité visible dans les profils argileux homogènes issus des altérites. Dans la plithite se différencie d'abord un premier horizon à structure prismatique. Plus à l'aval, d'autres horizons compacts à structure prismatique apparaissent ensuite en se superposant. Ils sont séparés par des horizons laminaires indurés (duripans). Les couches prismatiques successives se forment à l'aval et en dessous des premières, se disposant à la manière des tuiles d'un toit (fig. 3). Les plus anciennes se trouvent vers la surface, les plus jeunes à la base de l'ensemble prismatique. Le nombre d'horizons prismatiques superposés a tendance à augmenter vers l'aval, donnant des profils de plus en plus différenciés. Ces ensembles indurés sont liés à des entailles secondaires. Ils se développent dans les zones de circulations sub-superficielles de la nappe, et s'enfoncent au fur et à mesure du creusement des talwegs.

Figure 3 : Schéma de l'organisation latérale des horizons du sol à induration siliceuse de Sumidero. Noter leur disposition à la manière des tuiles d'un toit. Les horizons les plus jeunes se forment à l'aval et sous les horizons les plus anciens, probablement en relation avec l'enfoncement du réseau hydrographique.

2. Minéralogie

2.1. Les constituants

L'étude minéralogique a été réalisée à l'Ecole des Mines de Fontainebleau, par diffraction des Rayons X, selon les méthodes classiques sur poudre non orientée et fractions argileuses orientées (Thiry et al., 1983).

La composition des matériaux d'altération est homogène et les paragénèses minérales sont très appauvries (fig. 1 et 2). L'halloysite-10A est le minéral cardinal qui forme plus de 90% des altérites profondes, elle est toujours accompagnée d'halloysite-7A. On note la présence d'interstratifiés halloysite-smectite dans la majorité des horizons du sol ainsi que dans les taches grises de la plinthite, mais ils sont absents dans l'altérite. On note également la présence de smectite dans les horizons d'accumulation d'argile tels que les revêtements d'argile grise des horizons laminares. Ces argiles sont toujours accompagnées d'oxy-hydroxydes de fer, de quartz, de cristobalite basse température et de traces de tridymite. Les horizons pédologiques ont une composition similaire à celle des matériaux d'altération avec, toutefois, des taux plus élevés de quartz et de cristobalite dans les structures columnaires éluvées. Il faut encore signaler la présence de feldspaths plagioclastes, de traces d'amphiboles et de micas, qui sont des minéraux primaires résiduels et marqueurs d'épisodes volcaniques successifs.

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Le taux moyen de quartz estimé dans les matrices des altérites est d'environ 5%, alors qu'il n'est plus que de 1% dans les taches grises de la plinthite et dans les lits d'argile grise des horizons laminaires. Par contre les taux de quartz atteignent 10% dans les structures éluviées.

La cristobalite de ces formations est une cristobalite bien cristallisée, avec des raies de diffraction nombreuses et avec des largeurs comparables à celles du quartz (fig. 4). Par la finesse des raies de diffraction, les diagrammes de cette cristobalite sont complètement différents des diagrammes des cristobalites connues dans les formations sédimentaires ou de ceux des opales-CT communes dans les silicifications de surface.

![Diagramme de diffraction des rayons X sur poudre non orientée d'un échantillon argileux (Horizon laminaire inférieur) du profil de Sumidero. Les pics nets et fins de la cristobalite indiquent qu'il s'agit d'un minéral bien cristallisé. L'échantillon présente en même temps un peu de tridymite. Les raies non marquées sont dues à l'halloysite à 10 et 7Å.](image)

**Figure 4** : Diagramme de diffraction des rayons X sur poudre non orientée d'un échantillon argileux (Horizon laminaire inférieur) du profil de Sumidero. Les pics nets et fins de la cristobalite indiquent qu'il s'agit d'un minéral bien cristallisé. L'échantillon présente en même temps un peu de tridymite. Les raies non marquées sont dues à l'halloysite à 10 et 7Å.

### 2.2. Le problème de la cristobalite

La paragénèse à halloysite et cristobalite peut paraître étrange. Cependant il est possible d'envisager que de la cristobalite ait pu subsister lors de l'altération lixiviant qui a donné naissance aux altérites à halloysite. La solubilité du quartz est de 4 à 7 mg/l, celle de l'opale-CT de diatomite de l'ordre de 20 mg/l (Siffert, 1962; Iler, 1979; Garcia-Hernandez, 1981); mais celle de la cristobalite basse température est inférieure. La saturation en SiO2 de la kaolinite dans l'eau en absence de cations est de l'ordre de 4 mg/l, celle des différents minéraux argileux TOT alumineux (smectite et illite) s'échelonne entre 10 et 20 mg/l (Siffert, 1962; Fritz, 1981). La cristobalite est stable pour des teneurs supérieures à celles des minéraux smectitiques. Le domaine de formation de l'halloysite se situe entre celui de l'allogène et celui de la kaolinite en climat humide, c'est à dire un milieu où les solutions comportent 17 à 35 mg/l de SiO2 (Quantin, 1992). Dans un tel milieu le quartz se maintient et la cristobalite bien cristallisée peut subsister. D'autre part, dans l'hypothèse d'une néoformation de la cristobalite dans le sol, on s'attendrait à observer un enrichissement dans des horizons ou des structures spécifiques, ce qui n'est pas le cas.

Les rapports entre les intensités de diffraction des raies principales du quartz (3,34 Å), de la cristobalite (4,08Å) et de la bande (020) à 4,45Å de l'halloysite-7Å permet de préciser les variations relatives de ces minéraux. Les mesures effectuées directement sur les intensités n'ont évidemment aucun caractère absolu ou quantitatif. Mais pour ces matériaux qui ont une composition globale très similaire (halloysite et quartz), les rapports entre les
Les intensités sont significatives. On constate une grande constance du rapport des intensités de diffraction entre la cristobalite et le quartz (fig. 1 et 2). Les faibles variations observées se rapportent à la texture de l’échantillon. Les matériaux argileux illuviés affichent en effet des rapports Intensité Crist./Intensité Quartz un peu plus élevés (1,3) que les matériaux sablo-limoneux éluviés (0,7). Mais, en même temps, le rapport Intensité Crist./Intensité Halloys. est plus élevé dans les matériaux sablo-limoneux (2 à 5) que dans les matériaux argileux illuviés (1 à 2) ce qui suggère la concentration relative de la cristobalite dans les horizons éluviés.

Cette constance du rapport Intensité Crist./Intensité Quartz est remarquable. Elle exclut pratiquement la possibilité d’une formation ou d’une accumulation de cristobalite dans des horizons pédologiques. Les deux minéraux n’auraient en effet aucune raison d’être liés. En revanche, il faut envisager que quartz et cristobalite sont liés dans la roche-mère. De plus, du fait de la solubilité très différente des deux minéraux, la constance de ce rapport indiquerait que la cristobalite reste protégée des dissolutions à cause des teneurs en silice élevées dans la solution du sol lors de l’altération. Les variations observées du rapport entre matériaux illuviés et matériaux éluviés peuvent s’expliquer par la morphologie en plaquettes et la finesse de la cristobalite. Elle accompagne les illuviations argileuses.

2.3 Minéraux argileux et silice secondaire

La structure des différents horizons a été d’abord étudiée en microscopie optique au moyen de lames minces de sol orientées non couvertes. Par la suite les revêtements argileux des horizons laminaires, les taches d’argile grise et les pseudomycéliums des horizons de plinthite ont fait l’objet d’observations plus fines en microscopie électronique à balayage. Ces observations ont été réalisées dans les laboratoires de l’ORSTOM à Bondy. Deux modes de préparation des échantillons ont été utilisés: (i) la fraction argileuse est dispersée sur une lame enduite de résine polyester et couverte d’un microfilm de carbone et
(ii) de très fins fragments de sol non perturbé sont collés sur fond de carbone et métallisés à l'or. Les micro-analyses quantitatives ont été réalisées à l'aide d'une sonde EDX (Energy Dispersive X-ray Analyser) couplée à l'observation en microscopie électronique à balayage.

Le matériau argileux brun constituant le fond matriciel de l'altérite se compose d'une halloysite tubulaire brune à 10A. Les tubes ont 0,2 µm d'allongement. Dans les horizons prismatiques, le plasma du matériau dans le corps des prismes se compose de la même halloysite.

Dans les revêtements d'argile grise ainsi que dans les coeur des taches grises de la plinthe, on observe à la fois des argiles en grands feuillet minces et froissés d'une taille de 5 à 10 µm attribuées à des smectites, et des formes plus petites en lamelles pseudohexagonales attribuées à des halloysites en feuilles (Quintin, 1984), (fig. 6-1). Ces argiles sont assemblées par empilement (fig. 6-2) pour donner des revêtements centimétriques. Leur birefringence, à l'inverse de ce que l'on observe sur des argilanes, est peu marquée et se manifeste en microscopie optique par des plages d'extinction diffuse (Dubroeucq, 1991). Les images de ce matériau, observé en microscopie à balayage, montrent qu'au centre des empilements des feuillet d'argile existent des feuilles identiques mais leur composition est entièrement siliceuse (fig. 5-2 et 6-4). Toutefois, à l'échelle du micron, ces feuilles montrent sur leur surface une mosaïque de microcristaux tabulaires (fig. 6-6), à la différence des feuilles d'argile à surface plus lisse (fig. 5-1 et 6-3). Parfois, des irrégularités sphériques suggèrent l'existence, sous la surface, d'un matériau constitué de sphères de silice (fig. 6-5).

Les images de pseudomycelium, en microscopie à balayage, confirment qu'ils sont composés d'un faisceau de films de silice (fig. 7-1). Ces films sont souvent divisés en segments. Le corps de chaque filament est constitué d'un assemblage non orienté de sphères de silice d'environ 0,1 µm de diamètre (fig. 7-3). L'ensemble du filament est entouré d'un film d'argile fortement siliceuse, probablement une smectite (fig. 7-2, 7-4). Par sa structure en sphères nettement individualisées, on attribue cette forme de silice à de l'opale-A.

Il est probable que la silice des feuilles interstratiées dans les argiles soit elle aussi de l'opale-A. Des morphologies en sphères de silice ont été observées lors de l'altération de micas, par dissolution dans l'acide sulfurique (Jones et al., 1966) et lors de l'oxydation des gisements de pyrite (Sornein, 1980). Dans les puissants profils blancs du régolithe tertiaire d'Australie, l'opale se présente souvent sous forme de microsphères de silice assemblées en feuilles. Ces feuilles siliceux résultent vraisemblablement de l'altération par "décationisation" des feuilles argileux. La silice des couches tétraédriques des kaolinites se réorganise en microsphères disposées en feuilles (Rayot et al., 1992; Rayot, 1993). Dans d'autres situations on observe des couches de silice amorphe dans les espaces interféloïaires des macro-kaolinites de l'altération (Balbir Singh & Gilkes, 1993). Dans d'autres formations silicifiées, de la silice en feuilles a été interprétée comme résultant de la transformation de la kaolinite en opale (Roulin et al., 1986).

Des formes semblables de silice en assemblage de feuilles ont déjà été signalées dans les sols (Wilding and Drees, 1974; Drees et al., 1989). Ceci expliquerait à la fois la morphologie des feuilles siliceux en mosaïque de microcristaux tabulaires et l'absence de raies significatives dans les diagrammes de diffraction X. En effet, le spectre de l'opale-A ne donne qu'un bombement centré sur 4,10 A et 4,03 A (Jones & Segnit, 1971), en général masqué par la base des raies hk des argiles.

3. Variation saisonnière de la composition de l'eau du sol

Les deux sites étudiés appartiennent à la même zone climatique tropicale d'altitude (1000 m), relativement humide avec 1400 mm de précipitation annuelle mais à saison sèche marquée durant 4 à 6 mois. L'eau libre du sol a été prélevée à différentes profondeurs entre 0,6 m et 2,5 m le long d'une coupe de 100 m de long sur le site de Sumidero durant la saison pluvieuse 1990.
Figure 6 : Images des revêtements d'argile grise des horizons laminaires en microscopie électronique à balayage. (1) Aspect général de la fraction argileuse dispersée sur résine. On distingue de grands feuillets froissés de smectite, de petites plaquettes pseudohexagonales d'halloysite en feuillets, et des formes enroulées d'halloysite tubulaire. (2) Section d'un fragment de revêtement argileux montrant l'empilement des feuillets d'argile. (3) Aspect lisse de la surface d'un feuillet argileux (microanalyse figure 5-1). (4) Plaquettes de silice (microanalyse fig. 5-2) à surface lisse disposées sur un fragment argileux. (5) Feuillet de silice (microanalyse fig. 5-3) à surface boursouflée intercalés dans un empilement de feuillets argileux. (6) Aspect de surface des feuillets siliceux en mosaïque de cristaux tabulaires.
Figure 7 : Images de pseudomycelium de silice en microscopie électronique à balayage. (1) Aspect d’ensemble des filaments. (2) Un fin revêtement d’argile englobe le filament. (3) Détail des sphérules d’opale qui constituent le corps du filament. (4) Détail du film d’argile à surface boursouflée qui enveloppe les sphérules de silice.

Ce sont des eaux faiblement acides, le pH varie entre 5,7 et 6,18 avec une acidité qui a tendance à s’accentuer en fin de saison humide. Les teneurs en silice dans les eaux varient globalement entre 30 mg/l et 70 mg/l de SiO2. Elles sont relativement constantes quel que soit le volume des précipitations et augmentent en fin de saison pluvieuse. Par contre les teneurs en aluminium dans les eaux du sol sont plus faibles mais avec une forte variabilité de 0,5 mg/l à 5 mg/l Al2O3 (tableau). Les fortes teneurs suivent de un ou deux jours une occurrence de fortes précipitations. Ceci indique que les concentrations en aluminium dans les eaux du sol semblent liées directement au volume des pluies alors que celles de la silice varient saisonnièrement (Campos & Dubroeucq, 1990; Campos, 1991).


L'origine de la silice des eaux est un point important pour la compréhension des silicifications. On peut penser qu'elle provient des matériaux volcaniques récents des niveaux supérieurs du profil qui contiennent encore beaucoup de verres volcaniques. Mais les horizons laminaires déliminent des aquifères qui ne communiquent pas entre eux. On peut aussi envisager que la silice provient de la destruction des minéraux argileux dans les horizons de plinthite et que les eaux se chargent en silice déjà à ce niveau, pour circuler ensuite latéralement par les horizons laminaires.

Comparaison avec les cuirassements silicifiés anciens


1. Description des profils

Le point commun le plus remarquable entre les silcrètes anciens et les silicifications actuelles des sols volcaniques est la présence d'une structuration columnaire en horizons superposés séparés par des structures laminaires. Un profil typique peut être décrit à partir des silicifications qui affectent le sommet des formations kaolinitiques de l'Eocène inférieur du bassin de Paris. Les lentilles silicifiées ont de 0,5 à 2m de puissance. Ce sont des quartzites très durs, de couleur jaunatre, disloqués en blocs arrondis à surface mammelonnée. On y reconnaît de bas en haut les horizons suivants (fig. 8).

- Un horizon inférieur à granules siliceux millimétriques qui se soudent pour former des nodules centimétriques. Les granules sont formés de quartz microcristallins mélés d'oxydes de titane et soudés par de l'opale.
- Un ou deux horizons à structure columnaire séparés par des discontinuités laminaires horizontales. Ils sont formés de colonnes décimétriques à matrice de quartz.

Un horizon supérieur massif mais à structure interne noduleuse et pseudobréchique avec de nombreux vides de dissolution. Les vides isolent les formes nodulaires recouvertes d’un cortex d’oxydes de titane et des quartz automorphes se développent dans les vides.

**Figure 8** : Organisations macroscopiques d’un silcrète dans le sud du Bassin de Paris, France. Noter la superposition de corps columnaires coiffés de zones illuviées. Les illuviations à la base des horizons columnaires déterminent des discontinuités planaires.

**Figure 9** : Organisations micromorphologiques des dissolutions et dépôts successifs dans la matrice siliceuse des silcrêtes. Des dissolutions et dépôts successifs conduisent à l’accumulation relative des oxydes de titane et des quartz les mieux cristallisés. Les dépôts illuviés montrent en même temps une transformation de l’opale primaire en quartz microcristallins.

2. Micromorphologie

L’essentiel des structures micromorphologiques de ces cuirassements siliceux anciens résultent de dissolutions et recristallisations successives.

Dans la partie inférieure du profil, les granules sont formés de quartz ambiboids dans une matrice de quartz microcristallins (1-3 µm) contenant des pigments d’anatase. En
microscopie électronique, les kaolinites du sédiment initial présentent des corrosions et sont enrobées par des gels de silice.

Dans les horizons columnaires, les microstructures observées sur la paroi des fentes à l'intérieur des colonnes montrent une séquence organisée de différentes formes de silice (fig. 9). Le plancher des fentes est tapissé de fines lames de silice. Les lames superficielles, les plus récentes, sont formées d’opale avec de faibles teneurs en oxyde de titane. Les lames inférieures, plus anciennes, sont souvent noduleuses et formées de quartz microcristallins à teneur plus forte en titane. Cette séquence résulte d’une recristallisation progressive de l’opale en microquartz avec une perte de silice et une accumulation relative de titane (anatase). Au toit des fentes, il y a dissolution préférentielle de la matrice microcristalline et préservation des gros grains de quartz avec dépôt de "stalactites" de titane. À terme, l'intérieur des colonnes est entièrement restructuré et devient noduleux.

Dans l'horizon supérieur, les structures de dissolution dominent. Des vides irréguliers se développent et dégagent de nombreuses formes nodulaires entourées d’un cortex enrichi d’oxyde de titane. Elles témoignent d’une dissolution importante de la silice au sommet du profil conduisant à l’effondrement des structures initiales et leur transformation en horizon nodulaire.

A l’échelle du profil, les formes amorphes et cryptocrystallines de la silice prédominent à la base de la coupe alors qu’en surface ce sont les quartz microcristallins puis les quartz automorphes et quelquefois les nourrissages de quartz qui se développent (fig. 8). Dans cette séquence, chaque forme minéralogique et pétrographique de la silice est issue de la précédente par remise en solution et recristallisation sur place, traduisant le réajustement du mineral avec le milieu. Ces recristallisations sont le moteur des réorganisations micromorphologiques observées.

3. Mécanismes et environnements

Ces profils se développent sur des roches mères kaolinitiques (sédiments clastiques ou altérées) par dissolution incongruente de la kaolinite, avec exportation de l’aluminium et maintien en place de silice sous forme d’opale. Cette dissolution incongruente de la kaolinite implique l’existence d’un milieu acide à la base des profils.

A partir de ces formes de silice mal cristallisée se développent des recristallisations et dissolutions successives conduisant à la conservation des quartz les mieux formés en tête du profil et le dépôt de formes moins bien cristallisées à la base (Thiry et Millot, 1987). Il y a, au cours de l’évolution, enfoncement du profil siliceux dans la roche mère kaolinitique et les structures élaborées dans les horizons inférieurs sont transformées et détruites dans les horizons supérieurs.

L’essentiel de la silice provient de dissolutions en tête du profil, suivies de haut en bas d’une série de précipitations et de dissolutions successives. Mais la liaison intime entre les milieux appauvris et enrichis n’implique pas qu’ils fonctionnent en même temps. Les deux milieux fonctionnent alternativement. Durant la saison humide, l’eau de pluie dissout les horizons quartzitiques supérieurs pour produire des solutions qui contiennent jusqu’à 6 mg/l de SiO2. Durant la saison sèche, une concentration des solutions par évaporation d’un facteur de 2 à 4 est suffisant pour provoquer la précipitation de la silice. La distribution générale des formes de silice, avec du quartz en tête et de l’opale à la base, résulte d’une concentration progressive des solutions qui percolent.

Ces silicifications pédologiques se rencontrent dans des paléopaysages aux pentes faibles mais régulières. En Australie, elles arment des glacis au pied des plateaux. Les silicifications les plus remarquables s’observent dans les zones de raccordement avec les plaines, là où les circulations sont raîentes, mais restent importantes. De même l’induration des sols volcaniques se développe sur des surfaces régulières en pente douce (planèze) formées par de puissants épanchements de produits pyroclastiques ou de laves, et s’intensifie vers l’aval.

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Les indurations siliceuses actuelles dans les sols volcaniques, tout comme les cuirasses siliceuses anciennes, montrent la destruction de minéraux argileux, halloysite ou kaolinite. Cette hydrolyse incongruente des minéraux argileux à la base des profils demeure un point important. Elle implique un environnement acide dans lequel Al est plus soluble que Si. Dans les sols volcaniques indurés, qui sont globalement acides avec des pH de 5 à 6, il faut supposer que localement et temporairement on puisse avoir une baisse plus importante du pH, provoquée par des phénomènes d’hydromorphie. En effet, les profils actuels montrent que les horizons laminaires correspondent à des zones d’écoulement latéral de petites nappes perchées localisées dans les horizons de plinthite. De même, les profils de silcrètes anciens montrent très souvent à leur base des figures d’hydromorphie.


Dans les profils actuels comme dans les paléoprofils, la silicification pédocologique se développe aux dépens d’un minéral argileux décationisé, halloysite ou kaolinite. En effet, la présence de Ca ou Mg tamponnerait le milieu et entrainerait la recombinaison de la silice libre pour former des smectites ou d’autres minéraux argileux. Dans tous les cas on retrouve des climats avec alternance de saisons humides et sèches. C’est cette alternance qui vraisemblablement permet d’une part la libération de l’aluminium puis son exportation et d’autre part l’accumulation relative de silice et sa redistribution dans le profil. La silicification nécessite aussi des paysages ouverts (glacis, piémonts, versants) où les circulations évacuent les éléments dissous.

Références


Calcitic Accretion on Indurated Volcanic Materials
(Example of Tepetates, Altiplano, Mexico)

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Abstract

The aim of this paper is to show how calcitic accretion can contribute to induration of the tepetates. Calcific accretion has been studied in the Mexico basin and compared with one section located in the drier basin of El Carmen. Acicular fabrics are always the initial stage of precipitation which is often accompanied by calcitization of root mats. The progressive micritization of the initial forms is demonstrated to have played an important role in the stabilization of calcitic accretion. Formation of a hard, laminar crust on the top of the calcitic horizon has prevented the tepetates from subsequent erosion. Calcite accretion always occurred independently of the two processes responsible of tepetates induration, i.e. tepetates compaction and clay illuviation. We also demonstrate that there is no relationship between volcanic activity, sedimentation of volcanic materials and calcitic accretion. The process of calcitic accretion is concluded to have been discontinuous through time probably related to aeolian sedimentation and may be possibly contemporaneous with drier episodes.

Introduction

The circumstances under which tepetates becomes indurated have been widely discussed. Silica precipitation and clay illuviation have been recognized as the main processes which control the post-depositional evolution of tepetates. Calcite accretion is mentioned by most authors to be commonly present on and in tepetates; it has however, been rarely investigated, consequently its role on the induration of tepetates remains poorly documented. The stratigraphy of tepetates units and associated soils has not yet been thoroughly investigated. Tepetates are known to share some characteristics to duripans in which "deposition of calcium carbonate and illuviated clay is primarily controlled by the same process which explains the association of Si deposition with horizons of clay and carbonate accumulation". The hierarchy of features resulting from silica deposition, clay illuviation and calcium carbonate accumulation in duripans of Western United States has been discussed, however precise sequences of events could not be produced. In other regions, geologists have described calcitic accretion on volcanic materials while others have discussed the possible existence of specific relationships between carbonate accretion and volcanic activity.

The aim of this paper is to show how calcitic accretion can contribute to the induration of tepetates and other volcanic materials. By studying the morphology and hierarchy of pedological features in thin section, the sequential formation of tepetates is reconstructed and conditions of its induration are defined.
Materials and methods

Field investigations have been mainly conducted on the piedmont slopes of the Mexico basin covered by tepetates. The present study focusses on a topo-sequence from Texcoco lake to Sierra Quetzaltepec (Chalco soil map, 1/50,000) that has been previously described\(^6\) to \(^9\). Above the lagunar sediments of Texcoco lake, unconsolidated acid pyroclastic materials come to the surface whereas the piedmont slope is covered by tepetates. Calcitic concentrations appear on the pyroclastic materials and cover the piedmont to mid-slope with a progressive decrease in thickness. These calcitic concentrations were described and sampled near the village of Coatlinchan at the Santa Maria quarry. The reference profile selected consists from the top to the bottom of:

1. A Phaeozem, thin (40 cm), partially eroded, calcium carbonate free. It overlies with an abrupt limit the calcitic concentrations. A well developed root mat lies on the top of these concentrations.
2. A hardened, thin (a few centimeters) calcitic layer, a weakly developed laminar crust.
3. A calcitic horizon, 50 cm thick, which consists of white, friable calcitic infillings of horizontal fissures bound by some vertical ones; and of a few, large (few centimeters), open fissures. These large fissures are infilled with a loose packing of small crumby peds, while the lower wall of these large fissures is coated by a hardened calcitic layer (one centimeter thick) on which lies a root mat. The abundance of fissures gradually decreases with depth.
4. Below the calcitic horizon, within 150 cm, some thin fissures infilled with calcite and calcitic speckles are present; their abundance decreases with depth.

A continuous sampling was performed throughout the Coatlinchan profile, from the Phaeozem down to a depth of 4 m into the tepetates. In areas where the Phaeozem is eroded, the laminar crust (2) is more indurated, gets thicker and becomes laminar while the underlying calcitic horizon does not exhibit any transformation. Complementary samples were collected from this crust.

Differences of the thickness of the calcitic profile and its upper hardening are the only spatial variations observed in the whole Mexico basin. Additional samples were taken at the barranco de la Lechuza for comparison.

The tepetates of the Mexico basin do not contain internal calcitic accretion; interstratified Chromic Luvisols and Vertisols however, commonly exhibit at their base a calcitic sub-horizon which consists of a layer of hard, rounded calcitic nodules. This calcitic sub-horizon has been investigated and sampled at San Miguel Tlaixpan.

Calcitic accretion that exists around the Laguna Totolcingo, a basin drier than the Mexico one, have been studied for comparison. In a stratigraphic section observed in a small quarry above El Carmen village, west of the Laguna Totolcingo, the following calcitic accumulations have been observed:

- level 1, a calcitic profile on the top of the section which is similar to the Coatlichan one, although it is thinner;
- level 2, a sandy, calcitic layer with clayey aggregates which is lying upon a paleosol with vertic characters;
- level 3, below the paleosol, a second sandy calcitic layer lying again upon also a paleosol.

Equivalents of these calcitic accumulations were not observed in the Mexico basin.

Microscopic descriptions\(^20\) \(^21\) have been performed on large (8 x 13 cm) thin sections\(^22\), first under binoculars in order to characterize the distribution of calcitic features at meso-scale, then under the polarizing microscope at low and medium magnifications for studying crystalline fabrics. Crystals were observed under MPol at high magnifications on aggregates under SEM equipped with an EDAX microprobe.
Plate 1. SEM micrographs of acicular fabrics

Results

Crystal types.
Various types of crystals dominated by acicular forms have been observed (Plate 1).

Needles. Three sub-types have been recognized under SEM: (1) large (200-500 μm in length), in form of gutter, with sharp ends, smooth surface (micrographs 1 & 2), (2) short (30 μm in length) and rather thick, consisting of a dense packing of elongated, angular to sub-angular crystals, giving a heart-shape to needles (micrograph 4), (3) medium size, (50 μm), with a rugose surface (micrograph 3).

Rods. 0.5 μm thick, 2μm large and 30-50 μm in length present carved edges. Calcite rhombohedrons, a few microns in size occur on edges of rods, mainly observed in the lower part of the calcitic horizon (micrograph 6).

Cylinders, 10-20 μm in length, exhibit an internal cylindrical void, 2-3μm in diameter with abundant angular crystals at their surface (micrograph 5).

The crystalline fabric of the micritic ground mass could not be observed under the highest magnifications of MPol because of the small size of crystals and under SEM because of the very dense crystal intergrowth (Plate 2, micrograph 4 & 5).

Calcitic fabrics.
Acicular fabrics consist of interwining of various density of needles in association with some cylinders. Rods assemble parallel to each others or in spherolithic heaps. These fabrics never superimpose each other. They coat and infill primary channels which in the field appear as white speckles. They can be part of more complex fabrics in the calcitic horizon (fig. 1).

Fig. 1. Composite channel infilling. Located at bottom of calcitic horizon. (T) Tepetates ground mass. (1) Rods. (2) Large needles. (3) Small needles. (4) Illuvial clay.
Plate 2. SEM micrographs of various calcitic fabrics.

Root pseudomorph fabric (micrograph 2). The sclerenchyma morphology is preserved while the parenchyma can be: (1) preserved, cell walls are replaced by very small crystals less than 0.1 μm, (2) replaced by needles, (3) replaced by a thin floating ring of micrite. This fabric contain a rather high amount of silicium (fig. 2). The preserved parenchyma sub-type is only present at the top of the calcitic horizon. Root pseudomorphs display various stages of alteration between a grey, open micro-sparitic fabric to a pale yellow dense, undifferentiated micritic mass. Root pseudomorphs are common in the calcitic horizon, most of them are concentrated in the form of thin sub-horizontal layers of calcified root mats. Their abundance increases abruptly in the laminar crust.

![Graph showing elemental composition](image)

**Fig. 2. Elemental composition of a root pseudomorph.**

Stromatolithic fabric. It consists of spheroliths (40 μm in section) assembled in horizontal, mammilated micro-layers. Brownish yellow and translucent micro-layers are alternating. Each spherolith appears as a parallel, radial packing of cylindrical calcitic fibers, 2 μm in section and 25 μm in length (micrograph 3). Packing voids between the stromatolithic micro-layers are commonly infilled by fluorescent micrite.

Micritic fabrics. They are always very dense and display various morphologies. They can be continuous: (1) pale grey, translucent, (2) dark grey, mediumly opaque, (3) pale yellow, translucent. When they are discontinuous, they result of a packing of rounded pellets, 75-100 μm in
Fig. 31. Coatlinchan

Fig. 32. La Lucheza

<table>
<thead>
<tr>
<th>Facies</th>
<th>Stage of evolution</th>
<th>Pedogenic and sedimentary significance</th>
<th>Climatic conditions</th>
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<tr>
<td>Stromatolithic crust (S)</td>
<td><strong>Primary accretional facies</strong></td>
<td>Calcite accretion by cryptogamic vegetation</td>
<td>Strong seasonal contrast (similar to present)</td>
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<tr>
<td>Calcified root mat (R)</td>
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<td>CaCO₃ in excess</td>
<td>Less humid, landscape destabilization</td>
</tr>
<tr>
<td>Calcite depleted fabric (D)</td>
<td></td>
<td>Calcite dissolution because of erosion</td>
<td>More humid than present</td>
</tr>
<tr>
<td>Dense micrite (M)</td>
<td><strong>Secondary accretional facies</strong></td>
<td>Total recrystallization of primary facies</td>
<td>Surficial alteration under conditions similar to</td>
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<tr>
<td>Dense micrite with clay textural fragments (Mc)</td>
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<td>Total recrystallization of primary facies on an argillic horizon</td>
<td>present ones</td>
</tr>
<tr>
<td>Micritic pellets (Mp)</td>
<td><strong>Tertiary accretional facies</strong></td>
<td>Desiccation</td>
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<tr>
<td>Pellet fabric (P)</td>
<td><strong>Aeolian facies</strong></td>
<td>Aeolian sedimentation</td>
<td>Arid, strong aeolian deflation</td>
</tr>
</tbody>
</table>

Fig. 3. Micromorphology of laminar crusts and interpretation.
diameter. The ground mass of the pellets is a dark grey or a pale yellow micrite. When voids become larger, the acicular fabrics progressively merge into a grey continuous micritic mass.

**Pellet fabric.** It consists of a loose packing of rounded pellets which are often formed of a nucleus of various compositions (volcanic fragment or a clayey aggregate) and are coated by oriented clays while other pellets are micritic. The pellet fabric was only observed in the laminar crust of barranco de la Lucheza.

**Laminar crusts**
These crusts are characterized by: (1) an abrupt increase in calcium carbonate in comparison to the underlying calcitic horizon, (2) an abrupt limit with the overlying soil when this one exists, (3) a juxtaposition of horizontally layered micro horizons, (4) a predominance of micritic fabrics in which elongated fragments of clayey tepetates can be randomly dispersed. The sequence of the layered horizon is marked by various changes of the morphology and composition of each individual micro-horizon.

In Coatlinchan, where the Phaeozem is eroded, the following juxtaposition of micro-horizons has been observed from the top to the bottom (fig. 31):

1. a rather dense layering of calcitic spheroliths, 2-3 mm thick,
2. a dense grey micritic micro-horizon, 1 mm thick, with abundant, small, elongated fragments of clay features,
3. a root mat pseudomorph embedded in a packing of rounded micritic pellets,
4. a dense micritic micro-horizon similar to (2).

In the underlying layer, the micro-horizonation is less expressed while the micritic fabrics tend to predominate and contain fragments of spherolithic micro-horizon and root pseudomorphs. In large, open fissures, a comparable set of micro-horizons has been recognized with a layer of calcitic spheroliths on the top. Under the Phaeozem, the hardened calcitic layer appears similar, however the space between spheroliths is filled by phaeozemic ground mass locally sorted by illuviation.

At barranco de la Lucheza where the laminar crust is bare, the following micro-horizons have been recognized from the top to the bottom (fig. 32):

1. a dense algae colony,
2. a thin, dense, almost carbonate free, no birefringent micro-horizon,
3. a rather dense packing of micritic pellets,
4. a grey micritic, 500 μm thick lamellae,
5. a loose packing of pellets, 1 mm thick, consisting of various pellets, some carbonate free coated with clay and others micritic.

**Internal calcitic accretion in tepetates. Nodules in Paleo-Vertisols**
Rounded, hard, nodules in Paleo-Vertisols at San Miguel Tlaixpan display a progressive palmated sparitic invasion of the vertic fissural network. The nodules are characterized by the gradual merging of three types of fabrics: (1) sparite infills widened original fissures of the vertic ground mass, (2) fine vertic fragments in which fissures are filled by sparite, (3) very fine vertic fragments (10-20 μm in size) dispersed in a palmated sparitic ground mass. The palmated sparitic fabric is perforated by some channels and fissures in which the following hierarchy of features is observed: (1) a thin micritic coating, (2) a clay coating, (3) a loose sparitic infilling.

**Other internal calcitic accretion in tepetates**
Superimposed on volcanic material, calcitic accumulations (level 2 in the El Carmen section) appear in thin sections as:
(1) channel acicular fabric infillings in the top of level 2 which consists of a packing of pseudo-sands; this acicular fabric is partly micritized;

(2) a dark grey micritic ground mass in which are regularly distributed rounded carbonate free aggregates in the middle of level 2; this micrite is loose and becomes locally dense; it infills packing voids of pseudo-sands, this fabric is perforated by channels which are infilled by a partially micritized, acicular fabric.

(3) channel acicular fabric infillings at the bottom of level 2 which consist of a dark crumby soil fabric. As in top of level (2), this acicular fabric is partly micritized.

Calcified root mats do not exist in these calcitic profiles.

Relationship between calcitic accretion and tepetates
Calcitic accretion in Coatlinchan and La Lechuza profiles are always juxtaposed with an abrupt boundary with the adjacent matrix which can be, either tepetates, or textural clayey features which coat the voids where calcite has been segregated. In the laminar crust, fragments of elongated clayey features are often present embedded in a micritic fabric. Calcitic accretion are never covered by any other features, even when the laminar crust is overlaid by the Phaeozem. In the latter situation, illuvial features do not penetrate in the calcic horizon except within the stromatolithic layer.

Discussion

The genetic sequence of calcite accretion on tepetates

The lowermost position of acicular fabrics and their immediate juxtaposition to the indurated material, suggest that these fabrics represent an initial stage of calcite accretion in all investigated profiles. Calcite needles are presently considered as excreta of fungi, however microbial precipitation of calcite can also play a role. The initial stage of calcite accretion in the Coatlinchan profile is thus concluded to be controlled by cryptogamic vegetation and associated microorganisms. The variety of forms is probably in relation to various species of fungi and bacteria. Concentrations of root pseudomorphs along sub-horizontal lines indicates that root mats were existing during accretion of the calcic horizon. Progressive alteration from the top to the bottom of the calcitized roots suggests that calcite aggradated from the bottom to the top of the profile. We must suppose that in the past, similarly to present conditions, the root mat was always existing on the top of the calcitic profile which confirms the hypothesis of rising calcitization. Consequently, we must consider that each root mat corresponds to a former calcitic surface. The greater abundance of root mats in the laminar crust indicates that these crusts correspond to a relative equilibrium in calcium carbonate accretion. The high content in silicium of root pseudomorphs (fig. 2) is in relation with the abundance in tepetates of silica in form of volcanic glass and phytoliths. Roots have probably absorbed silicium in excess and stocked it partly in their cells. After their death, silicium was trapped in calcitic accretion.

Acicular and root pseudomorph fabrics were progressively replaced by micrite (fig. 4). The high micro and meso-porosity of the acicular fabrics make them to be highly sensitive to dissolution, root pseudomorphs are less sensitive because of a smaller porosity. Local recrystallization of the calcitic fabric into a dense micrite is explained to result from limited solute movements. The high density of the micritic fabric prevented subsequent tranformations of its internal morphology by percolating water which could only dissolve its outer edges. The progressive replacement of all acicular fabrics and many root pseudomorphs into a micritic fine mass is suggested to reduce the sensivity of
the calcitic horizon to dissolution, (2) induce a hardening of this horizon which will prevent it from erosion.

<table>
<thead>
<tr>
<th>Stages of micritization</th>
<th>Incipient</th>
<th>Progressive</th>
<th>Total Desiccation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acicular fabrics</td>
<td>loose micrite</td>
<td>continuous dense micrite</td>
<td>micritic pellets</td>
</tr>
<tr>
<td>Root pseudomorphs</td>
<td>not affected</td>
<td>micritization of sclerenchyma cell pseudomorphs</td>
<td></td>
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</table>

Fig. 4. Stages of micritization

Two sub-types of pellet fabrics have been observed in the laminar crust. The micritic subtype is considered to result from desiccation of a continuous micritic fabric while the second one because of the composition of its nucleus (rock fragment or clay aggregate) and its clayey coating could have been transported by saltation from a playa. The mixing of the two sub-types in La Lucheza would indicate that the micritic subtype can be also wind transported. Their presence at the top of the laminar crust indicates that during some periods: (1) this layer was at the surface, (2) a playa existed in the vicinity and was the source for supplying the carbonate free pellets, (3) strong winds prevailed favoring aeolian erosion and saltation. These periods were undoubtedly characterized by a drier climate than presently and strong winds.

The micro-horizonation and juxtaposition of various calcitic fabrics of the laminar crust suggest that it has a polyphased genesis (fig. 4). Root mat pseudomorphs correspond to a climatic phase during which vegetation was well developed and when a soil was covering the laminar crust. Pellet micro-horizons, on the contrary, indicate as demonstrated above, absence of overlying soil and aridity. Micritization of pellet fabric should correspond to re-establishment of more humid conditions. The "stromatolitic crust" and algae colonies is be discussed in the next paragraph.

Occurrence of some calcium depleted features at the bottom of the Phaeozem indicates that leaching of calcium carbonate is active under present-day conditions at the interface of the Phaeozem and the calcitic accretion. The leached carbonates are probably fixed by algae in the "stromatolithic crust". This assumption is supported by an absence of physical and chemical alteration of these crusts. Their presence in wide open fissure indicate that these algae can live inside the soil which means consequently they can develop also at the surface of the laminar crust under the Phaeozem.
stromatolitic encrusting is however, active since some time as shown by the incorporation of fragments of former "stromatolitic" crusts into some micritic micro-horizons. The algae colonies has been, on the contrary, observed only on bare laminar crusts. The carbonate free micro-horizon just beneath these algae colonies indicates that algae are able to leached carbonates. The hierarchy of pedological features on the top of the tepetates after their sedimentation in Mexico basin can be interpreted as the following:
(1) Compaction of the tepetates probably synchronous of its deposition.
(2) Development of a polyphased illuvial soil on the top of the tepetates which resulted in channelling due to root and faunal activity and in horizontal cracking due to desiccation or ice-lensing; then these channels and fissures were penetrated by various illuvial clays.
(3) Calcitic accretion took place after all these illuvial phases, the absence of intermixing between illuvial features and calcitic ones indicates that the environmental change was abrupt; the calcitic accretion was progressive, ascendant and continuous. The purety of all calcitic features suggests that during this phase no other soil forming processes have significantly interferred with the calcitic accretion. This accretion seems to have happened under an aridic moisture regime. Living organisms accumulated CO3Ca because of its excess. Moisture conditions were only sufficient to alter biogenic form into micrite.
(4) Laminar crust was generated on the top of the calcitic accretion when unconsolidated surface horizons were eroded and probably the accretion of calcium carbonate decreased; as discussed above this crusting is polyphased.
(5) Unconsolidated soils, e.g. Phaeozem have developed upon the laminar crust in relation to a more stable, wetter climate, and probably some new deposits of aeolico-colluvial origin.

The genetic sequence of calcite accretion inside the tepetates
Absence of a root mat and of a laminar crust in the buried calcitic profile at El Carmen section indicates that occurrence of only acicular and micritic calcite represents an initial stage of calcitic accretion in comparison to the Coatlinchan profile. The El Carmen profile would have never been colonized by a well developed vegetation and never been exposed by erosion to subaerial alteration. This would possibly indicates that calcitic profiles developed on the tepetates from different regions, although they may share some similar morphological characteristics, result from a sequence of pedo-sedimentary events that are specific at a regional scale of geomorphic and climatic conditions and may also be of different ages. The main difference of the El carmen profile in comparison to the Coatlinchan one lies in the occurrence of two distinct cycles of calcitic accretion, genetically related to deposition of aeolian materials. The first cycle appears to begin by a phase of sedimentation of pseudo-sands on a dark crumby soil fabric that is followed by the accretion of biological acicular calcite, immediately accompanied by its micritization. A new sedimentation of pseudo-sands initiates the second cycle that is characterized by accretion of weakly developed, acicular and micritic fabrics.

Conditions of calcitic accretion of nodules in the Paleo-Vertisols significantly differs from those in tepetates. Accretion of palmated sparite within the nodules is considered to result from a chemical precipitation which occurred in relation to water saturation episodes, possibly seasonal. The hierarchy of pedological features in these nodules also permits to reconstruct the genetic sequence of pedological events:
(1) genesis of an illuvial Vertisol,
(2) palmated sparitic accretion,
(3) weak alteration of sparite into micrite followed by an illuvial phase,
(4) new phase of sparitic accretion.

**Origin of calcium in calcitic accretion in tepetates**

Calcium that supplied calcitic accretion on the tepetates may be of three origins: (1) released during weathering of primary minerals, (2) supplied by aeolian dust, (3) of magmatic origin. Although abundant fresh primary feldspars and easily weatherable volcanic glass and phytoliths in the ground mass of tepetates indicate that since deposition of the parent materials, the ground mass has almost not suffered weathering. There is a the possibility that part of calcium was supplied through weathering of primary minerals of an overlying soil material. As previously suggested, an aeolian origin is supported by the synchronous deposition of aeolian pseudo-sands and formation of the acicular fabric, observed at El Carmen section. A magmatic origin has also been invoked.

**Contribution of calcitic aggradation to induration of tepetates**

Processes, i.e. compaction of tepetates ground mass and clay illuviation which lead to tepetates induration occurred before calcitic aggradation started. Calcitic accretion contributed to further induration of tepetates in two ways: (1) their upper layer, affected by horizontal cracking, was first stabilized by calcitic aggradation, (2) then the calcitic horizon was sealed by a laminar crust which has protected the tepetates from further erosion. The initial sealing happened at the end of calcitic aggradation. Presently a "stromatolithic" crust favors stabilization of the tepetates surface when they become exposed to atmospheric agents.

**Conclusions**

Calcitic accretion contributes to induration of tepetates in two ways: (1) cementation of their uppermost part which is usually fragmented, (2) formation of a laminar crust which protects the tepetates from erosion when the unconsolidated soil above the tepetates, e.g. the Phaeozem, is eroded. The earlier phases of induration, i.e compaction of the ground mass and clay illuviation appear to be totally independent from the calcite aggradation while cementation by amorphous silicium and opal has not occurred in the studied tepetates. The high content in silicium of the tepetates results of the abundant volcanic glass shards and phytoliths observed. In opposition to previous conclusions formulated on duripans in western United States, our results suggest that in the studied profiles, calcite accretion occurred independently from clay illuviation or neoformation of silica. Although the calcitic accretion that affected the uppermost part of the tepetates shares some similar morphological characteristics to the type 2 calcic horizon of Gile's model, their micromorphology has fully demonstrated that they are considerably more complex than previously suggested. Their polyphased formation clearly indicates that calcitic accretion was a discontinuous process, repeatedly interrupted by phases of sedimentation. Future investigations should be conducted with the help of quaternary geologists in order to obtain a reliable chronological framework of the successive pedo-sedimentary events that are recorded in the calcic horizons of the tepetates.

Results presented in this paper also suggests that mechanisms of calcite accretion are not specific in volcanic contexts in comparison to other settings.

**Literature cited**

Formation of Petrocalcic Horizons in Soils from Basic Pyroclastics under the Semiarid Climate of Lanzarote (Spain)

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1 Introduction
The Island of Lanzarote (800 km², 29 °N) consists of eruptive rocks, which originate from six different eruptive phases (miocene to holocene) and offers a unique opportunity to study soils in different landscapes of different age (Tab. 1). The geochemistry of the rocks is basic to ultrabasic with minor variations. The prevailing moisture regimes according to Soil Taxonomy are ustic tending to aridic at low elevations and xeric at higher elevations. The corresponding temperature regimes are hyperthermic and thermic. A conspicuous feature of the north-eastern Canary Islands and the drier parts of the others is, that the older landsurfaces are dominantly covered with thick carbonate accumulations. Due to erosion of the upper part of the soils, the calcrite has been exposed in these vast areas. The soils of all steps within the chronosequence under investigation show a distinct increase of development and even of lime enrichment with age. The purpose of this paper is to describe the extend, morphology and origin of the carbonate accumulation as well as there impact on soil properties and land use.

2 Material and Methods
The analyzed profiles (methods comp. (4), (7), (8)) were selected from the data, collected after mapping of two areas in each of six different landscapes of Lanzarote. The main criterion for selection was the maximum stage of soil development within every landscape. Age, parent material, soil unit, location and climatic parameters are presented in Tab. 1. The soils of the older series are characterized by severe erosion and accumulation of soil material (e.g. III-510 - erodet, III-502 - accumulated and the polygenetic profile I-800) (9). The more recent soils are less or not affected by erosion (4).

Tab. 1: Analyzed soils in relation to the geological formations of Lanzarote, Canary Islands (Spain)

<table>
<thead>
<tr>
<th>Geol. formation, Age</th>
<th>Parent material</th>
<th>Soiltype, FAO(1988)</th>
<th>No. and location</th>
<th>masl, Lm, Precip.</th>
<th>Temp. °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVB recent</td>
<td>lapilli &amp; cinders</td>
<td>Eutric Regosol</td>
<td>IVB-101 Montana Negra</td>
<td>130 150-200</td>
<td>18</td>
</tr>
<tr>
<td>-260 y.</td>
<td>ashlapilli &amp; cnd.</td>
<td>Eutric Lephtosol</td>
<td>IVB-313 Caldera Blanca</td>
<td>180 100-150</td>
<td>18</td>
</tr>
<tr>
<td>IVB subrecent</td>
<td>lapilli &amp; cinders</td>
<td>Motlic Andosol</td>
<td>IVB-605 Monte Corona</td>
<td>440 150-200</td>
<td>16</td>
</tr>
<tr>
<td>-6,000 y.</td>
<td></td>
<td>Motlic Andosol</td>
<td>IVB-660 Monte Corona</td>
<td>420 150-200</td>
<td>16</td>
</tr>
<tr>
<td>III upper</td>
<td>lapilli &amp; cinders</td>
<td>Camblic Calcisol</td>
<td>III-502 El Perez</td>
<td>230 100-150</td>
<td>17</td>
</tr>
<tr>
<td>pliocene</td>
<td>ashlapilli &amp; cnd.</td>
<td>Camblic Calcisol</td>
<td>III-510 El Perez</td>
<td>250 100-150</td>
<td>17</td>
</tr>
<tr>
<td>-40,000 y.</td>
<td></td>
<td>Haplic Calcisol</td>
<td>III-020 Lomo de Camacho</td>
<td>320 150-150</td>
<td>17</td>
</tr>
<tr>
<td>brassett</td>
<td></td>
<td>Brassic Luvisol</td>
<td>III-570 Estm. de los Dolores</td>
<td>270 100-150</td>
<td>17</td>
</tr>
<tr>
<td>I pliocene</td>
<td>cinders &amp; basalt</td>
<td>Sali Calcic Luvisol</td>
<td>I-800 Malaya Chica</td>
<td>415 150-200</td>
<td>16</td>
</tr>
</tbody>
</table>

3 Results and Discussion

3.1 Occurrence of Soils
Depending on the age of the landscape, a sequence of Leptosols/Regosols (depending on content of gravels >2 mm) (landscape IVB) – Andosols (Haploxerands) (landscape IVA) – Calcisols/Luvisols (depending on stage of erosion) (landscape III) – heavily eroded sites with remnants of polygenetic soils (landscape II, III) have been found. This leads to the assumption of a soil forming sequence of Leptosol/Regosol → Andosol → Cambisol → Calcisol/Luvisol → polygenetic soils. The Calcisols, Luvisols and upper parts of polygenetic soils are due to the content of salts (depending on their position on the Island) partly to describe as Solonchaks.
First there is a differentiation according to the age of the landscape, and secondly according to the position within the landscape. In the youngest, only 260 years old Leptosols and Regosols, the properties of the parent material are still dominant.
In the about 6,000 years old landscape, out of lapilli and cinders, diagnostic A- and B-horizons with andic properties are developed. This is the only area on Lanzarote where Andosols according to the FAO-classification occur. From coarser cinders near or on the slopes of volcanoes, soils are not as developed as these from finer lapilli, so again Leptosols are to be found.

In the landscape III, about 40,000 years old, lithogenic properties are more or less lost and pedogenic properties as loamy texture, lime enrichment, brunification and so on are distinctively developed. Erosion and accumulation are important processes and sequences of Eutric Leptosols - Haplic Calcisols - Chromic Luvisols with petrocalcic horizon - colluvial Calcisols can be found (Fig. 1). Due to anthropogenic surface layers of fresh pyroclastics (to minimize evaporation) an andic phase occur in most soils under use.

Fig. 1: Soil maps and soil profiles of landscape III (left) and I (right)
Fig. 2: Geological sketch of Lanzarote, investigated sites and carbonate content of soils
In older landscapes (IIb, IIa, I) polygenetic soils with several sequences of relictic Luvisols, Vertisols and Nitisols divided by petrocalcic horizons do occur. These soils, almost as remnants on high plains and footslopes, are in present time heavily affected by soil erosion. Dominant by area are rock outcrops and petrocalcic horizons as well as Leptosols, Regosols and Calcisols resting on petrocalcic horizons.

3.2 Amount, Distribution and Morphology of Carbonates
Carbonate increases distinctly with soil development (e. g. as expressed by the formation of clay and oxides (5)), occurring with increasing age of the soil in greater contents and within a bigger range of depth. In the youngest soils IVB about 1 kg/m² (Tab.2) carbonate has been accumulated, mainly in some cm thick Ck-horizons, about 10 cm below the surface (Fig. 2), where pyroclastic layers are finer in texture than in the average. The Ck-horizons are only slightly hardened. The carbonate forms microcalcite in the soil matrix and microsparites and sparites in enclosed pores of the lapilli. In the soils IVa up to about 10 kg/m² carbonate has been accumulated in numerous thin (2-5 cm) Ck- and Ckm-horizons between 30 to 300 cm depth. The Ckm-horizons of greater depth frequently have two 0.5 to 1.5 cm thick hard shells facing each other in the center of the horizons. Predominantly, a root mat is located between the shells. Vertical pipes of carbonate accumulation, 5-15 cm in diameter, are frequent from 30 to 150 cm depth. The carbonate also forms microcalcite in the soil matrix and microsparites and sparites in enclosed pores of the lapilli. In the hard shells in the center of the Ckm-horizons the lapilli has been displaced by light brown to yellowish-brown matrix. The matrix is horizontally oriented and are smooth to wavy. The carbonate rich bands frequently consist of poorly developed segregations or concretions. The lapilli are fresh to nearly fresh, the alteration being katamorphous, pellicular and dotted.

In the soils III from pyroclastics up to more than 100 kg/m² carbonate has been accumulated in Bwk- and Btk-horizons, in a consolidated thick Cwkm-horizon, and also in numerous thin (2-5 cm) Ckm-horizons to more than 300 cm depth as in IVa. Carbonate occurs in the B-horizons as crackfilling and soft powdery lime. The Cwkm-horizon has a coarse laminar to blocky structure. The big structural units frequently have a fine laminar shell on the surface and usually show a horizontal layering, where carbonate-rich soil and carbonate impregnated lapilli alternate. There are many zones where the lapilli has displaced by light brown calcic matrix or calcic concretions, forming an almost continuous phase with occasional discrete pores, which are often connected by white or pale grey calcic matrix, indicating, that they form channels in which the calcite has been precipitated. In other zones, the lapilli has been cemented by light brown calcareous matrix or calcic concretions. In soils III from massive basalt with high content of gravels and stones, carbonate has been accumulated in greater depth than in soils from pyroclastics within Bt-horizons and as crack filling in the basalt.

On older landsurfaces carbonate has been accumulated in often very thick Bkm-horizons and as filling material in cracks of relictic Vertisols. In Profile I-800, for which a polygenetic development in 8 steps is assumed (9), about 1,700 kg/m² carbonate has been accumulated down to 450 cm depth, mainly in a 170 cm thick Bwkm-horizon. Carbonate occurs in (sandy) IVa-soils in greater depth than in older soils, reflecting the higher water capacity and smaller leaching rates in older (loamy to clayey) soils ((2), (3)). In contrast of this, in the youngest IVb-soils with the smallest water capacity, the carbonate occurs in a very shallow depth. This leads to the assumption, that a part of the carbonate is of eolian origin and in IVb-soils (and partly in IVa-soils, see below) washed down as particles to layers with finer texture.

3.3 Mg-substitution of Calcite
A smaller part of the carbonate in profile IVa-660 and most of the carbonate in III-510, III-570 and of I-800 is found to be low- and high-Mg-calcite ((10), Tab. 2). The Mg-substitution is considered by chemical extractions as well as by a shift of the d (112) by X-ray examination (1). Chemical extractions have been carried out with 0.3M(NH4)2 9 H2 1 EDTA (after exchange with NH4Cl and washing the samples) and with 1% HCl. In the younger soils IVa and IVa with both extractions more Ca and Mg as the CO3-eqivalent was extracted, indicating a dissolution of volcanic glass and giving no quantitative information about the Mg-substitution of the calcite in these soils. In stronger weathered soils up to 10 % of the carbonates are MgCO3. X-ray examination shows no shift of the
calcite peak for IVB-soils and of a Levante-dust sample (Fig. 3). In IVA-soils partly (as in IVA-660-12) a shift to about 3.03 Å and in older soils regularly a shift to 3.03 to 3.02 Å is to observe. The Mg-substitution should be favoured in the older soils which show in a 1/2.5 soil-water extract a Mg/Ca ratio of 0.2 to 0.3 (meq/meq) in topsoils and of ≈1 in subsoils ((4), (1)).

Fig. 3: X-ray diffraction patterns of calcites from soils of different age

3.4 Age and Isotope Ratios of Carbonates
For a set of carbonate enriched horizons, 14C-age and the ratio of 18O/16O (δ18O) and 13C/12C (δ13C) is known (7). The 14C-age of carbonate from a pipe (100 cm depth) of profile IVA-660 is 1,850 y, of two laminar crusts at 260 and 280 cm depth 11,000 and 6,000 y respectively. Samples from older soils have an age which confirms the general idea of soil development in Lanzarote and age of parent material (Tab. 1): 8,000 and 14,500 y for Bwk and Cwk in III-516, 12,000 and >35,000 y in Btk and Bwkm of I-800. From 16 samples, out of 5 different soils, 14 samples have a δ18O value in a range of -0.3 to -1.9, indicating a more or less uniform temperature regime during carbonate formation. Only two samples, from IVA-660 for which the 14C-age seems to be too high for the formation within the soil, δ18O is with -4.1 and -4.9 significant different and suggesting a temperature regime for carbonate formation which is 8 to 12 °C higher than for the other carbonates.

3.5 Sources of Carbonate
Due to differences in δ18O and degree of Mg-substitution as well as of higher 14C-age comparing to the age of soil IVA-660, different sources of Ca are probable. Since all soils under investigation are far from the groundwater, Ca-sources can only be the parent rock (5), Ca from eolian additions and from seaspray. Eolian additions are evident by the occurrence of quartz. The basaltic material is free of quartz, a Levante-dust sample (collected in Lanzarote) has 19 % quartz and 18.5 % calcite. The addition of elements from seaspray is indicated by a K-uptake for illitization ((4), (6)) which can not be completely explained by addition of K-bearing minerals (illite, mica, K-feldspars) from eolian
dust. Ca from seaspray is taken into account with 0.3 l/m²a (4). For profile III-510 and I-800 due to the slope position an addition of Ca by lateral water movement appears possible but can not be quantified. The upper part of profile III-502 (0-152 cm) is accumulated carbonatic soil material from the slope.

Tab. 2: Quantities of carbonates, of Ca in carbonate, loss from primary material, of quartz, of Ca from eolian dust-calcites (quartz accompanying) and of Ca from seaspray (in kg/m²)

<table>
<thead>
<tr>
<th>Soil</th>
<th>Depth cm</th>
<th>CaCO₃</th>
<th>MgCO₃</th>
<th>Ca bound in carbonate</th>
<th>Ca loss from basaltic material</th>
<th>Quartz</th>
<th>Ca from eolian dust</th>
<th>Ca from seaspray</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVB-101</td>
<td>0-100</td>
<td>1.5</td>
<td>?</td>
<td>0.6</td>
<td>&gt;0.01</td>
<td>1.0</td>
<td>0.4</td>
<td>0.03</td>
</tr>
<tr>
<td>IVB-313</td>
<td>0-17</td>
<td>1.3</td>
<td>?</td>
<td>0.5</td>
<td>&gt;0.16</td>
<td>1.2</td>
<td>0.5</td>
<td>0.03</td>
</tr>
<tr>
<td>IVA-605</td>
<td>0-100</td>
<td>1.3</td>
<td>?</td>
<td>0.5</td>
<td>11</td>
<td>14</td>
<td>6</td>
<td>0.7</td>
</tr>
<tr>
<td>IVA-660</td>
<td>0-100</td>
<td>3.5</td>
<td>?</td>
<td>1.4</td>
<td>11</td>
<td>17</td>
<td>7</td>
<td>0.7</td>
</tr>
<tr>
<td>IVA-660</td>
<td>100-324</td>
<td>10.5</td>
<td>?</td>
<td>4.2</td>
<td>n.d.</td>
<td>0.0</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td>III-502</td>
<td>0-152</td>
<td>145</td>
<td>n.d.</td>
<td>58</td>
<td>n.d.</td>
<td>193</td>
<td>77</td>
<td>-</td>
</tr>
<tr>
<td>III-502</td>
<td>152-320</td>
<td>266</td>
<td>n.d.</td>
<td>106</td>
<td>n.d.</td>
<td>202</td>
<td>81</td>
<td>5</td>
</tr>
<tr>
<td>III-510</td>
<td>0-81</td>
<td>125</td>
<td>14</td>
<td>50</td>
<td>23</td>
<td>51</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>III-0200</td>
<td>0-450</td>
<td>174</td>
<td>n.d.</td>
<td>70</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>5</td>
</tr>
<tr>
<td>III-570</td>
<td>0-140</td>
<td>17</td>
<td>2.2</td>
<td>7</td>
<td>47</td>
<td>89</td>
<td>35</td>
<td>5</td>
</tr>
<tr>
<td>I-800</td>
<td>0-450</td>
<td>1486</td>
<td>179</td>
<td>595</td>
<td>n.d.</td>
<td>460</td>
<td>206</td>
<td>-</td>
</tr>
</tbody>
</table>

For younger soils the biggest source of Ca is the parent material, which contains about 8% Ca (1 m³ lapilli = 80 kg Ca, 1 m³ basalt = 190 kg Ca), but for the youngest soils IVB the time for weathering was obviously too short to mobilize the Ca for carbonate from the parent material. The amounts of Ca bound in carbonates are about equal to the import of Ca from eolian dust, but have partly been reprecipitated as micromorphological observations indicate. The fact that only a part of the eolian carbonate can be dissolved in these soils, suggests also the amount of an annually import of 4 to 5 g calcite/m². Since these sites have only a lichen flora and very small amounts of organic carbon, the concentration of H₂CO₃ in the soil solution must be very low and the dissolution of carbonate by fast water transport in the gravelly-sandy soils is therefore incompletely.

In the IVA soil the carbonate can be explained as Ca-loss from the parent material by weathering and precipitation as CaCO₃. Nevertheless, a part of the soil-carbonate seems to be of eolian origin. This can be recognized by the age of the carbonate in deeper Ck-horizons as well as of the ¹⁸O/¹⁶O Isotope ratios which indicate a higher precipitation temperature. These conditions may have been realized within the Sahara area. All carbonate horizons of IVB soils and most horizons of the IVA soil show under X-ray observation the same position of the d (112)-reflex as the calcite from the Levante-dust (with no or very low Mg-substitution).

The carbonates of the older soils have a higher Mg-substitution and the age of the carbonates corresponds with the age of the soil. For III-510 the carbonate can be explained by weathering and eolian addition. Nevertheless, this profile is eroded, which means the Ca source from the parent material was originally higher and the amount of carbonate may have been increased by lateral addition. In general, in the soils of landscape III the carbonate Ca should originate from the rock and from eolian additions, the latter in reprecipitated form. Ca-addition from seaspray seems to be negligible for all soils. Profile I-800 has been eroded and buried several times, partly with fresh material, partly with already weathered material may be also with carbonatized soil material. The composition of elements as well as of clay minerals indicates for the whole soil about 70% of volcanic parent material and about 30% of eolian material. Therefore we assume a similar situation for this polygenetic soil as for landscape III.

4 Impact on Soil Properties and Land Use

The soil development leads in general to an increase of space for roots, water capacity, available nutrients, and enrichment of salts as well as of a decrease of nutrient reserves, exceptionally of Ca (4). The soil properties are unsuitable for land use in the youngest soils-IVb and suitable for older soils. Suitability through enrichment of carbonates within the rooting zone is lowered in the soils III and older.
On slopes the space for roots is limited by Cwkm-horizons in landscape III and by Bwkm-horizons in older landscapes. Since the precipitation is below 200 mm, water capacity is the most limiting factor. In the soils of the examples in Fig. 1, the available water capacity is below 100 mm in Regosols and Haplic Calciicisols of landscape III, on slopes with an inclination >10 %. In the example of landscape I, a low available water capacity occurs in Leptosols and Calciicisols. In both landscapes, a shallow soil depth results from erosion of topsoils. In landscape III, the slopes are recently under use, terraced and covered by man made lapilli layers and therefore protected against soil erosion. Landscape I is heavily affected by recent soil erosion, therefore very shallow soils occurs over basalt and petrocalcic horizons. The very thick petrocalcic horizon is dissected by deep gully erosion. Soil erosion is naturally promoted with the enrichment of sea salts by limited leaching rates in the very clayey soils.

Since the leaching rates decrease with age of the soils, carbonate accumulates recently within the rooting zone in landscapes III and older, forming Bwkm- and Btkm-horizons. A part of the carbonate fills cracks, an other part occurs as soft powdery lime within the soil matrix and lowers the availability of some nutrients (e.g. Fe, Mn, P). The P-retention amounts in carbonate free horizons of III - S70 up to 35 % (100 % = 5 mg P/g soil) and is with 50 to 70 % in Bwk- and Btk-horizons of landscape III in the same order as in andic horizons of landscape IV A.

5 Conclusions
- Carbonate accumulation increases in the semiarid climate of Lanzarote distinctly with age of soils.
- Sources of Ca for carbonate formation are almost Ca released by weathering from the basaltic rock and eolian additions of calcite, the latter mostly in reprecipitated form.
- Precipitated carbonate has low to high Mg-substitution.
- Carbonate occurs partly in consolidated Cwkm-horizons in soils of upper pleistocene age and in Bwkm-horizons in soils of higher age.
- Through soil erosion these horizons occur in many soils in shallow depth, limiting the space for roots and the available water capacity.
- Partly, the carbonate occurs in soils of upper pleistocene and older age as soft powdery lime, lowering the availability of nutrients as Fe, Mn and P.

6 Literature Cited
(5) JAHN, R., GUDMUNDSSON, Th. & STAHR, K. (1985): Carbonatization as a soil forming process on soils from basic pyroclastic fall deposits on the island of Lanzarote, Spain. CATENA SUPPLEMENT 7, p. 87-97.
Introduction.
Cemented layers in tephra that may or may not be pedogenic are widespread in the Pacific Rim. They profoundly influence farming and, if managed incorrectly, may render the soil unproductive and impart severe damage to the local ecology. Their characterization and meaningful classification is important for the use, management, and reclamation of the soils of which they are part. They have been given local names such as tepetate, talpetate, and cangahua, but these terms are not used consistently. These layers, or pans, have properties in common with pans in soils formed from a great variety of other parent materials, but problems with their classification and the consequences of misuse are more severe than in other soils. In this paper we will discuss issues pertaining to the characterization and classification of cemented pans with emphasis on pans in tephra.

Classifications of Tepetate.
The classification of cemented pans has been reviewed by Nimlos (1). An ancient scheme was used by “campesinos” in the Valley of Mexico to rate exposed tepetate for ease of reclamation. They recognized white, yellow, and red tepetate; the white kind containing carbonate cement was the hardest and the most difficult to reclaim. A later system proposed three classes of tepetate: without carbonates, with carbonate lamellae, and with disseminated carbonates.

A modern system by Dubroeucq et al. (2) for the Valley of Mexico and adjoining areas classifies tepetate into tephra indurated by geologic processes (volcanogenetic) and tephra modified by pedologic processes (pedogenetic). They recognize three types of volcanogenic tepetate that differ in the temperature at which they were deposited, as a. hot ash flows, or nubes ardientes, b. moderate temperature hydromagmatics or pyroclastics of cinders, tuff breccias, and accretions of ash nodules, and c. cool mudflows or lahares. These types are further classified by particle size and degree of cementation. Pedogenic tepetate is classified by the cement, silica or carbonate, and by color, degree of induration, and horizon, C or Bt. The Dubroeucq system allows a nearly infinite number of classes that are not necessarily mutually exclusive. For instance, one class of volcanogenic tepetate (TVk) is cemented with secondary carbonates which are likely to be pedogenic.

Quantin (3) notes that Tepetates are strictly localized on piedmonts, plateaus, and glacis in ustic moisture regimes, are formed through successive geological and pedological processes, and can be classified after their stratigraphic series and their consistence “of fragipan or petrocalcic firmness”.

Another classification system is that of Vera and Lopez (4) for indurated tephra in Ecuador (cangahua). There is a geologic taxonomy that recognizes volcanic materials of various particle sizes that were cemented on deposition and materials that were cemented following reworking as mudflows or slumps. This does not separate tephra whose cementation has been modified by pedogenic processes.
The classification of pans in Soil Taxonomy (5).

Soil Taxonomy recognizes the fragipan, duripan, petrocalcic horizon, petrogypsic horizon, placic horizon, and ortstein. All pans are in part defined by morphological characteristics. In terms of their hardness, the fragipan is defined as being hard or very hard when dry, and firm and brittle when moist; dry fragments slake or fracture when placed in water. The duripan differs in that it is all silica-cemented and dry fragments from some subhorizons do not slake in water. The petrocalcic horizon is an horizon cemented by carbonates and does not slake in water. The placic horizon is a horizon cemented by sesquioxides and organic matter and ortstein is a cemented spodic horizon. Petrogypsic horizons are restricted to gypsiferous parent materials, but the placic horizon has been identified in soils formed from pyroclastics in South America that are locally called Nadi (6). Cemented ortstein has been identified in tephra in Alaska and elsewhere.

Cemented layers of geologic origin are not considered soil horizons in Soil Taxonomy and are, therefore, outside the purview of soil classification. Nevertheless, different kinds of cemented or hard geologic materials that abruptly underlie the soil are recognized as lithic contact, if the coherent material has strength equivalent to a hardness of >3.0 on the Mohs scale, as paralithic contact if the strength is equivalent to hardness <3.0 on the Mohs scale, and as petroferric contact if the material is cemented primarily by iron compounds and meets some other criteria.

The distinction between pedogenic pans and cemented layers of geologic origin is important and deserves some discussion. In Soil Taxonomy, it hinges on the separation of soil from non-soil. The distinction is important not only for defining disciplinary turf but for practical purposes because the distribution and position of a cemented soil horizon can be expected to be closely related to that of other horizons of the modern soil and, except for buried soils, to the modern land surface. A soil horizon influences the hydrology of the soil in a predictable manner and it can be studied and mapped with methods that are standard working tools of pedologists. The distribution and characteristics of cemented geologic layers, on the other hand, are, except in very young landscapes, less predictable, their influence on hydrology is uncertain, an their mapping requires methods that are more the tools of geologists than pedologists.

Soil, in Soil Taxonomy, is defined as the collection of natural bodies containing living matter and supporting or capable of supporting plants out-of-doors (and) the lower limit of soil, therefore, is normally the lower limit of biological activity which generally coincides with the common rooting depth of native perennial plants. While this definition was an improvement over earlier definitions that required evidence of soil forming processes, it would have excluded many duripans and petrocalcic horizons and some fragipans. It was therefore amended that where (the soil) contains thin cemented horizons that are impermeable to roots, the soil is as deep as the lowest horizon. A horizon, in turn, is defined a few pages later, as a layer that has been produced by soil forming processes. This definition still leaves considerable room for judgment. Usually, in the absence of roots, the presence of structure that differs from that of the parent material, clay skins or silica coatings, significant accumulation of carbonates, and other attributes that can be related to features of the overlying soil, are considered sufficient evidence of soil forming processes. Micromorphological evidence is often useful.

Several of the definitions of pans in Soil Taxonomy are not as precise as those of other diagnostic horizons and taxa. They lack, to a large extent, the specific and rigorously defined boundary conditions that distinguish Soil Taxonomy from older systems of soil classification. The definition of the fragipan, for example, as noted by Witty and Knox (7), could be more appropriately called a description of common properties than a definition. Other definitions are inconsistent. Fairly rigorous criteria for the separation of duripans from fragipans and petrocalcic horizons, for example, are contained in the definition of duripans, but there are no corresponding criteria in the definitions of fragipans or petrocalcic horizons. In many cases, the evidence for a geologic or pedogenic origin is tenuous, especially if a pedologic process modifies a geologic feature. The
classification of certain soils in the northeastern United States, for example, has shifted back and forth several times during the professional career of the current authors depending on whether an undeniably hard and brittle layer was considered a fragipan or simply compacted glacial till. One reason for the deficiencies in the classification of pans is lack of agreement on which attributes should be addressed. Formal classification systems, such as that of Dubroeucq et al. (2) or the higher categories of Soil Taxonomy, pay attention primarily to the kind of cement. Soil Taxonomy considers the structure, continuity, and consistence of duripans for the separation of a taxa at lower categorical levels, e.g. Typic and Haplic subgroups of Durixerolls. Yet, for practical purposes, the identification of the cement may be unimportant relative to a host of other characteristics such as the degree of cementation, morphology, depth, thickness, its spatial relationship to the land surface and to overlying horizons as well as its hardness in relation to morphology, moisture content, distribution of cements, and drying and wetting cycles.

Classification of exposed tepetate.

Erosion of the soil overlying tepetate is widespread in Mexico and Ecuador (8). Usually, the whole solum is eroded. In many watersheds in the Valley of Mexico two-thirds of the land surface is completely eroded, the indurated pan is exposed, and vegetation is absent. It is not clear to what extent exposed tepetate is considered in the various classification systems. In Soil Taxonomy, pan horizons at the soil surface meet, technically, neither the definition of a duripan or petrocalcic horizon, which are defined as subsurface horizons, nor that of soil, which must be supporting or capable of supporting plants.

Werner (9) and Miehlich (10) report instances in which horizons that, upon exposure, form tepetate cannot be recognized in their uneroded state. Yet, their identification is extremely important for making management decisions. Soil Taxonomy recognizes a somewhat analogous situation in the definition of plinthite an iron-cemented horizon that [upon exposure] changes irreversibly to an ironstone hardpan. Plinthite has, however, recognizable and definable characteristics before it hardens.

Characteristics of cemented pans.

Although cemented pans influence the use and management of soils more profoundly than most other soil horizons or layers and the reclamation of soils containing pans is difficult and expensive, relatively little research on their characterization and classification has been done. Much of the research that has been done lacks continuity and focus.

Cementation

The 1951 edition of the Soil Survey Manual (11), the current manual when Soil Taxonomy was being developed, defined cementation as a brittle hard consistence caused by some cementing substance other than clay minerals. It recognized three classes of cementation that were not quantitatively defined and in which moisture content was only specified for indurate which, among other criteria was defined as cementation that does not soften under prolonged wetting. (This definition was apparently based exclusively on field observations. Although cemented pans remain brittle when wet, the current authors are not aware of any laboratory data that do not show some softening of pans upon wetting.) This definition being inadequate, Soil Taxonomy defined the degree of cementation in duripans as being strong enough that dry fragments of some subhorizon do not slake in water, even during prolonged wetting.

In the new edition of the Soil Survey Manual (12), 8 classes of rupture resistance of specimen that have been submerged in water for one hour after air-drying are identified. Rupture resistance is determined by a field procedure developed by Grossman (personal communication) in which soil
specimens of a defined size are subjected to pressure tests by squeezing them between fingers, standing on them, or dropping a geologic hammer on them. The investigator develops a tactile sense of limits by applying force to an appropriate top-loading balance. Nimlos (13) found that the test determined the correct cementation class in 15 of the 18 specimen of tepetate he tested. Future definitions of duripans will probably use the classes of rupture resistance of the new Soil Survey Manual.

In the laboratory, the unconfined compressive strength of a pan is usually determined by shaping specimens to a standard size, equilibrating their moisture content either by suspending them over a water table or on a pressure plate and measuring their resistance to rupture with a proving ring.

Strength in different parts of pans and in replicate samples of the same part differs greatly. In one study of duripans and petrocalcic horizons (Nettleton, 1993, personal communications) the index of variability (SD/mean *100) for 10 replicate samples from a given pan ranged from 34 to 82 pet. for oven-dry samples and from 29 to 71 pet. for moist (equilibrated at 0.033 MPa) samples. Unconfined compressive strength also varied greatly from soil to soil and did not seem to differ greatly (table 1) between two groups of soils in the western United States and various tepetates from Mexico (14). The data suggested that the strength of the pans is related to clay content in Durixeralfs and to bulk density in Aridisols and tepetates containing carbonates.

<table>
<thead>
<tr>
<th></th>
<th>Number of Samples</th>
<th>Unconfined Compressive Strength (MPa)</th>
<th>Bulk Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Oven dry</td>
<td>Moist</td>
</tr>
<tr>
<td>Durixeralfs W. US*</td>
<td>8</td>
<td>2.6 - 8.6</td>
<td>0.5 - 2.7</td>
</tr>
<tr>
<td>Aridisols W. US*</td>
<td>8</td>
<td>1.4 - 5.6</td>
<td>0.2 - 4.0</td>
</tr>
<tr>
<td>Tepetate Mexico**</td>
<td>18</td>
<td>0.9 - 14.5</td>
<td>0.4 - 8.2</td>
</tr>
</tbody>
</table>

* Nettleton, pers. communications; ** Nimlos and Hillery (13)

Table 1. Strength and bulk density of Duripans and Petrocalcic horizons.

Measuring unconfined compressive strength in the laboratory, especially if the procedure includes equilibration at various moisture tensions, is slow and expensive. Considering the large variability, a large number of field estimates by the above method is more useful than a few more precise laboratory determinations. Although no hard data are known to these authors, rupture resistance is probably related to morphological features of pans and to the temperature and number of drying cycles after a pan has been exposed. Tepetate, for one, is known to harden appreciably after the overlying soil has been removed by erosion.

For the assessment of the vulnerability of pans that change strength upon exposure and wetting and drying, a series of measurements after appropriate treatment is needed. It is hoped that criteria for relating the effect of wetting and drying to observable morphological characteristics of pans can be developed.

Morphology.

Careful morphological studies are indispensable prerequisite for any study of the genesis of pans, particularly those involving questions on pedologic or geologic origin. Furthermore, a thorough understanding of the morphology of pans can be a valuable aid in the recognition of different kinds of pans, in making estimates of the characteristics of pans that cannot be directly measured in the field, in optimizing the selection of samples for laboratory characterization, and in transferring knowledge. Micromorphology has probably contributed more to our understanding of pan horizons than other fields of pedology. Many fragipans and some duripans have characteristic morphology such as a coarse prismatic structure. Outside very dry climates, they commonly have bleached,
vertical streaks that form a polygonal pattern in a horizontal plane and that are paths for what little water may move. Carbonate cemented pans are often platy at their upper boundary and they may have been fractured through the growth of carbonate crystals. Roots, often flattened, are concentrated in these streaks. In duripans, silica coatings are concentrated in the lower part of the vertical streaks in weak pans and across the top of the prisms in stronger pans. Presence of silica-cemented domains in the lower part of vertical streaks is diagnostic for the separation of duripans from fragipans. The degree of cementation and probably differences in strength are related to the presence of these coatings. In calcareous pans, intergrades between duripans and petrocalcic horizons, the silica coatings accumulate primarily at the top of prisms.

Conclusions.
Clearly, the development of a satisfactory system for the characterization and classification of pans requires imaginative, detailed, and, given the difficulty of access and the cost of analyses, expensive research. We believe that the use of any such system can be greatly facilitated if the relationships between characteristics and the distribution of pans can be related to soil-forming factors. This is why research on the genesis of pans is important and why diagnostic criteria that have a genetic basis are useful. But research on genesis should consider practical needs. Criteria for classification preferably should reflect genesis, but genesis should not be the criterion for classification. Without question, the classification of pans in formal classification systems, such as the higher categories of Soil Taxonomy, could and should be improved, but any attempt to include in a formal classification system all of the criteria that may be critical for the use, management, and reclamation of individual kinds of some soil, somewhere, would make such a system unwieldy. Besides, it would never be completed. Hence, for practical purposes, the most useful information may be contained in detailed and site specific descriptions and characterizations of individual kinds of soils that describe critical attributes by standard methods.

Literature cited.


Indurated Volcanic Ash Soils in Japan. 
Their Characterization, Land Use and Management

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Introduction.
The Volcanos in the circum-Pacific volcanic belt have erupted a tremendous volume of tephra. Japan is one of the representative volcanic countries in the world, and Andisols cover more than half of the upland crops fields in this country. Though indurated volcanic ash soils have been regarded as a problem soil, they have been mostly reclaimed for upland crops since 1950 promalga
tion by Japanese government.

Soils.
We introduce four indurated volcanic ash soils, “Masa” in the southwestern foot of Mt. Fuji, “Nigatsuchi” in the western plateau of Mt. Aso, “Kora” in the southwestern foot of Mt. Kaimon and the placic Spodosols from Towada tephra (Fig. 1). The morphological features of those indurated volcanic ash soils are shown in table 1 to 4.

Fig. 1 Location of indurated volcanic ash soils studied

1 “Masa” soil
The indurated layers of “Masa” soils are composed of basaltic scoria or volcanic gravels on the foot of Mt. Fuji and those are divided into two types by the difference of parent materials. “Ekasmasa” is derived from Sunazawa lapilli erupted from Fuji volcano at 3000 Y.B.P. and “Jarimasa” has the indurated layer of volcanic sands or gravels with the thickness of several m, the only upperest part of whose is cemented.
The surface horizons overlying the indurated layer show black color with high humus content. The buried black and high humic horizons occur under the indurated layer composed of scoria.

TABLE1 Profile description of “Masa” soil
Altitude: 300m
Slope characteristics: Gently slope on a mountainside
Climate condition: Ann. temperature: 12.8°C, precipitation: 2990mm
Parent materials: Basaltic ash and scoria
Land use: Natural grassland

| 0-20cm | Black (7.5YR2/1), moist, sandy loam; abundant small gravel, abundant humus, c (compactness index measured by a penetrometer): 20 |
| 20-35cm | Dark reddish brown (5YR3/2), moist, sandy loam; abundant scoria, c: 34, "Masa" |
| 35-50cm | Brownish black (7.5YR3/2), moist, sandy loam; abundant scoria, c: 26, "Masa" |
| 50-75cm | Brownish black (5YR3/1) and brown (5YR4/6), moist; scoria layer |
| 75-95cm | Black (5YR1.7/1), moist, clay loam; c: 17 |

2 "Nigatsuchi" soil

"Nigatsuchi" soil is a multi-storied soil and is classified to Duruudands or Melanudands. This profile have thick humus horizons consisting of the top humus horizons and the second indurated horizons (6000 to 30000 YBP by $^{14}$C analysis). "Nigatsuchi" soils are the buried volcanic ash soils which become irreversibly very firm with subangular blocky or chestnut structure in surfacing condition. The land consolidation for the development of farm land in "Nigatsuchi" soils area caused the remarkable decrease of upland crop production by removing the top soil in depth of 1 to 2 m and surfacing of "Nigatsuchi" soils. The pyroclastic flow, "Aso-4" erupted from Aso volcano at 80000 Y.B.P. based in "Nigatsuchi" soil area.

**TABLE 2 Profile description of "Nigatsuchi"**

| Source | Kubotera and Yamada (1993) |
| Location | Oozu town, Kumamoto prefecture |
| Classification | Duruudands or Melanudands |
| Altitude | 260m |
| Slope characteristics | Gently slope on a mountainside |
| Climate condition | Ann. temperature: 15.5°C, precipitation: 1980mm |
| Parent materials | Volcanic ash |
| Land use | Orchard (Chesnut tree) |

| 0-24cm | Black (7.5YR1.7/1), moist, light clay; moderate medium granular; very friable, slightly sticky, slightly plastic; smooth clear boundary; c: 13 |
| 24-60cm | Brownish black (7.5YR3/2), moist, light clay; weak very fine to fine subangular blocky; friable, slightly sticky, slightly plastic; smooth gradual boundary; c: 23, Akaboy, 6600Y. B.P. |
| 60-80cm | Brownish black (7.5YR3/1), moist, light clay; weak fine subangular blocky; friable, slightly sticky, slightly plastic; smooth gradual boundary; c: 21 |
| 80-108cm | Black (7.5YR1.7/1), moist, heavy clay; moderate fine to medium subangular blocky; friable, slightly sticky, slightly plastic; smooth clear boundary; c: 22, 10000Y. B.P. "Nigatsuchi" |
| 100-130cm | Dark brown (7.5YR3/3), moist, heavy clay; moderate fine to medium subangular blocky; friable to firm, slightly sticky, slightly plastic; wavy clear boundary; c: 21, 15000Y. B.P. "Nigatsuchi" |

3 "Kora" soil

"Kora" is the indurated layer derived from volcanic sands and gravels (or scoria) erupted from Kaimon volcano at 1000Y. B.P. "Kora" means a carapace in Japanese because of hardness and
shape resemblance between them. "Kora" soils show the black and high humic surface horizon in 10 to 50 cm thickness overlying indulated layer followed by the buried A horizons.

TABLE3 Profile description of "Kora" soil

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Ei town, Kagoshima prefecture</td>
</tr>
<tr>
<td>Classification</td>
<td>Durudands</td>
</tr>
<tr>
<td>Altitude</td>
<td>80m</td>
</tr>
<tr>
<td>Slope characteristics</td>
<td>Gently slope on a hill</td>
</tr>
<tr>
<td>Climate condition</td>
<td>Ann. temperature:17.8°C, precipitation:2140mm</td>
</tr>
<tr>
<td>Parent material</td>
<td>Volcanic ash, scoria and pumice</td>
</tr>
<tr>
<td>Land use</td>
<td>Forest (Japanese cedar)</td>
</tr>
</tbody>
</table>

A 0-50cm Black (7.5YR1.7/1), moist; c=16
2Cml 50-67cm Brownish black (10YR3/2), dark brown (10YR3/4~7.5YR3/4), moist; abundant rock fragment (2-5mm); c=32: "Kora"
2Cm2 67-80cm Brownish black (10YR3/2), dark brown (10YR3/4), moist; c=30: "Kora"
3C 80-87cm Brownish black (10YR2/3), moist; scoria layer (2-5mm); c=26
4Ab 87-95cm Brownish black (10YR2/2), moist; abundant pumice (2-10mm); c=24
4Bb 95-130cm Yellow orange (10YR7/4), yellow brown (10YR6/6), moist; abundant pumice (2-10mm); c=16

4 Placic soil
Spodosols are developed at higher altitude than 800m and Andisols at lower altitude than that, showing a climosequential relation in southern Hakkoda at 10 km north of Towada volcano. Spodosols show a multisequum profile having two E horizons, two spodic horizons and one placic horizon derived from Towada-a rhyolitic tephra (1000Y.B.P.) and Towada-Chuseri dacitic tephra (5500Y.B.P.), respectively.

TABLE4 Profile description of Placic soil

<table>
<thead>
<tr>
<th>Source</th>
<th>S. Shoji, et al. (1988)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Akanuma, Towada city, Aomori prefecture</td>
</tr>
<tr>
<td>Classification</td>
<td>Placorthod</td>
</tr>
<tr>
<td>Altitude</td>
<td>790m</td>
</tr>
<tr>
<td>Slope characteristics</td>
<td>3% south face in a mountainside</td>
</tr>
<tr>
<td>Climate condition</td>
<td>Ann. temperature: 5~6°C, precipitation: &gt;2000mm</td>
</tr>
<tr>
<td>Parent material</td>
<td>Volcanic ash</td>
</tr>
<tr>
<td>Land use</td>
<td>Natural forest (beach)</td>
</tr>
</tbody>
</table>

Oe 6-5cm Black (7.5YR1.7/1), moist, silty clay
Oa 5-9cm Dark brown (10YR3/3), moist; loam; moderate fine blocky; friable, slightly sticky, slightly plastic; abrupt wavy
E 0-5cm Dark reddish brown (5YR3/4), moist; loam; massive, very friable, slightly sticky, slightly plastic; abrupt wavy
Bsm 5-8cm Dull yellowish brown (10YR5/4), moist; sandy loam; moderate very fine platy, slightly sticky, slightly plastic; abrupt wavy; Towada-a, 1000Y.B.P.
CB 8-13cm Brownish black (7.5YR2/2), moist; clay loam; moderate fine to medium blocky, firm, slightly sticky, slightly plastic; clear wavy
2Ab 13-18cm Brownish gray (10YR4/1), moist; light clay; moderate fine to medium subangular
blocky, sticky, plastic; abrupt wavy

2Bmb 25-28cm Dark reddish brown (2.5YR3/4). moist, loam; massive, very friable, slightly sticky, slightly plastic; abrupt irregular; placic layer

2Bwb 28-35cm Bright brown (7.5YR5/6). moist, loam; massive, very friable, slightly sticky, slightly plastic; abrupt wavy

2C1 35-55cm Bright brown (7.5YR5/8). moist, loamy sand; single granular, loose, nonsticky, nonplastic; abrupt, smooth

2C2 55-65cm Yellowish brown (10YR5/6). moist, loamy sand; loose, nonsticky, nonplastic; Chuseri, 5000 Y. B. P.

Characterization.

1 "Masa" soil

The indurated horizon has SI. or SCL soil texture characterized by abundance of 0.2 to 0.5 mm fraction and the clay content of those soils is obviously lower than the upper A horizon. The primary minerals of the indurated and non-indurated horizons is a similar composition dominated by colored volcanic glass which contains high calcium and magnesium, but those cations do not accumulate in the indurated horizons.

Thin section of the indurated fragments shows a close packing structure and coarse materials (skeleton grains) are interconnected by intergranular braces of fine materials (plasma).

Allophane is major part of clay fraction in A, 2Cm1 and 2Cm2 horizons. A fragment of the indurated horizon is not markedly fractured in acid oxalate solution which is dissolving agent of allophane. An indurated fragment does not slake or fracture when placed in water. When air dried undisturbed clods are soaked in 1N HCl solution, they collapse most intensely. A large amount of silica, alumina and iron of indurated clods are dissolved in 1N HCl, indicating that 1N HCl is more efficient in dissolving those as compared with 1N NaOH.

Those results indicate that induration of "Masa" formed from lappili, ash or scoria (3000 Y. B. P.) is not due to duripan or clay pan, and is characterized by particle size distribution, the micromorphology and silica rich amorphous materials.

### TABLE 5 Characterization of "Masa" soil

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Total (wt. %)</th>
<th>Organic carbon (%)</th>
<th>Bulk density (g/cm³)</th>
<th>pH (H₂O)</th>
<th>Exchangeable bases (cmol/kg)</th>
<th>CEC (cmol/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>clay silt sand</td>
<td></td>
<td></td>
<td></td>
<td>Ca Mg K Na</td>
<td></td>
</tr>
<tr>
<td>0-20</td>
<td>A</td>
<td>25 32 43</td>
<td>8.0</td>
<td>0.77</td>
<td>6.3</td>
<td>5.9 0.8 0.3 0.2</td>
<td>25.4</td>
</tr>
<tr>
<td>20-35</td>
<td>2Cm1</td>
<td>14 16 69</td>
<td>0.8</td>
<td>1.19</td>
<td>6.5</td>
<td>1.7 0.5 0.3 0.2</td>
<td>8.5</td>
</tr>
<tr>
<td>35-50</td>
<td>2Cm2</td>
<td>17 15 69</td>
<td>0.9</td>
<td>1.00</td>
<td>6.4</td>
<td>1.6 0.5 0.1 0.1</td>
<td>7.9</td>
</tr>
<tr>
<td>50-75</td>
<td>3C3</td>
<td>22 26 53</td>
<td>0.3</td>
<td>0.85</td>
<td>6.4</td>
<td>1.4 0.5 0.2 0.6</td>
<td>8.0</td>
</tr>
<tr>
<td>75-95</td>
<td>4Ab</td>
<td>9.6</td>
<td>0.41</td>
<td>6.6</td>
<td>19.0</td>
<td>2.2 0.3 0.3 0.3</td>
<td>44.7</td>
</tr>
</tbody>
</table>

| Depth (cm) | Horizon | Base saturation (+) | Phosphate absorption (mgP2O5/100g) | Primary mineral composition
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>on (%)</td>
<td></td>
<td>OL Au Hy Op Pl VG (% in 0.05 to 0.2mm)</td>
</tr>
<tr>
<td>0-20</td>
<td>A</td>
<td>28</td>
<td>2620</td>
<td>11 1 3 1 18 66</td>
</tr>
<tr>
<td>20-35</td>
<td>2Cm1</td>
<td>32</td>
<td>1440</td>
<td>4 1 2 1 15 78</td>
</tr>
<tr>
<td>35-50</td>
<td>2Cm2</td>
<td>35</td>
<td>1460</td>
<td>5 2 2 11 82</td>
</tr>
<tr>
<td>50-75</td>
<td>3C3</td>
<td>34</td>
<td>1260</td>
<td>4 3 5 5 21 62</td>
</tr>
<tr>
<td>75-95</td>
<td>4Ab</td>
<td>49</td>
<td>2910</td>
<td>3 2 1 13 79</td>
</tr>
</tbody>
</table>

490
2. "Nigatsuchi" soil

"Nigatsuchi" is not indurated in the buried condition and the formation of hardening of "Nigatsuchi" is due to air drying of moist unsolidified soil materials. The indurated fragment in "Nigatsuchi" does not slake even when replaced in water. Shown in FIG.2, the shear strength value of soil fragment in "Nigatsuchi" (3Ab1 and 3Ab2 horizons) increases with the decreasing of the moisture content of that. The volume of "Nigatsuchi" remarkably decrease with drying. Penetrometer values are less than 25 mm for undried samples and more than 30 mm for air-dried samples. Root elongation is remarkably difficult when penetrometer values are more than 28.

The clay content is much higher in 3Ab1 and 3Ab2 soils of "Nigatsuchi" than in overlying soils of them and also there is the difference in primary composition between them. But, there is little difference in the content of oxalate solubles between "Nigatsuchi" soils and others. We have studied for solving the indurating process of "Nigatsuchi".

TABLE6 Characteristics of "Nigatsuchi" soil

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Total (wt.%) clay</th>
<th>Silt</th>
<th>Sand</th>
<th>Organic carbon (%)</th>
<th>Bulk density (g/cm³)</th>
<th>pH (H₂O)</th>
<th>Exchangeable bases:</th>
<th>CEC (cmol/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-24cm</td>
<td>A1</td>
<td>35</td>
<td>30</td>
<td>34</td>
<td>12.7</td>
<td>0.48</td>
<td>5.8</td>
<td>Ca</td>
<td>Mg</td>
</tr>
<tr>
<td>24-60cm</td>
<td>A2</td>
<td>31</td>
<td>34</td>
<td>35</td>
<td>7.1</td>
<td>0.04</td>
<td>5.6</td>
<td>5.2</td>
<td>0.5</td>
</tr>
<tr>
<td>60-80cm</td>
<td>2Ab</td>
<td>72</td>
<td>24</td>
<td>14</td>
<td>11.7</td>
<td>0.45</td>
<td>5.5</td>
<td>10.4</td>
<td>1.7</td>
</tr>
<tr>
<td>80-108cm</td>
<td>3Ab1</td>
<td>65</td>
<td>30</td>
<td>5</td>
<td>6.6</td>
<td>0.49</td>
<td>5.6</td>
<td>4.8</td>
<td>3.3</td>
</tr>
<tr>
<td>100-130cm</td>
<td>3Ab2</td>
<td>65</td>
<td>30</td>
<td>5</td>
<td>6.6</td>
<td>0.49</td>
<td>5.6</td>
<td>4.8</td>
<td>3.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Heavy mineral (%) in 0.1 to 0.2mm</th>
<th>Heavy mineral composition (%)</th>
<th>Light mineral composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-24cm</td>
<td>A1</td>
<td>16</td>
<td>23</td>
<td>54</td>
</tr>
<tr>
<td>24-60cm</td>
<td>A2</td>
<td>16</td>
<td>54</td>
<td>22</td>
</tr>
<tr>
<td>60-80cm</td>
<td>2Ab</td>
<td>8</td>
<td>62</td>
<td>19</td>
</tr>
</tbody>
</table>
### Depth and Horizon Analysis

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Oxalate soluble (%)</th>
<th>Pyro. soluble (%)</th>
<th>Total analysis (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Si</td>
<td>Al</td>
<td>Fe</td>
</tr>
<tr>
<td>0-24cm</td>
<td>A1</td>
<td>2.45</td>
<td>9.87</td>
<td>2.98</td>
</tr>
<tr>
<td>24-60cm</td>
<td>A2</td>
<td>3.84</td>
<td>15.77</td>
<td>4.20</td>
</tr>
<tr>
<td>60-80cm</td>
<td>2Ab</td>
<td>3.83</td>
<td>13.33</td>
<td>3.94</td>
</tr>
<tr>
<td>80-108cm</td>
<td>3Ab1</td>
<td>2.36</td>
<td>7.40</td>
<td>4.35</td>
</tr>
<tr>
<td>100-130cm</td>
<td>3Ab2</td>
<td>3.81</td>
<td>16.43</td>
<td>3.93</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Total analysis (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>K₂O</td>
</tr>
<tr>
<td>0-24cm</td>
<td>A1</td>
<td>0.66</td>
</tr>
<tr>
<td>24-60cm</td>
<td>A2</td>
<td>0.50</td>
</tr>
<tr>
<td>60-80cm</td>
<td>2Ab</td>
<td>0.46</td>
</tr>
<tr>
<td>80-108cm</td>
<td>3Ab1</td>
<td>0.50</td>
</tr>
<tr>
<td>100-130cm</td>
<td>3Ab2</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Source: Kubotera and Yamada (1993)

Exchangeable cations and CEC were quoted from K. Kaoru and T. Koga (1980). Those data were obtained using the soils with the same horizon sequence near Takaono.

1) Ho: Common hornblende, Wp: Weathered particle, Qz: Quartz, T-VG: Transparent volcanic glass, C-VG: Colored volcanic glass

2) Pyro. soluble: Pyrophosphate soluble

![FIG. 2 Induration of "Nigatsuchi" by drying](image)

3 "Kora" soil

"Kora" was composed of scoria or volcanic gravels erupted from Kaimon volcano at 1000 Y.B.P.
This tephritic materials are basaltic andesitic in chemical composition and contain volcanic glass, plagiclase, pyroxenes and olivine. The typic “Kora” is cemented enough so that it can not be cut by a spade. The CEC value of almost all the “Kora” is lower than 10 and the degree of cation absorption exceeds 100% in an abundance of Ca, Mg and Na cations.

As all the primary minerals appear unweathered in thin section observation, “Kora” is not formation by weathering process of tephra, but most probably by solidification of hot tephra soon after its depositon. Thus, both HCl and KOH solution are not efficient in dissolving silica, alumina and iron.

**TABLE7 Characteristics of “Kora” soil**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Total (wt.%)</th>
<th>Organic carbon</th>
<th>pH (H2O)</th>
<th>Exchangeable bases Ca</th>
<th>Mg</th>
<th>K</th>
<th>Na</th>
<th>CEC (cmol/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20 cm</td>
<td>A</td>
<td>23 clay, 23 silt, 54 sand</td>
<td>12.6</td>
<td>5.48</td>
<td>2.79</td>
<td>2.30</td>
<td>1.42</td>
<td>6.42</td>
<td>37.1</td>
</tr>
<tr>
<td>20-30 cm</td>
<td>2Cm1</td>
<td>1.0 clay, 0.6 silt, 1 sand</td>
<td>6.54</td>
<td>2.39</td>
<td>1.96</td>
<td>1.23</td>
<td>3.56</td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td>30-50 cm</td>
<td>2Cm2</td>
<td>0.6 clay, 0.6 silt, 0.6 sand</td>
<td>6.18</td>
<td>1.45</td>
<td>1.40</td>
<td>0.91</td>
<td>3.29</td>
<td>4.1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Hot 5% KOH soluble SiO2, Al2O3</th>
<th>Hot 12N HCl soluble SiO2, Al2O3, Fe2O3, TiO2, CaO, MgO, K2O, Na2O</th>
<th>CEC (cmol/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20 cm</td>
<td>A</td>
<td>3.86, 7.58</td>
<td>10.84, 13.63</td>
<td>8.12</td>
</tr>
<tr>
<td>20-30 cm</td>
<td>2Cm1</td>
<td>2.49, 8.01</td>
<td>15.58, 18.06</td>
<td>9.25, 11.18</td>
</tr>
<tr>
<td>30-50 cm</td>
<td>2Cm2</td>
<td>2.22, 5.38</td>
<td>13.67, 12.50</td>
<td>5.99, 2.37</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Total analysis SiO2, Al2O3, Fe2O3, TiO2, CaO, MgO, K2O, Na2O, MnO, P2O5, Ig.loss</th>
<th>CEC (cmol/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-30 cm</td>
<td>2Cm1</td>
<td>43.46, 19.26, 16.30, 1.65, 5.47, 4.74</td>
<td>8.92</td>
</tr>
<tr>
<td>30-50 cm</td>
<td>2Cm2</td>
<td>48.85, 18.15, 13.58, 0.98, 6.90, 5.55</td>
<td>4.85</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Oxalate soluble Si, Al, Fe</th>
<th>Pyro. soluble Si, Al, Fe</th>
<th>CEC (cmol/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>67-80 cm</td>
<td>2Cm2</td>
<td>2.05, 3.76, 1.89</td>
<td>0.42, 0.02</td>
<td>8.12</td>
</tr>
</tbody>
</table>

Source: S. Hanai (1952) and S. Hanai and A. Shinagawa (1952) except oxalate and pyrophosphate solubles

**4 Placic soil**

Placic Spodosols derived from Towada-Chusseri tephra (5500Y.B.P. ) is overlayed by non-placic Spodosols originated from Towada-a tephra (1000Y.B.P.) in southern Hakkoda. Soil acidity is strong acid in the Oa horizon and tend to become weaker with depth. There is the positive correlation among the clay content, organic carbon content and CEC and those values are higher in Oa, 2Ab and 2Eb horizons. Bulk density is relatively high in CB and 2B horizons. The DCB soluble Fe and acid oxalate soluble Fe content is highest in the placic horizon and higher in 2Ab and 2Eb horizons. The DCB soluble and acid oxalate soluble Al content is higher in 2Eb and 2B smb (placic) horizons. The abundant thready mottleings in 2Eb horizon indicate the redoximorpholic features. Those show that the Fe and Al accumulations in the placic Spodosols
TABLE 8 Characteristics of "Placic" soil

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Total (wt.%)</th>
<th>Organic carbon (%)</th>
<th>Bulk density (g/cm³)</th>
<th>pH (H₂O)</th>
<th>Exchangeable bases (cmol/kg)</th>
<th>CEC (cmol/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>clay silt sand</td>
<td></td>
<td></td>
<td></td>
<td>Ca Mg K Na</td>
<td></td>
</tr>
<tr>
<td>5-0cm</td>
<td>Oa</td>
<td>31 56 13</td>
<td>27.7</td>
<td>0.25</td>
<td>4.3</td>
<td>2.13 3.05 1.14 0.33</td>
<td>52.8</td>
</tr>
<tr>
<td>0-5cm</td>
<td>E</td>
<td>13 36 51</td>
<td>5.7</td>
<td>0.68</td>
<td>4.7</td>
<td>0.14 0.17 0.14 0.12</td>
<td>20.9</td>
</tr>
<tr>
<td>5-8cm</td>
<td>Bsm</td>
<td>8 32 59</td>
<td>2.9</td>
<td>0.88</td>
<td>4.8</td>
<td>0.66 0.05 0.05 0.08</td>
<td>13.7</td>
</tr>
<tr>
<td>8-13cm</td>
<td>CB</td>
<td>5 29 67</td>
<td>1.0</td>
<td>0.99</td>
<td>4.9</td>
<td>0.03 0.02 0.04 0.08</td>
<td>5.7</td>
</tr>
<tr>
<td>13-18cm</td>
<td>2Ab</td>
<td>24 39 37</td>
<td>9.7</td>
<td>0.43</td>
<td>4.9</td>
<td>0.09 0.14 0.12 0.13</td>
<td>22.4</td>
</tr>
<tr>
<td>18-25cm</td>
<td>2Eb</td>
<td>29 33 38</td>
<td>7.5</td>
<td>0.54</td>
<td>5.1</td>
<td>0.05 0.07 0.07 0.11</td>
<td>18.5</td>
</tr>
<tr>
<td>25-28cm</td>
<td>2Bsbmb</td>
<td>15 31 54</td>
<td>3.2</td>
<td>0.89</td>
<td>5.5</td>
<td>0.03 0.02 0.02 0.07</td>
<td>18.8</td>
</tr>
<tr>
<td>28-35cm</td>
<td>2Bwb</td>
<td>8 28 64</td>
<td>1.2</td>
<td>0.60</td>
<td>6.0</td>
<td>0.05 0.03 0.01 0.04</td>
<td>7.8</td>
</tr>
<tr>
<td>35-55cm</td>
<td>2C1</td>
<td>7 3 90</td>
<td>0.6</td>
<td>0.60</td>
<td>6.1</td>
<td>0.07 0.04 0.01 0.04</td>
<td>3.5</td>
</tr>
<tr>
<td>55-65cm</td>
<td>2C2</td>
<td>6 1 94</td>
<td>0.2</td>
<td>0.60</td>
<td></td>
<td></td>
<td>2.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Base phosphate DCB soluble (%)</th>
<th>Oxalate soluble (%)</th>
<th>Pyro. soluble (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Al</td>
<td>Fe</td>
<td>Al</td>
</tr>
<tr>
<td>5-0cm</td>
<td>Oa</td>
<td>13</td>
<td>56</td>
<td>0.41</td>
</tr>
<tr>
<td>0-5cm</td>
<td>E</td>
<td>3</td>
<td>63</td>
<td>0.44</td>
</tr>
<tr>
<td>5-8cm</td>
<td>Bsm</td>
<td>2</td>
<td>69</td>
<td>0.59</td>
</tr>
<tr>
<td>8-13cm</td>
<td>CB</td>
<td>3</td>
<td>53</td>
<td>0.38</td>
</tr>
<tr>
<td>13-18cm</td>
<td>2Ab</td>
<td>2</td>
<td>94</td>
<td>1.36</td>
</tr>
<tr>
<td>18-25cm</td>
<td>2Eb</td>
<td>2</td>
<td>96</td>
<td>1.67</td>
</tr>
<tr>
<td>25-28cm</td>
<td>2Bsbmb</td>
<td>1</td>
<td>97</td>
<td>1.54</td>
</tr>
<tr>
<td>28-35cm</td>
<td>2Bwb</td>
<td>2</td>
<td>93</td>
<td>0.99</td>
</tr>
<tr>
<td>35-55cm</td>
<td>2C1</td>
<td>4</td>
<td>89</td>
<td>0.57</td>
</tr>
<tr>
<td>55-65cm</td>
<td>2C2</td>
<td>6</td>
<td>64</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Source: S. Shoji, et al. (1988)

Land Use and Management

The areas of "Masa", "Nigatsuchi" and "Kora" soils are estimated to be 223, 70, 117 km², respectively. Almost all those areas were covered with natural grasses and secondary forest trees before 1950. Proceeding with the food increase policy by Japanese government and the development of the agricultural equipments, the greater part of those areas turned into the farm land. Placic Spodosols in southern Hakkoda has been under natural mixed forests of conifer and broad-leaved trees.

1 "Masa" area

The presence of indurated layer in "Masa" was the knottist problem for cultivation of upland crops in the western foot of Mt. Fuji in Shizuoka prefecture. "Masa" soil commonly have the indurated layer of 40 to 50 cm depth within 30 to 50 cm from the soil surface. Subsoiling of the indurated layer and mixing of the surface soil and indurated soil brought the immediate effect on subsoil improvement through the enlargement of the rooting zone, improvement of the its water status and decreasing of soil erosion hazard. The production of upland crops remarkably increased by the soil amelioration (Suzuki and Yamada 1964).
2 "Nigatsuchi" area

The potential indurated horizon of "Nigatsuchi" soils is generally below 50 cm depth from the soil surface and is fairly weathered. So it contain a large amount of active alumina and iron and small amount of plant available nutrients. Making the top soil of "Nigatsuchi" soils used to cause a tremendous decrease of crop production. Soil improvement should be conducted without bringing this horizon to the surface.

TABLE 9 Yield of sorghum and nutrient content of leaves in different land improvement

<table>
<thead>
<tr>
<th></th>
<th>First plant</th>
<th>Second plant</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top soil peplacig over &quot;Nigatsuchi&quot;</td>
<td>56.6</td>
<td>48.7</td>
<td>2.08</td>
<td>0.61</td>
<td>2.17</td>
<td>0.72</td>
<td>0.31</td>
<td>367</td>
<td>33</td>
<td>25</td>
<td>14</td>
</tr>
<tr>
<td>Surfacing of &quot;Nigatsuchi&quot;</td>
<td>40.0</td>
<td>30.5</td>
<td>1.82</td>
<td>0.49</td>
<td>2.25</td>
<td>0.71</td>
<td>0.27</td>
<td>251</td>
<td>39</td>
<td>16</td>
<td>10</td>
</tr>
</tbody>
</table>

Source: Miyuichi et al. (1976)

3 "Kora" area

"Kora" is distributed in northwestern hills of Kaimon volcano in Kagoshima prefecture. "Kora" soils usually have an indurated layer of 20 to 40 cm depth. Since this pan is extremely firm and plant roots cannot penetrate this layer, crop production is seriously reduced when its upper boundary occurs within 40 cm from the soil surface. Rake dozers are used for subsoiling and removal of "Kora". Production of wheat, sweet potato, and rape-seed was doubled by the soil improvement (Matsushita et al. 1960).

TABLE 10 Production change of upland crops by "Kora" removal

<table>
<thead>
<tr>
<th></th>
<th>Potato (root, ton/ha)</th>
<th>Wheat (grain, m³/ha)</th>
<th>Rape (seed, m³/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No treatment</td>
<td>5.8</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Removal</td>
<td>13.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Source: Matsushita et al. (1960)

Conclusion

Japan is one of the representative volcanic countries in the world. Introduced two indurated volcanic ash soils, "Masa" soil in the foot of Mt. Fuji and "Kora" soil in southern part of the Satsuma Peninsula, needed the subsoil improvement for farm land reclamation. The indurated layers in those soils were originated from scoria or volcanic gravels. The induration of "Masa" is characterized by particle size distribution and silica rich amorphous materials and that of "Kora" may be caused by solidification of hot tephra soon after its depositon, but not formation by weathering process of tephra.

"Nigatuchi" is the buried volcanic ash soil distributed in the western foot or plature of Mt. Aso, and the age of soils is estimated to 10000 Y.B.P. in youngest one and 30000 Y.B.P. in oldest one. "Nigatuchi" is never indurated in buried condition, but irreversibly solidifies by air drying of moist unsolidified soil material. Placic Spodosols originated from Towada tephra in higher altitude than 800 m show the
climosequence with Melanudands being in lower area than 800m in southern Hakkoda.

References
Hanai, S., and A. Shinagawa. 1952. Studies on the "Kora" horizons distributed in the southern Satsuma Peninsura (2) Contents of free silica, alumina and iron in soils and ratio of acid fuchsin to methylen blue absorbed by soils (in Japanese with English summary)
The Talpetate of the Central-Pacific Region of Nicaragua:
a Palagonitized Tuff from the Masaya Volcano

Christian Prat* and Paul Quantin**. *ORSTOM, Col. Los Morales, A.P. 57297, 06501 México, Mexique; **ORSTOM, 93143 Bondy CEDEX, France.

Abstract: In the Central Pacific area of Nicaragua, a talpetate (an indurated horizon) was studied through field morphological observations of soils profiles along toposequences, microscopy of thin sections, mineralogical, physical, and chemical analyses.

The talpetate is a volcanic tuff. Composed of basaltic andesite ashes with labrador and pigeonite of the tholeiitic series. Most of the basaltic glasses were "palagonitized" when the tuff was deposited, or shortly afterwards, thus leading to the formation of ferriferous smectites. However, a subsequent meteoric weathering was superimposed on this primary one. As a result halloysite formed under a tropical climate characterized by a well-pronounced dry season. Under a more humid climate and in Andisols over the talpetate, gibbsitans, mangans, and allophans formed on the surface and in the cracks of the talpetate. The porosity of talpetetes is very high (≤65% of the dry weight) and mainly results of the voids formed by the packing of microclites.

The results of this study show that this talpetate is a volcanic tuff spread over 2 500 km², mainly west of the Masaya caldera. This tuff is the result of one or several piroclastic surges that took place during the phreato-magmatic explosions in the caldera of Masaya some 2 000 years ago. The presence of "armoured" nodules of ash accretion and the superimposition of "massive" with "armoured nodules" layers following the preceding landforms are typical of a phreato-magmatic event.

We propose to change the ambiguous term talpetate for "palagonitized tuff of Masaya" as new name for this indurated horizon of the Central-Pacific area of Nicaragua.

Introduction.

In some volcanic soils of Nicaragua, Mexico, and in other countries of Central America (Dubreucq et al., 1989; Zebrowski et al., 1992), there is an indurated horizon called "talpetate" or "tepetate" which makes agriculture difficult and whose origin is controversial.

The word talpetate comes from tepetate a náhuatl word (tetl = rock and petatl = bed) which means "bed-rock" (Siméon, 1885; Incer, 1985). In spite of the fact that its etymology indicates that it is an indurated horizon, it does not give more information about its characteristics.

Until the work of Prat (1991), there were two opposite points of view on the origin and the characteristics of talpetate. According to geologists, this horizon is the equivalent of a tuff called "Masaya tuff" or "Retiro tuff", which has as its origin a pyroclastic flow from a phreato-magmatic explosion (Williams, 1983) or could be an aerial volcanic deposit (the "triple layer" of Bice, 1980). In both cases, the Masaya caldera is identified as the source of this material. On the other hand, pedologists consider talpetate as an aerial deposit of fine volcanic ashes cemented later by lixiviation and accumulation of clay, silica and oxides of iron and aluminium, such as what happens in a B horizon (Marín et al., 1971; Rodriguez, personal communication, 1985). However Prat (1991) clearly showed that it is a tuff emitted by the Masaya volcano with a phreato-magmatic origin, which under some special conditions suffered changes due to pedogenic processes.

Our purpose is to detail some aspects which clearly show the origin and the characteristics of talpetate as well as its presence in the soils of the Central-Pacific region of Nicaragua.
Materials and Methods.

Through its spatial distribution and its characteristics, it is possible to deduce the volcanic origin of the *talpetate*. However, differences in climate between the banks of the lake of Managua and those of the Pacific coast, and the heights of the Sierras of El Crucero-Las Nubes, have as a result different soil features. On the other hand, it is sometimes difficult to distinguish with precision *talpetate* from all the others horizons more or less indurated.

After a short presentation of the spatial distribution of the *talpetate* whether at the profile, toposequence or regional level, we intend to study through macro and microscopic observations (optical microscopy, SEM with a Castaing micro-probe, TEM, XRD), as well as physical-chemical analysis, the characteristics of some indurated horizons from a series of profiles distributed along a northeast-southwest cross-section of the Central Pacific region of Nicaragua.

Results.

The area under study covers 5,000 km². It is delimited by the Pacific ocean at the west, the banks of the lake of Managua at the north and the banks of the lake of Nicaragua at the southeast. Between these plains, lays the Sierra of Los Marrabios which reaches 950 m over sea level.

This region belongs to the meridional domain (Isthmic Central America) of the Caribbean plaque where the plaque of Coco passes underneath (Mc Birney and Williams, 1965). The changes of natural and human environment along the longitudinal cross-section from the lake of Managua to the Pacific are progressive. Nevertheless, we go from an annual rainfall under 1,000 mm spread over 6 months in the plains of the grabben (tropical to dry subtropical climate) to a maximum of 1,800 mm spread over 9 to 10 months in the upper part of the relief (humid tropical climate).

Schematically, the *talpetate* present in the volcanic soils of the Central Pacific region of Nicaragua is described as an indurated horizon, pale olive brown (10YR5/6) when dry, and dark brown (10YR3/2) when humid, fine silty with a massive structure crossed by roots in good sanitary conditions and by many biological tubes and cracks filled with fine soil. The bulk density is less than 1 g/cm³. In spite of its induration, *talpetate* usually slakes in the water. In this case, and according to the US soil classification, it is not a duripan but a fragipan. Sometimes, in the case of the reddish *talpetates*, they do not slake in water. The thickness of this layer varies from a few centimeters to one meter, and it is located near the surface except for some cases where it can be found up to 3 meter deep. Actually, *talpetate* is not formed by one horizon but by a superimposition (from 3 to 7 layers in average) of massive and nodular horizons. The nodules are armoured and look like onions 0.5 to 2.0 cm of diameter. At the base of the *talpetate*, often it is possible to observe the presence of leaf prints.

1. Distribution

1.1. Profiles

The stratigraphic organization is constant with the following pattern, from the surface down:

* A humic horizon, thin to very developed, sometimes formed by many humic horizons superimposed and containing remains of precolombian pottery and obsidian.

* An indurated horizon (*talpetate*) formed by different layers, alternately with nodules and massive. The upper layer, a brown olivaceous color, is crossed by many cracks filled by fine soil, while the lower layer is grayer with a coarser texture and presents a lithic limit with the underlying horizon. The nodules are formed by a “core” wrapped by layers of very fine ashes. They are called armoured nodules. Sometimes, it is possible to find prints of leaves of *Ficus* sp. on the basal part of the *talpetate*.

* A sandy to sandy loam horizon, brown, thin (< 10 cm) of basaltic sands, more or less weathered, with a very fine to very coarse texture.

* A series of horizons a few centimeters thick, formed by soldered cinders and separated by sand. At the layer base, there are prints of vegetation (grasses?).
* A silty to sandy horizon, reddish brown, several tens of centimeters thick, with pumice sand very weathered.
* A sandy horizon of pumice slightly weathered and with a very variable thickness (0 up to 1 m).
* A silty to sandy horizon, brown olivaceous, several tens of centimeters thick with basaltic sand fairly weathered.
* A horizon of basaltic lapilli, black, slightly or non weathered, several tens of centimeters thick.
* A silty brown horizon, with angular polyhedral structure with basaltic sand.

In spite of the difference in thickness of the horizons and of the nature and degree of weathering of the materials, it is possible to find more or less the same stratigraphic organization of the soils: some profiles present very complete sequences, while others are very simplified.

If we compare this stratigraphy with the one defined by geologists, in particular Bice (Figure 1), it is obvious that they are the same: our talpetate is present at the level of the "Masaya tuff" (as defined by this author) with the same morphological characteristics while we identified centimetric layers of soldered cinders corresponding to his "triple layer".

Different studies give the talpetate an age between 6,000 and 1,300 years BP, 4,000 years BP being the most probable age. Thanks to the help of archeological findings of human bones remains and of a whole piece of pottery under the talpetate (Prat, 1991), we can define the style of the pottery as the “bichrome in plate” style. This style corresponds to the period between 2,400 to 1,500 years BP, and probably this pottery corresponds to the end of this period (between 2,000 and 1,500 years BP).

![Figure 1. Schematic profile of the geological stratigraphical sequence of the region of Managua (according to Bice, 1980).](image)

1.2. Toposequence

The study of toposequences longitudinal to the general slope or transverse to it shows that the positions of the talpetate are the following (Figure 2):

- Very close to the surface, under an Ap or mixed with this horizon. It is present as desegregated blocks.
- Close to the surface, under an Ap. It is formed by two or more layers whose characteristics have been described above. The closest layer to the surface is usually semi-destroyed and it is mixed with the Ap horizon while the others are quite homogeneous.
- Very deep (up to 4 m), under one or more humic horizons, with alternating layers of fine and round coarse sand with dispersed remains of pottery and obsidian. The talpetate is formed by well shaped layers as described above.

- Absent. The soils are on the top of a ridge or in the bottom of a talweg.

Figure 2. Pedologic toposequence of San Judas, Managua (stratigraphy is related with the geological sequence of Managua given by Bice) (Prat, 1991).

The talpetate follows the relief and very often its slope is higher than 50%. Its thickness varies also as a function of the slope. In fact, the topographical position of the profile influences the characteristics of the talpetate: on the slopes and/or at the bottom of a talweg, the talpetate is present, more or less well developed, whereas on the ridge of hills or of micro-relief, it is near the surface, very destroyed and even absent.

The closer to the caldera of the volcano of Masaya the more important the number and thickness of the layers of talpetate is. For instance, at 30 km from the caldera, the talpetate is a few centimeters thick, whereas at 10 km it is 1 m thick, and at the border of the caldera, it is more than 10 m thick!

These observations show that the horizons covering the talpetate have an alluvial-eolic-colluvial origin. This does not exclude the possibility of eolical materials being deposited afterwards and with time being swept by the wind and/or the rain. With regard to the talpetate it is very probable that it covered all the relief in an irregular way due to the local obstacles, accumulating from the top to the bottom of the depression and being thicker near the Masaya volcano caldera. In some cases the talpetate was protected from erosion by the accumulation of sediments which covered it.
1.3. Region
The soil map surveys realized by the cadastral organization (1968-1972) show that it is likely to find a duripan, fragipan or a talpetate in the following soil classes: Inceptisols typic Durandepts and mollic Vitrandepts, Mollisols duric Haplustolls - typic Durustolls - duric Argiustolls.

By using these maps and those established by the geologists (Bice, 1980; Williams, 1983) as well as our own observations over a period of four years in all the Central-Pacific region, we could define better the distribution of the talpetate (Figure 3).

Figure 3. Distribution of the talpetate in the Central-Pacific region of Nicaragua.

2. Characteristics of the horizons under study
Ten profiles were observed and analyzed in detail. They are representative of the different conditions of the natural and human environment and of the soils which have an indurated layer in the area studied. We grouped the horizon in the following classes: talpetate under dry tropical climate, talpetate under humid tropical climate, soldered cinders, grey talpetate. We added the "triple layer" of Bice (1980) and the "El Retiro tuff" (Zoppis Bracci, 1968; Williams, 1983) called also "Masaya tuff" (Bice, 1980) to compare them with our horizons.

2.1. Physical-chemical characteristics
The results of some of the physical-chemical characteristics of three kinds of indurated horizons are shown in Table 1.
Table 1: Some physical-chemical characteristics of the talpetate, the soldered cinders and the cinders cemented by carbonates.

<table>
<thead>
<tr>
<th></th>
<th>Talpetate</th>
<th>Soldered cinders</th>
<th>Cinders cemented by CaCO₃</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Color</strong></td>
<td>Brown olivaceous to reddish brown</td>
<td>Black olivaceous</td>
<td>Grey olivaceous with white dots</td>
</tr>
<tr>
<td><strong>pH water</strong></td>
<td>6 to 7</td>
<td>6.5 to 7.5</td>
<td>&gt; 8</td>
</tr>
<tr>
<td><strong>Bulk density</strong></td>
<td>2.7</td>
<td>2.85</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>Apparent density</strong></td>
<td>0.9 - 1</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Porosity</strong></td>
<td>50 to 70</td>
<td>40 to 75</td>
<td>50 to 70</td>
</tr>
</tbody>
</table>

It was possible to distinguish two classes of tepetates as a function of their position in the climate-toposequence as shown in Table 2:

Table 2: Some chemical characteristics of talpetate under dry tropical climate with a long dry season and under humid tropical climate with a very short dry season.

<table>
<thead>
<tr>
<th></th>
<th>talpetate under dry tropical climate with a long dry season</th>
<th>talpetate under humid tropical climate with a very short dry season</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>pH water</strong></td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td><strong>pH KCl</strong></td>
<td>≥ 5</td>
<td>≤ 5</td>
</tr>
<tr>
<td><strong>pH NaF</strong></td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td><strong>CIC</strong></td>
<td>20 ≤ CIC ≤ 40</td>
<td>20 ≤ CIC ≤ 40</td>
</tr>
<tr>
<td><strong>S/T</strong></td>
<td>S/T ≥ 50%</td>
<td>20% ≤ S/T ≤ 50%</td>
</tr>
<tr>
<td><strong>P assim. (Olsen)</strong></td>
<td>3 ppm</td>
<td>64 ppm</td>
</tr>
<tr>
<td><strong>K available</strong></td>
<td>S/T ≥ 50%</td>
<td>20% ≤ S/T ≤ 50%</td>
</tr>
<tr>
<td><strong>“Free iron” oxides</strong></td>
<td>3 ppm</td>
<td>64 ppm</td>
</tr>
</tbody>
</table>

(From Methra and Jackson)

2.2. Chemical composition

The complete analysis of the different horizons shows that those materials have a composition of andesite with labrador and pigeonite, a composition very close to that of a basalt (Table 3).

Table 3. Chemical composition of the soldered cinders, triple layer, Masaya tuff, grey talpetate, talpetate of cold and of humid climates.

<table>
<thead>
<tr>
<th></th>
<th>Soldered cinders</th>
<th>Triple layer (Bice, 1980)</th>
<th>Masaya tuff</th>
<th>Grey Talpetate</th>
<th>Talpetate of ustic climate</th>
<th>Talpetate of udic climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>53.26</td>
<td>52.51</td>
<td>53.11</td>
<td>54.03</td>
<td>50.04</td>
<td>39.32</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>15.23</td>
<td>18.36</td>
<td>17.01</td>
<td>16.51</td>
<td>21.66</td>
<td>28.26</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>13.79</td>
<td>12.18</td>
<td>13.39</td>
<td>12.8</td>
<td>16.46</td>
<td>23.53</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.18</td>
<td>1.31</td>
<td>1.35</td>
<td>1.26</td>
<td>1.45</td>
<td>1.97</td>
</tr>
<tr>
<td>MnO₂</td>
<td>0.30</td>
<td>0.22</td>
<td>0.19</td>
<td>0.28</td>
<td>0.40</td>
<td>0.75</td>
</tr>
<tr>
<td>CaO</td>
<td>8.44</td>
<td>8.39</td>
<td>8.75</td>
<td>7.12</td>
<td>5.68</td>
<td>2.74</td>
</tr>
<tr>
<td>MgO</td>
<td>4.12</td>
<td>3.56</td>
<td>4.16</td>
<td>3.72</td>
<td>2.11</td>
<td>2.03</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.90</td>
<td>1.17</td>
<td>0.81</td>
<td>1.41</td>
<td>0.54</td>
<td>0.24</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.68</td>
<td>1.99</td>
<td>1.14</td>
<td>2.63</td>
<td>1.51</td>
<td>0.83</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.10</td>
<td>0.33</td>
<td>0.1</td>
<td>0.23</td>
<td>0.15</td>
<td>0.31</td>
</tr>
<tr>
<td>Ki</td>
<td>5.92</td>
<td>4.84</td>
<td>5.29</td>
<td>5.54</td>
<td>3.91</td>
<td>2.36</td>
</tr>
<tr>
<td>Kr</td>
<td>3.74</td>
<td>3.40</td>
<td>3.51</td>
<td>3.70</td>
<td>2.63</td>
<td>1.53</td>
</tr>
</tbody>
</table>

It appears that talpetates (except for the “grey” one) are weathered, their weathering degree being relatively variable as a function of the talpetate analyzed (Fig. 4 and 5).
The comparison of weathering of an horizon in a soil profile under a dry tropical climate and a humid one, allows identification of this process (Figure 6). In the case of the profiles from El Crucero, the main differences between the chemical composition of the horizons are due to their different nature: basaltic tuff and cemented cinders. But the low Ki (2.2) of the first layer in relation with the other ones is a proof of a pedological alteration. In the case of the profiles from Los Altos de Sto. Domingo, there is also a lixiviation process. The rate of silica decrease from the bottom to the top as well as Mn, Mg, Na and P, while the opposite happens for iron and aluminium.
2.3. Mineralogical composition

The microscopical observations show that the same components are found both in the cinders and in the talpetate, but there is a very important difference in the proportion of some of them, especially the percentage of palagonite and volcanics glasses: they are the main components of talpetates but they are present in very small amounts in the soldered cinders (Table 4).

Table 4. Mineralogical composition of soldered cinders and talpetates.

<table>
<thead>
<tr>
<th></th>
<th>Soldered cinders</th>
<th>Talpetate of ustic climate</th>
<th>Talpetate of udic climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palagonite</td>
<td>10</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Dacitic glass</td>
<td>40</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Basaltic glass</td>
<td>30</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>15</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Magnetite</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Pyroxene</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Olivine</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Others</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

A clear difference can be noted between soldered cinders and talpetates: in the cinders, the primary minerals with 14 Å clays predominate, and in the case of talpetates, the primary minerals with this kind of clays can be found, but they do not predominate over the other components. In fact, in this kind of talpetates, there is more smectites than 7 Å and 10 Å halloysite. Allophane is always present but in small quantities.

In the case of talpetates under humid tropical climates in Andisols, there is gibbsite while the talpetates under dry climates do not have. Allophane is also present but in larger amounts.

2.4. Micromorphology

The observations with an optical microscope, either in natural light or in UV, clearly show the differences already discussed between the different kinds of talpetates (Table 5).

The palagonite, which results from weathering of basaltic glasses (Bonatti, 1965; Honnорez, 1967), formed the main part of talpetates; while in the case of soldered cinders, palagonite is present only from time to time. Palagonite is of a characteristic orange color with abundant pores. All of these voids have a cortex or are bordered by rims of material of lighter colors or are filled with dark materials.

The microanalysis show that in the first case, there are important losses of silica and bases; while the concentration of iron and aluminium increases. As a consequence of these losses, allophanic and halloysite products are formed (SiO$_2$/Al$_2$O$_3$ de 2.8 a 1.8). In the second case, the weathering of the palagonite doesn't involve losses of components. The SiO$_2$/Al$_2$O$_3$ ratio of 5 of the materials in the closed voids, when related with the data obtained with the XRD, shows that this products are smectites.

Table 5. Comparison of the micromorphological characteristics of soldered cinders, talpetates under dry tropical climates and talpetates under humid tropical climates.

<table>
<thead>
<tr>
<th></th>
<th>Soldered cinders</th>
<th>Talpetate under dry tropical climate</th>
<th>Talpetate under humid tropical climate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Relative Surf (%)</td>
<td>Size (mm)</td>
<td>Relative Surf (%)</td>
</tr>
<tr>
<td>NATURE OF THE MICROLITES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palagonite</td>
<td>5 to 10</td>
<td>≤ 2.0</td>
<td>60</td>
</tr>
<tr>
<td>Clear glasses</td>
<td>40</td>
<td>≤ 3.0</td>
<td>15</td>
</tr>
<tr>
<td>Dark glasses</td>
<td>30</td>
<td>≤ 3.0</td>
<td>15</td>
</tr>
<tr>
<td>Magnetite</td>
<td>5</td>
<td>≤ 0.5</td>
<td>5</td>
</tr>
<tr>
<td>Plagioclases (labrador, andesine)</td>
<td>15</td>
<td>≤ 1.0</td>
<td>10</td>
</tr>
<tr>
<td>Pyroxenes (Augite)</td>
<td>&lt;5</td>
<td>≤ 1.0</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Olivine</td>
<td>1</td>
<td>≤ 0.5</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>
Table 5. Comparison of the micromorphological characteristics of soldered cinders, *talpetates* under dry tropical climates and *talpetates* under humid tropical climates.

<table>
<thead>
<tr>
<th></th>
<th>Soldered cinders</th>
<th><em>Talpetate</em> under dry tropical climate</th>
<th><em>Talpetate</em> under humid tropical climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>POROSITY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Void / Solid</td>
<td>50</td>
<td>≥ 60</td>
<td>≥ 60</td>
</tr>
<tr>
<td>Roots porosity</td>
<td>0 to 2-3</td>
<td>≤ 2 mm</td>
<td>15 mm to cm</td>
</tr>
<tr>
<td>Bubbles in glasses</td>
<td>30-40</td>
<td>20 to 100 μm</td>
<td>30-40</td>
</tr>
<tr>
<td>Packing voids</td>
<td>50-60</td>
<td>60 to 5 μm</td>
<td>30-40 to 100 μm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 to 20 μm</td>
<td>30-40</td>
</tr>
<tr>
<td>EDAFIC FEATURES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organo-argillans</td>
<td>(+)</td>
<td>(+)</td>
<td>+</td>
</tr>
<tr>
<td>Sesquioxides (Fe, Mn) coatings</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gibbsitans</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Areas with loss of iron and concentration of iron near the roots</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Black matricial plasma of the palagonite</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>SPECIAL FEATURES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orange matricial plasma of the palagonite</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Cortex forming rims of weathering around the voids of sideromelane and palagonite</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Periporal and intraporal coating of the voids of sideromelane and palagonite</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Armoured nodules</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

*+: Present; -: Absent; (+): Rare.

**Discussion and Conclusions**

*Talpetate* is made of basaltic andesite material with pigeonite and labrador; this means it is a volcanic product whose composition borders between basalts and andesites. It belongs to the series of the tholeiites, which indicates that the magma had its origin in the fusion of the oceanic plate but was a little bit “contaminated” when passing through the tephra crust. The primary minerals prevailing in the soldered cinders and the “triple layer” of Bice, are essentially dark basaltic glasses and, to a certain extent, andesitic and dacitic glasses. There are also plagioclases (labrador, andesite), augite, magnetite, and traces of cristobalite, quartz and hematite. In the case of the secondary minerals, the palagonitization of glasses led mainly to the formation of ferriferous smectites. Under a humid tropical climate and in an Andisol, there are also processes of illuviation-concentration around the voids and formation of gibbsite, allophane and halloysite. Under a dry tropical climates and in a brown soils with andic characteristics there is halloysite but little allophane formation.

The presence in *talpetates* and in soldered cinders of products such as magnetite, microlites of glasses, palagonite, armoured nodules (Fisher and Schmincke, 1984) among others, proves the volcanic origin of these materials. The difference between them is not due to a meteorical weathering, but to a geological one. That means *talpetates* are a phase of a phreato-magmatic eruption where the conditions at the moment of the explosion (especially the water/solid ratio) were different. In one case weathering of the glasses by water resulted in palagonite and later in ferriferous smectites, whereas in other cases, this kind of weathering did not happen. Nevertheless, in all cases, the fusion and/or weathering of the glasses soldered them together, producing the induration of *talpetates*.

The physical-chemical and microscopic characterization of *talpetates* and soldered cinders confirms the field observations. So, through them, we could define the source and possible development of events which generated these materials.
Talpetates, also called "Masaya tuff" or "The Retiro tuff" (whereas the soldered cinder is the "triple layer" of Bice), are volcanic tuffs deposited 2,000 years ago during one or several phreato-magmatic explosions of the Masaya volcano. These kind of explosions are the result of the contact between the phreatic water supplied by the lakes of Managua and Nicaragua with the magma of the volcano. These explosions generated devastating surges of semi-liquid material (Sheridan and Wohletz, 1983) destroying and molding the vegetation... and people. These explosions also formed clouds of dust, cinders and ashes where the armoured nodules were formed (Fisher and Schmincke, 1984). These surges and aerial deposits covered 2,500 km² mainly west of the Masaya caldera. This orientation is partly due to the orientation of the winds blowing from east to west during the main part of the year. Due to their physical-chemical and morphological characteristics as well as their origin, we propose to call the talpetates we studied "palagonitized tuff of Masaya". We must not forget that this product appears a few years after Christ, which means yesterday in geological time. It also covers the richer and more crowded region of Nicaragua. The Masaya volcano is still active...

Literature cited.
Characterization and Agriculture Assessment of Two "Talpetate" Profiles in Nicaragua


Abstract. Soils derived from pyroclastic materials, with a cemented layer—locally called "talpetate"—occupy about 15 percent of the Pacific Region of Nicaragua. The soils are known to have a limited crop productivity (6). Two soils from the region were studied in the field and in the laboratory. Potential crop production for maize and sugar-cane calculated by a crop simulation model appears to be limited when the hardened layer is at shallow depth as the uptake of nutrients and moisture available in the subsoil is restricted. Aluminium and silicon contents in the talpetate are higher than in overlying and underlying horizons. The Al: Si ratio indicates that the silicon is bound by the allophane which after irreversible dehydrating, acts as the main cementing agent. There is no micromorphological evidence of silica cementation and therefore the talpetate does not meet the criteria of a duripan.

Introduction. In some soils in the Pacific Region of Nicaragua a process of cementation has been active. This has resulted in a duripan like layer (Figure 2) derived from volcanic deposits, which in Nicaragua is called "talpetate" (6; 8; 12). The word is derived from the Aztec, who called it in their native language (Nahuatl) "tepetatl", which means stone matting. The term "tepetate" used in Mexico, refers to the same phenomenon (8).

Figure 1 Distribution of soils with a talpetate (hatched) and the location of NI010 and NI011

Figure 2 Soil NI010 with a 19 cm thick talpetate at 23 cm depth.
Talpetate soils are common in Nicaragua. They occupy about 2,500 square kilometres, which corresponds to 15 percent of the total Pacific region of Nicaragua (6). In Figure 1 an impression is given of the distribution of the soils with a talpetate. Prat (9) presents evidences that the talpetate is a kind of volcanic tuff layer, deposited about 2,000 years ago by the Masaya volcano. He proposes to change the name of talpetate into "tuff of Masaya". One or various violent explosions which led to the transformation of the volcano in the actual caldera were followed by surges of pyroclastic materials. After deposition the tuff was transformed by different weathering processes.

In 1992 two representative talpetate soils, located in the Pacific Coastal Plain of Nicaragua were studied for incorporation in the Central American Soil Reference Collection and Database (CASREC). Description and sampling of the soils was carried out by the "Centro Agronómico Tropical de Investigación y Enseñanza" (CATIE), Turrialba, Costa Rica and the "Universidad Nacional Agraria" (UNA) of Nicaragua in collaboration with the International Soil Reference and Information Centre (ISRIC), Wageningen, The Netherlands. Duplicates of these soils were collected in order to start the creation of a national soil collection of Nicaragua at UNA and for ISRIC's world soil collection. The samples were studied and analyzed, and the results, including also a characterization of the talpetate and an evaluation of the agricultural potential of these soils, are presented in this paper.

**Background information.** The climate of the Pacific Coastal Plain is characterised by high temperatures (> 25°C) during the whole year and a rainfall of about 1400 mm (5). According to the Köppen climate classification it belongs to the area with a Tropical Savanna Climate (Aw*), characterised by marked dry and wet seasons. Rainfed agriculture is therefore limited. The Pacific Coastal Plain consists of a 35 km wide strip of land, parallel to the Pacific coast at one side and the volcanic cordillera of W-Nicaragua at the other. It consists of Cretaceous and Tertiary sediments, mostly sandstones together with schists, limestones and breccia, as well as some Quaternary rocks. All are covered in part by very deep pyroclastic deposits and re-deposited sediments of recent age (17).

**Methodology.** A detailed description for both soils was made (14), and large undisturbed monoliths were taken for soil expositions in Costa Rica, Nicaragua and The Netherlands. Soil samples were analyzed at ISRIC's soil laboratory according the procedures as described by van Reeuwijk (11). The comprehensive field and laboratory data were processed with the ISRIC's Soil Information System (15; 16). Soils were taxonomically classified according to FAO-Unesco (4) and USDA Soil Taxonomy (13). In addition, a micromorphological study was carried out and microchemical analyses were done making use of SEM-EDAX in order to examine the cementing agent of the talpetate. For both soils a qualitative evaluation of relevant land qualities according to the Framework for Land Evaluation (3) was realized. For soil NI010 maize cultivation, and for NI011 sugarcane cultivation were evaluated. Both crops are of great importance in the Pacific Coastal Plain of Nicaragua, the former as a subsistence crop, the latter as a cash crop (12). Important land and soil qualities, and relevant aspects of soil management were determined and potential production was calculated with the crop simulation model WOFOST (1; 10).
Results and discussion.

Field description and classification. The first soil NI010 is located near "Los Rizos", along the main road from El Crucero to Masachapa at the Pacific coast (Figure 1). It is at about 41 km from the capital Managua and at 17 km from the Pacific coast.

The topography is undulating to rolling. Slopes gradients vary from 4-16%. The parent material consists of pyroclastic deposits. The actual land use is restricted to grazing land. The natural vegetation is a grassed shrub land with scattered trees. In the past the land was used for maize, beans and tomatoes, but without good production.

The soil is a shallow, moderately well drained, dark yellowish brown to (dark) brown, silty clay loam to silt loam soil mixed in the topsoil with fresh talpetate fragments. The soil material has a weak to moderate structure and is moderately porous. Below 23 cm there is a 19 cm thick strongly cemented broken platy layer, locally called "talpetate". In the deeper subsoil, at about 70 cm depth, there is a second talpetate layer. The talpetate meets the criteria for a duripan and the soil is classified as a Haplic Phaeozem, duripan phase (4) and as an Entic Durustoll (13).

The second soil NI011 is located near the sugar mill "Ingenio Julio Buitrago" near Montelimar, at about 60 km from the capital Managua and at 2 km from the Pacific coast (Figure 1).

As part of a fluvo lacustrine plain, the topography is level to very gently sloping. Slopes have a gradient of less than 2%. The parent material is unconsolidated and has a mixed composition consisting of pyroclastic and sedimentary rocks, which have been reworked. The soil occurs in the moist transition of the Subtropical Dry Forest zone. Forests have been removed and the actual land use is medium level arable farming, with a moderate level of inputs, like fertilizers, pesticides, and mechanization. The present crop is sugar-cane, seasonally irrigated.

The soil is a deeply developed, moderately well drained, dark brown to dark reddish brown loam, mixed with fresh talpetate fragments. It is strongly to moderately structured, moderately permeable and highly porous. Below about 42 cm, a strongly cemented, discontinuous platy talpetate is found of variable thickness. In the subsoil, below the talpetate, the soil material shows evidence of high biological activity and also strong thixotropic characteristics caused by a high content of allophane. Like the first soil (NI010) this soil keys out as a Haplic Phaeozem, duripan phase (4) and as Entic Durustoll (13).

Analytical characterisation. The sand content increases for both soils at talpetate depth. However the allophane content of the talpetate is higher than the clay content so that incomplete dispersion and/or removal of clay during pretreatment must be inferred. It is clear that particle size distribution data of volcanic soils also in this case should be treated with caution (7). Below the talpetate, soil NI010 and soil NI011 present a steady increase of silt and clay content. Both soils have a low to very low bulk density, characteristic for soils derived from pyroclastic deposits.

Figure 3a and 3b present "depth versus property profiles" for three chemical properties. The organic carbon percentage, the sum of the exchangeable bases (calcium, magnesium, potassium and sodium), and the soil acidity (pH-H₂O and pH-KCl). The sum of the exchangeable bases of soil NI010 is very high although the talpetate has a distinct lower content. The topsoil has a high organic carbon content compared to the lower layers in the
profile. The organic carbon content of the topsoil of NI011 is also high. The soil is high in exchangeable bases especially in the talipetate due to the high content of calcium. Both soils are neutral to slightly alkaline.

![Graphs showing sum bases, pH-H2O, pH-KCl, and organic carbon against soil depth for NI010 and NI011.](image)

**Figure 3a and 3b** Sum bases, pH-H2O, pH-KCl and Organic Carbon against soil depth for NI010 and NI011.

![Graphs showing moisture retention curves (pF graph) for NI010 and NI011.](image)

**Figure 4a and 4b** Moisture retention curves (pF graph) for NI010 and NI011.
Figure 4a and 4b present the moisture retention curves or pF graphs. The available moisture in the topsoil of NI010 is very high (22%) due to the fine soil particles which retain water. Large pores are more frequent in the topsoil then lower in the profile but the overall porosity of the soil is high. Soil NI011 has a very high amount of available moisture (23%) in each horizon, both above as well as beneath the talpetate. Large pores are more frequent in the topsoil then lower in the profile.

Soil suitability and environment assessment. The results of the evaluation are presented in a comprehensive listing of land qualities in Table 1. The lay-out of the list is such that it directly shows the major constraints for agriculture, which are briefly discussed here.

Soil NI010 has sufficient natural fertility for moderate yields of traditional subsistence crops, like maize (2). The immediecy of a continuous hard layer at shallow depth (23 cm) limits the potential for mechanization. Damage can occur to machinery when for instance ploughing of the soil is done without taking into account the proximity of the layer. In addition, the layer restricts root penetration. Roots can only pass through fissures in the hardened layer. Therefore hardly any root is found below the layer and plants cannot benefit from nutrients and moisture available in the subsoil. For most crops the amount of water stored above the talpetate is not sufficient for high and sustainable yields (Available Water Capacity is 48 mm/23 cm soil). For cropping, irrigation is required but is difficult to acquire in view of the undulating topography, the lack of surface water and the deep groundwater level. There is a risk of erosion, especially when crops are cultivated that do not offer a good protection of the soil surface against rain impact. Also the undulating topography enhances the erosion process.

The soil lends itself to the actual low-input farming with simple tillage tools, on account of its poor rooting conditions and poor moisture availability. It is marginally suitable to high input mechanised agriculture, unless, special management practices are applied like breaking of the talpetate and irrigation. It is unlikely that at the short term these high inputs will be applied.

Potential agricultural production is somewhat reduced in comparison to soils without a talpetate. Calculations with the crop simulation model WOFOST (1; 10) showed 10% yield reduction for maize for this soil with a talpetate at 23 cm, no reduction for soils with a talpetate at 40 cm and 25% for soils which are extremely eroded and present the talpetate at 10 cm for a growing season with an average rainfall.

Soil NI011 is easy to work at all moisture conditions making use of a high degree of mechanization, which is also favoured by the flat topography. The soil as a product of reworked parent material of mixed composition, has a moderate level of natural fertility for a wide range of crops (medium CEC).

The relative shallowness of the soil due to the talpetate at a depth of 42 cm, can offer some difficulties. The layer is discontinuous and fine roots can pass by. The amount of water stored in the topsoil above the talpetate is limited (Available Water Capacity is 99 mm/42 cm soil), so crops have to make use of water stored in deeper layers. Taking into account the high water needs of sugar-cane, additional water have to be provided, mainly in the dry season in order to guarantee sustainable yields.

Potential agricultural production is somewhat reduced in comparison to comparable soils
TABLE 1 - Evaluation of land qualities of soil NI010 and NI011

<table>
<thead>
<tr>
<th>LAND QUALITY</th>
<th>Availability (1)</th>
<th>Hazard/Limitation (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>vh</td>
<td>h</td>
</tr>
<tr>
<td></td>
<td>n</td>
<td>w</td>
</tr>
</tbody>
</table>

vh = very large  
h = high  
m = moderate  
l = low  
vl = very low

n = not present  
w = weak  
m = moderate  
s = serious  
vs = very serious

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>NI010</th>
<th>NI011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation regime</td>
<td>total radiation</td>
<td>1</td>
</tr>
<tr>
<td>Temperature regime</td>
<td>day length</td>
<td>1</td>
</tr>
<tr>
<td>Climatic hazards (hailstorm, wind, frost)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Conditions for ripening</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Length growing season</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Drought hazard during growing season</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SOIL</th>
<th>NI010</th>
<th>NI011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential total soil moisture</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Oxygen availability</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Nutrient availability</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Nutrient retention capacity</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Rooting conditions</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Conditions affecting germination</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Excess of salts</td>
<td>salinity</td>
<td>2</td>
</tr>
<tr>
<td>sodicity</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Soil toxicities (e.g. high Al sat.)</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LAND MANAGEMENT</th>
<th>NI010</th>
<th>NI011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial land preparation</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Workability</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Potential for mechanization</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Accessibility</td>
<td>existing</td>
<td>1</td>
</tr>
<tr>
<td>potential</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Erosion hazard</td>
<td>wind</td>
<td>2</td>
</tr>
<tr>
<td>water</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Flood hazard</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Pests and diseases</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

512
without a talpetate. Calculations with the crop simulation model WOFOST is reduced in comparison to comparable soils without a talpetate. Sugar-cane yields decline 11% for soils with a talpetate at 42 cm, 6% for soils with a talpetate at 60 cm and 16% for soils which are more eroded and present the talpetate at 30 cm.

**Micromorphological and microchemical analyses of the talpetate.** Examination of thin sections confirms the volcanic origin of the talpetate layer of both soils (NI010 and NI011). The material is compacted and there are very few pores, except in a few restricted zones where burrowing soil fauna has disturbed the material, which may account for the discontinuity of the layer. The micromass of the talpetate layer consists of light to very light reddish yellow clay. It is optically isotropic with common inclusions of very fine crystalline minerals. Most of them have a fibrous habit (maximum length 6 μm), presumably aggregates of newly formed layer-lattice silicate clay minerals produced by weathering of the ash. X-ray diffraction analysis confirms the presence of halloysite. The larger particles (coarse silt and coarser) are identified as volcanic glass (d up to 5 mm), feldspars, pyroxenes, fragments of volcanic rock, etc. The reddish yellow colour of the isotropic micromass is the result of extremely finely divided ferric oxides/hydroxides released through weathering. High percentages of oxalate extractable aluminium and silicon (Figure 5a and 5b), and high percentages of aluminium as measured by SEM-EDAX were found. The ratio of extracted amounts of Al and Si of the talpetate is 1.2 and therefore all Si is bound by the allophane (7). It is postulated that the isotropic (=amorphous) micromass consists dominantly of allophane. This constituent is thought to be responsible for the cementation of the layer, allophane acting as a cementing agent after irreversible dehydration. This does not coincide with the findings of Prat (9) who presents data of talpetates formed in a relative allophane poor environment.

The talpetate does not meet the requirements of a duripan as defined in Soil Taxonomy (13) because silica is not the main cementing agent. This is confirmed by micromorphological study.

![Figure 5a and 5b](image-url)

Figure 5a and 5b  Acid oxalate extractable Fe, Al and Si for NI010 and NI011.
Conclusions. Rooting conditions, nutrients and moisture availability and the potential for mechanization of the soil can be negatively affected when the talpetate is continuous and at shallow soil depth. In eroded soils the talpetate may be at the surface, and the soil has no agricultural value any more. Calculations with the crop simulation model WOFOST give first estimations of the yield reductions. Breaking of the talpetate will require high inputs which are not available in the region. Evidence exist that allophane in these soils acts as a main cementing agent of the talpetate and not silica as is normally presumed.

Acknowledgements. This study has been made possible thanks to the contributions of L.P. van Reeuwijk, ISRIC's soil laboratory, O.H. Boersma (SEM-EDAX determinations), W.C.W.A. Bomer (map drawing), M. Jimenez of CATIE and J. Cortés, J. Gámez, J. Gutierrez, F. Salmerón of UNA (fieldwork).

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Federal Republic of Germany.
Indurated Horizons in Poorly Drained Volcanic Soils from Chile

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INTRODUCTION. The volcanic ash soils in Chile are spread between 34°30′ and 47°00′ S.L., from a subhumid to perhumid climate. Two main categories can be distinguished among them: those with a great amount of allophanic materials, considered as Andisols, and those very young volcanic soils, without allophanic compounds, whose properties are inherited from the parent materials.

The soils with allophanic compounds are considered as "trumaos" and "nadis", both types being the most important in the central-south part of the country. Nadi soils cover a surface of about 450,000 ha and they are concentrated from 39°00′ to 44°00′ S.L.

Nadi soils are similar to trumaos from a chemical and physical viewpoint, although their morphology is different. The presence in nadi soils of indurated horizons, locally known as "fierrillos", that create poor drainage conditions, constitute the main morphological difference. These cemented horizons form underneath the ash soil and over the glacialfluvial deposits. It may be a thin hard layer, continuous or discontinuous, composed mainly of iron oxides and organic matter. Sometimes it takes the shape of a moderately cemented ferruginous sandstone.

Following Soil Taxonomy (Soil Survey Staff, 1975 and Soil Survey Staff, 1992) the thin hard layer of iron oxides is a placic horizon and it is considered a barrier to root penetration and water infiltration. It has been observed that, after breaking by deep plowing the horizon becomes hard again after some years.

Until now several kind of "fierrillos" have been identified in the field, however their physico-chemical properties have not been determined. We consider that a precise description of these limiting horizons is very important from different points of view. First, through the description of their properties, the broadening or even the modification of the definition of placic horizon could be suggested. Second, the genetic relationships between the horizon and the volcanic ash soil may be better known and third, a more precise knowledge of its properties may increase our understanding about the drainage problems created by these limiting horizons and perhaps provide a better method for managing and improving the drainage of the soils.

MATERIALS AND METHODS. The "fierrillos" analized were sampled from fifteen nadi soils in the Region "Los Lagos" in the south of Chile. Five were selected for this study. (Figure 1).
Figure 1. Location of sampled “fierrillos” from soils in The Region "Los Lagos" in the south of Chile.
The samples selected were the following:

- Alerce soil. It corresponds to a very thin ferrugineous sandstone and the soil is an Hapludand.

- Maullín soil. It is a cemented ferrugineous sandstone and the soil is an Hapludand.

- Chepu soil. It is a thin laminar horizon, strongly cemented. The soil is a Placaquand.

- Calonje soil. Thin laminar horizon, strongly cemented; the soil is a Placaquand.

- Quilanto soil. It is a non typical "fierrillo", rock-like structure found mostly near the surface in a Typic Hapludand.

The methods used were those indicated by the USDA in Soil Survey Laboratory Methods (Soil Conservation Service, 1982).

**Physical analysis.** The following measurements were performed in triplicate:
- Color, when dry and moist.
- Bulk density.
- Resistance to penetration.
- Consistency, when dry and moist.
- Water retention at 33 and 1,500 kPa, when dry and moist.

**Chemical analysis.** The following determinations were performed:
- pH in water and 1N KCl (soil:solution ratio = 1:2,5)
- Organic carbon (Walkley-Black).
- Extractable Fe and Al using dithionite-citrate (Fe₈ - Al₈), acid oxalate (Fe₀ - Al₀) and 0.1 M sodium pyrophosphate (Fe₀ - Al₀) solutions, measured by atomic absorption espectrometry (AAE).
- Extractable Si using dithionite-citrate and acid oxalate solutions (Si₈ - Si₀), determined by AAE.
- Extractable Mn using dithionite-citrate solution (Mn₈), measured by AAE.
- Total Fe, Al and Mn using neutron activation analysis (NAA).
- Phosphate retention (Saunders).

**RESULTS AND DISCUSSION.** The morphology of the "fierrillos" is summarized in Table 1. Alerce and Maullín are cemented ferruginous sandstones; Chepu and Calonje are typical "fierrillos", i.e. cemented horizons with a tendency to a horizontal layering. These last two present two layers when moist, which disappear upon drying. There is no satisfactory explanation for this phenomenon at present.

Quilanto presents a totally different morphology, mostly similar to a rock than a genetic horizon, and its origin seems to be more likely geogenic than pedogenic. This horizon is similar to ironstone, although Quilanto breaks very easily.
Table 1. Morphology of "fierrillos" from nadi soils of Los Lagos Region.

<table>
<thead>
<tr>
<th>Property</th>
<th>Alerce</th>
<th>Maullin</th>
<th>Chepu</th>
<th>Calonje</th>
<th>Quilanto</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry color</td>
<td>Very pale brown 10YR7/4</td>
<td>Brownish yellow 10YR6/8</td>
<td>Reddish yellow 7.5YR6/8</td>
<td>Yellowish brown 10YR5/8</td>
<td>Black 2.5Y2/0 (70%) Yellow 7.5YR5/6 (30%)</td>
</tr>
<tr>
<td>Moist color</td>
<td>Strong brown 7.5YR4/6 (821)</td>
<td>Strong brown 7.5YR4/6 (601)</td>
<td>Dark reddish brown 2.5YR3/4</td>
<td>Strong brown 7.5YR4/6</td>
<td>Black 2.5Y2/0 (70%)</td>
</tr>
<tr>
<td></td>
<td>Black 5YR2.5/1 (154)</td>
<td>Red 2.5YR4/6 (301)</td>
<td>Black 5YR2.5/1</td>
<td>Black 5YR2/0</td>
<td>Reddish brown 5YR4/6 (30%)</td>
</tr>
<tr>
<td></td>
<td>Red 2.5YR4/8 (38)</td>
<td>Black 5YR2.5/1 (101)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Texture</td>
<td>Loamy sand</td>
<td>Sandy loam</td>
<td>not det.¹</td>
<td>not det.¹</td>
<td>not det.¹</td>
</tr>
<tr>
<td>Estructure Grade</td>
<td>Masive</td>
<td>Masive</td>
<td>Masive</td>
<td>Masive</td>
<td>Masive</td>
</tr>
</tbody>
</table>

¹ not determined due to strong cementation

Physical properties. Physical properties are presented in Table 2.

Table 2. Physical properties of "fierrillos" from nadi soils of Los Lagos Region.

<table>
<thead>
<tr>
<th>Property</th>
<th>Alerce</th>
<th>Maullin</th>
<th>Chepu</th>
<th>Calonje</th>
<th>Quilanto</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$ (g cm⁻³)</td>
<td>1.00</td>
<td>1.37</td>
<td>1.32</td>
<td>1.37</td>
<td>1.88</td>
</tr>
<tr>
<td>Consistency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dry moist</td>
<td>Slightly hard firm</td>
<td>Hard Very firm¹</td>
<td>Slightly hard Very firm</td>
<td>Very hard Firm</td>
<td>Extremely hard Extremely hard</td>
</tr>
<tr>
<td>Resistance to penetration (kg cm⁻²)</td>
<td>dry</td>
<td>1.1</td>
<td>3.3</td>
<td>1.9</td>
<td>&gt;5</td>
</tr>
<tr>
<td></td>
<td>moist</td>
<td>0.7</td>
<td>4.2</td>
<td>3.1</td>
<td>&gt;5</td>
</tr>
</tbody>
</table>

¹ consistency of the modules
Bulk density. Values for bulk density are comparable to those reported by Arancibia (1990) and Barros (1988) for "fierrillos" from "trumao" and "nadi" soils of Los Lagos Region, and those reported by Mella and Kühne (1985) for the "fierrillo" from Freire soil.

It could be expected that the ferrugineous sandstones presented the lowest values, because their cementation is moderate and the porous space abundant. This is in fact the case for Alerce, but Maullín presents a bulk density of 1.37 g cm$^{-3}$ which is similar to the indurated horizons, Chepu and Calonje. This relatively high bulk density could be due to fine gravas incorporated in the sandstone, making the bulk density similar to that of an indurated horizon.

Water retention. Table 3 shows the results obtained for water retention and organic carbon (OC) content.

There is a great dispersion in the figures for the different "fierrillos", even though the values found in dry and moist conditions increase as OC increases. However, some of the values have an erratic behavior. Maullín soil shows a higher water retention in the moist sample than in the dry sample, both at 33 and 1,500 kPa. This relationship is not present for all the "fierrillos". This point needs further study.

Table 3. Water retention at 33 and 1,500 kPa, dry and moist, and OC, for "fierrillos" from nadi soils of Los Lagos Region.

| "Fierrillo" | Water retention | OC
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>33 kPa</td>
<td>1,500 kPa</td>
</tr>
</tbody>
</table>
|             | dry     | moist | (%) | dry     | moist | (%) | (%)
| Alerce      | 61,6    | 64,3  | 33,2| 42,0    | 33,2  | 42,0 | 5,6 |
| Chepu       | 48,2    | 51,1  | 35,9| 44,2    | 35,9  | 44,2 | 3,6 |
| Calonje     | 39,0    | 42,7  | 23,6| 26,3    | 23,6  | 26,3 | 2,5 |
| Maullín     | 33,0    | 29,4  | 14,7| 13,9    | 14,7  | 13,9 | 1,4 |
| Quilanto    | 38,0    | no det.| 26,7| not det. | 26,7  | not det. | 1,1 |

1 insufficient sample

Chemical properties.

Organic carbon. Organic carbon (OC) content is relatively high for these horizons, considering they are subsurface cemented horizons. Those "fierrillos" located in a position of low terraces such as Alerce and Chepu present a greater OC. It may be postulated that there is an association between water content of the soil and OC.
Arancibia (1990) reported 3.0 % in "fierrillos" from Chiloé Island and Barros (1988) 3.1 % in "fierrillos" from soils near the city of Puerto Montt (41°25' S.L.).

Iron and aluminum. Iron is the most abundant element in the indurated horizons analyzed (Table 4).

Table 4. Total and extractable iron in "fierrillos" from ñadi soils from "Los Lagos" Region.

<table>
<thead>
<tr>
<th>&quot;Fierrillo&quot;</th>
<th>Fe&lt;sub&gt;t&lt;/sub&gt;</th>
<th>Fe&lt;sub&gt;d&lt;/sub&gt;</th>
<th>Fe&lt;sub&gt;o&lt;/sub&gt;</th>
<th>Fe&lt;sub&gt;p&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alerce</td>
<td>8.6</td>
<td>4.2</td>
<td>2.3</td>
<td>0.17</td>
</tr>
<tr>
<td>Maullin</td>
<td>8.6</td>
<td>4.7</td>
<td>5.2</td>
<td>0.05</td>
</tr>
<tr>
<td>Chepu</td>
<td>20.0</td>
<td>17.7</td>
<td>12.1</td>
<td>1.70</td>
</tr>
<tr>
<td>Calonje</td>
<td>24.1</td>
<td>16.4</td>
<td>9.1</td>
<td>0.51</td>
</tr>
<tr>
<td>Quilanto</td>
<td>39.5</td>
<td>29.0</td>
<td>8.6</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Alerce and Maullin, ferrugineous sandstones, present similar Fe<sub>t</sub> and Fe<sub>d</sub> and much lower than the indurated horizons. The indurated horizons themselves also present similar values. Quilanto with a different morphology presents very high Fe<sub>t</sub> and Fe<sub>d</sub> values.

We may assume that the Fe<sub>t</sub> and Fe<sub>d</sub> are the fractions responsible for the high degree of cementation considering that dithionite-citrate solution solubilizes most of the Fe present in the sample.

Mella and Kühne (1985) measured Fe<sub>d</sub> for "fierrillos" Alerce, Frutillar and Freire and they found it to be 2.4; 4.5 and 2.8% respectively. These values are slightly low if we consider these are "fierrillos" belonging to highly developed ñadi soils. The dispersion in the values could be due to the variability in composition of the parental materials and different local microenvironments even though pedogenically they originate from similar processes.

On the contrary there is no such clear association between Fe<sub>o</sub> and physical properties. Ferrugineous sandstones (Alerce and Maullín) also have less Fe<sub>o</sub> than cemented "fierrillos" (Chepu and Calonje) and Quilanto. Arancibia (1990) found 7.55 and 3.44% Fe<sub>o</sub> for "fierrillos" Queilén and Coipomó. Barros (1988) reports 9.7% for Tepual. The values found in this study agree with the values just mentioned.

Fe<sub>p</sub> which represents Fe complexed to organic matter is low for all "fierrillos" studied, except Chepu. There are very few values in the literature for this Fe fraction. Fe<sub>p</sub> does not present any correlation with OC.
Table 5 shows the results for total Al($\text{Al}_t$) and for extractable Al fractions.

Table 5. Total and extractable aluminum in "fierrillos" from "Los Lagos" Region.

<table>
<thead>
<tr>
<th>&quot;Fierrillo&quot;</th>
<th>$\text{Al}_t$</th>
<th>$\text{Al}_d$</th>
<th>$\text{Al}_o$</th>
<th>$\text{Al}_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alerce</td>
<td>13.2</td>
<td>1.6</td>
<td>7.2</td>
<td>1.10</td>
</tr>
<tr>
<td>Maullín</td>
<td>11.8</td>
<td>1.4</td>
<td>2.3</td>
<td>0.33</td>
</tr>
<tr>
<td>Chepu</td>
<td>7.2</td>
<td>2.5</td>
<td>1.8</td>
<td>1.10</td>
</tr>
<tr>
<td>Calonje</td>
<td>7.9</td>
<td>3.8</td>
<td>1.4</td>
<td>0.38</td>
</tr>
<tr>
<td>Quilanto</td>
<td>3.5</td>
<td>2.5</td>
<td>0.8</td>
<td>0.16</td>
</tr>
</tbody>
</table>

As opposed to Fe, Al$_t$ is higher for the ferrugineous sandstones (Alerce and Maullín) than for the indurated horizons (Chepu and Calonje). Quilanto contains less Al$_t$ than the other "fierrillos".

Al$_d$ is very similar for all "fierrillos" although the two sandstones (Alerce and Chepu) present lower values than the indurated horizons (Chepu and Calonje) and Quilanto. It may be possible that Al$_d$ accounts for the cementation of the horizons although weaker than in the case of Fe$_d$.

On the other hand, there is no association between horizon morphology and Al$_o$. The indurated horizons, Chepu and Calonje, present very similar values, while Alerce presents a comparatively high value for which there is no clear explanation.

Arancibia (1990) reported 3.18 and 2.76% Al for "fierrillos" Queilén and Coipomó. Barros (1988) reports 2.51% for Tepual. All these are indurated horizons.

The results reported by the mentioned authors and the ones presented in this study would indicate that there is no relationship between morphology of the "fierrillos" and Al$_o$.

In the same way as Fe, there is no association between Al$_d$ and horizon morphology, probably due to the great variability shown by organic compounds and its complexes with Fe and Al.

Manganese and Silicium. Table 6 presents the results obtained for total Mn ($\text{Mn}_t$) and for the corresponding extractable fractions of Mn and Si in dithionite-citrate and acid oxalate solutions ($\text{Mn}_d$, $\text{Si}_d$ and $\text{Mn}_o$).

Manganese is an important component in Quilanto, where $\text{Mn}_t$ is 5.40%. Of this value, 83% is extractable in dithionite-citrate solution. McKeague et al (1968) found average $\text{Mn}_d$ values of 2.9%
for placic horizons of Spodosols of Canada. On the other hand,

Table 6. Total manganese and extractable manganese and silicium in "fierrillos" from nadi soils from Los Lagos Region.

<table>
<thead>
<tr>
<th>&quot;Fierrillo&quot;</th>
<th>Mn total</th>
<th>Mn_d</th>
<th>Si_d</th>
<th>Si_o</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alerce</td>
<td>0.05</td>
<td>0.003</td>
<td>0.12</td>
<td>3.40</td>
</tr>
<tr>
<td>Maullin</td>
<td>0.07</td>
<td>0.009</td>
<td>0.21</td>
<td>1.40</td>
</tr>
<tr>
<td>Chepu</td>
<td>0.02</td>
<td>0.006</td>
<td>0.16</td>
<td>0.12</td>
</tr>
<tr>
<td>Calonje</td>
<td>0.06</td>
<td>0.018</td>
<td>0.20</td>
<td>0.25</td>
</tr>
<tr>
<td>Quilanto</td>
<td>5.40</td>
<td>4.50</td>
<td>1.49</td>
<td>0.57</td>
</tr>
</tbody>
</table>

placic horizons of Spodosols of Germany and New Zeland present values less than 0.2%. (Avery et al, 1977). Rutherford and Taylor (1981) have reported Mn_d values less than 0.1% for placic horizons in Great Britain.

Si_d is very low and similar for all the "fierrillos" analyzed, except Quilanto; Si_o is important in the sandstones with values of 3.4% for Alerce and 1.4% for Maullin. It appears, therefore, that there is some relationship between horizon morphology and Si_o, indicating that Si does not influence cementation in the "fierrillos" studied.

Iron and Aluminum associated with different soil fractions. Based on the associations proposed by Sadzawka (1984), Fe and Al extracted fractions were assumed to be part of various soil fractions (Figures 2 and 3).

All Fe fractions are lower for the ferrugineous sandstones (Alerce and Maullin) than for the indurated horizons (Chepu and Calonje). Crystalline Fe is very high in Quilanto. This value is probably due to its special and different morphology.

The ferrugineous sandstones present lower values for non-crystalline Fe than the indurated "fierrillos" and Quilanto. Humus fraction is very low for the sandstones and higher for the indurated horizons. Quilanto also presents a very low value. Crystalline Fe presents variable values.

Figure 2 shows that non-crystalline iron is important in the indurated "fierrillos", but crystalline Fe is also present in appreciable quantities. It is difficult to conclude which is the main fraction involved in the cementation of these horizons. For Quilanto it may be safe to assume that crystalline Fe is the main cementing agent.

These results agree with those of Barros (1988) in nadi soils, who found that non-crystalline Fe in these soils is very low in the
Figure 2. Iron fractions in "fierrillos" from ñadi soils in Chile.
Figure 3. Aluminum fractions in "fierrillos" from ñadi soils in Chile.
surface horizons and increases with depth up to 9.7%. Fe humus in turn decreases as depth increases.

The ratio FeO/Fe in the "fierrillos" analyzed range from 0.30 to 1.11. According to Schwertmann (1993) this ratio is 100 times higher when the dominant Fe mineral is ferrihydrite instead of goethite. In concretions from gley soils in Holland he found a ratio of 0.7 for soils in which the dominant mineral was ferrihydrite, and a ratio of 0.07 when the dominant mineral was goethite.

Our results lead to the conclusion that in some "fierrillos" ferrihydrite is the dominant Fe mineral (Chepu and Maullin) and in the others ferrihydrite is a co-dominant mineral.

According to our experience and the data already discussed the ferruginous sandstones should be considered as pre-placic horizons which by a continuos accumulation of Fe oxides, mainly ferrihydrite would become in time true placic horizons.

The values for Al fractions (Figure 3) are lower than those for Fe using the same extracting solutions. Al associated with allophane and imogolite is higher in the sandstones (Alerce and Maullin) than in the indurated "fierrillos" (Chepu and Calonje) and Quilanto. There is no association between morphology and the allophane and humus Al fractions.

These values are quite lower than those reported for placic horizons in Spodosols, which is certainly due to the differences in parental materials. The data shown here lead to conclude that Al is not an important cementing agent in the "fierrillos" analyzed.

LITERATURE CITED.


The Tepetates of the Central Mexican Highlands: Prehispanic and Modern Impact of Agriculture and Water Management

M. Aliphat Fernández and G. Werner. GEAC, México D.F., México; Justus Liebig Universität, D-35390 Giessen, Germany.

Abstract

Soil erosion exposing tepetate hardpan soils is a serious problem in the Central Mexican Highlands. Soil scientists agree that the erosion has been caused by human impact on the landscape. However, there is no clear agreement regarding to which period of human occupation the erosion can be attributed. The extent of the erosion problem suggests an early initiation of this process. This paper presents evidences that the erosion in the Central Mexican Highlands may have begun at a later date than previously reported, and that it was a much more accelerated process.

1. Introduction

Exposed Tepetate soils are a prominent feature on the landscape in the Central Mexican Highlands. The objective of this paper is to examine some of the evidences which link tepetate soils with past human agricultural pursuits. First, the paper discusses the origins and features of this peculiar soil condition, the cultural history of the region and then provides material for the understanding of the environmental and demographic context of Prehispanic agricultural activities in the area. It is paid attention to water and slope management techniques which would have maximized soil protection and agricultural yields. It is proposed, that the deterioration of these systems followed the European Conquest and, together with the introduction of small livestock, marks the beginning of a great episode of soil erosion and exposure of tepetate layers.

2. Framework

Based on results of mapping in the Central Mexican Highlands which has been undertaken over the past few years (WERNER 1988 a; WERNER et al. 1978), it can be said that 20 % of the total mapped surface is irreversibly damaged by soil erosion. That is to say, the sub-horizons on ancient volcanic ash soils are now exposed because of erosion, and have formed hardened layers (hardpans) (Fragipans/Duripans). These layers are called "tepetates", from the Nahuatl words "tetl", or stone and "petate", or mat. At present, these surfaces are unsuitable for agriculture or reforestation.

Tepetates are found at altitudes of less than 2,750 m a.s.l., with rainfall of between 450 and 900 mm/annum, specific conditions which relate to the content and solubility with the rainwater of silica, which is liberated from the volcanic glasses and phytoliths of these soils during its development. Tepetates are also found in agricultural regions with a slope of more than 5 %. However, these hardened volcanic soils are rarely found in areas under forest cover.

Under such climate conditions, sub-horizons of volcanic sediments which are rich in silica develop. These horizons are coming to the surface owing to erosion of the upper layer due to agricultural activities, that means the actions of man against his natural environment. Once exposed, these horizons harden.

While undertaking the mapping work in the Central Mexican Highlands a great quantity of obsidian (volcanic glass) artefacts and ceramic sherds was found on the top of tepetate surface. The following hypothesis developed from the observation: Prehispanic populations had inhabited the zones now
characterized by tepetate soils. To test this hypothesis, a map of eroded and tepetate soil areas was prepared and compared with a map of Prehispanic settlements drawn by GARCIA COOK in 1976 (WERNER, 1986).

The result of this comparison was the observation of a high correlation between the areas of eroded soils and the location of human settlements from the Prehispanic period. As well, based on evidence from the field, the following general observations can be made: first the ceramic sherds are found on the top of the tepetate surface. Second, generally the sherds are found in the Holocene or Colluvium layer, at a depth of between 0-30 cm. They are found on top of this layer above Horizon B of a Chromic or Vertic Cambisol. Third, ceramic materials are found in the Fluvisols and Colluvisols in agricultural regions, but rarely in areas under forest. Sherds are never found in Horizon B of the existing Chromic or Vertic Cambisols, and are never found in horizons or tepetate subsoils exposed to the surface.

The presence of sherds and obsidian materials testifies a Prehispanic population when the artefacts are found on non eroded surfaces (complete soil profiles), or when they are found on tepetate surfaces which were already exposed in Prehispanic times, and on soils which are eroded due to agriculture. In the latter case, the horizons which have existed above the tepetate have been eroded and transported by rainfall and runoff, leaving heavy matter such as stones, ceramic sherds and obsidian fragments on the surface.

Based on these observations a second causal hypothesis was proposed: The agricultural practices of Prehispanic populations caused the erosion of the surface soils (WERNER, 1986). Thus, the erosion would be attributed to human actions in the period preceding the arrival of the Europeans. It is the goal of this paper to examine some of the evidence available to test the possible causal relationship. Data from two time periods are considered: first, the agricultural techniques of Prehispanic population in relation to soils and erosion are discussed. Second, agricultural activities in the Tlaxcala zone during the intervening colonial period are examined with emphasize on the impact of European contact on the Central Mexican Highlands.

3. Cultural History of the Study Area

3.1. Prehispanic Period

The Texcoco region is located on the eastern shore of the now dessicated lake of Texcoco (Fig. 1). It is bounded to the north by the Papalotla River, up to the Patlachique Range which separates this area from the neighbouring Teotihuacan Region. The Sierra Nevada serves as a topographic division between the Texcoco region in the Basin of Mexico and the Puebla-Tlaxcala Valley to the east. The Cerro Tlaloc, a northeasterly mountain of the Sierra Nevada is the most important elevation at this point (4250 m a.s.l.). The Ixtapalapa peninsula serves as the southern limit of the area. This peninsula separated the freshwater lakes of Chalco and Xochimilco from the saline Texcoco Lake in the past. The ancient shore of the lake at an elevation of 2235 m a.s.l., was the western boundary of the region. The area was irrigated at regular intervals by the Papalotla, Coxcacuaca, Texcoco, Chapingo, Santa Monica, San Bernardino and Coatepec rivers, and in ancient times comprised seven major ecological zones: 1) Lacustrine; 2) Saline Lakeshore; 3) Deep soil alluvium; 4) Lower piedmont (2230 - 2350 m a.s.l.); 5) Middle piedmont (2500 - 2750 m a.s.l.) and Sierra (>2750 m a.s.l.)(SANDERS, 1976). Ancient Texcoco was centrally located on a wide pocket of deep soil alluvium, thus controlling these well drained and fertile soils, as well as the moderately fertile soils of the lower and middle piedmont (sandy loams) (SANDERS et al.,1979).

The first stage of human adaptation to the region is represented by the Paleoindian Culture, represented by hunters of extinct megafauna (35,000 - 8,000 years B.P.). A second stage, is from (ca. 6,000 - 900 B.C.). It is expressed as an ecologically and demographically stable period in which maize agriculture was probably adjunct to a basic hunting and gathering economy. Stage III (900 - 100 B.C.)
is a period of rapid population growth and the colonization of the basin by a food producing and ceramic manufacturing population. Settlements are located on the lower edge of the lower piedmont, just above the alluvial plain, with easy access to the lake shore, deep alluvial soils and the piedmont. The most important pioneer populations were located in hamlets in the area of the Rio Papalotla. Between 700 - 300 B.C., the agricultural population of the Teotihuacan and Tecxoco regions became well established, and by the turn of the Christian Era they had become the major focal populations in the Central Highlands of Mexico.

The population densities of this period are surprisingly high, which implies several things. There is the appearance of, first, highly productive maize varieties (Toluque or -type) and, second, intensive agriculture practices as terracing of sloping landscapes and floodwater irrigation. The close spacing of communities indicates this intensive and probably continuous cultivation of the land (SANDERS 1981).

Figure 1. The Central mexican highlands (Sanders, 1981).
Clima y evolución de la densidad y de los tipos de sitios prehispánicos en Tlaxcala.

Legenda:
- Columnas 1-T: Fases culturales (seg. A. GARCIA COOK).
- Ext. vertical: densidad media de sitios por 100 km² (seg. datos de R. ABASCAL).
- Ext. horizontal: duración de las respectivas fases culturales.
- • Sitios con terraza habitacional y de cultivo.
- O Sitios con terraza para cultivo.
- * Sitios con control de agua (canales).
- x Sitios de depósitos para agua y sistemas de cultivo intensivo (chinampas, cemelones).


Figure 2. Climate and prehispanic settlements in Tlaxcala (Lauer, 1979).
Stage IV (100 B.C. - A.D. 1350) shows the emergence and establishment of great urban centres, as a reflection of previously unprecedented process of nucleation and partial decline of the "rural" populations. Teotihuacan shines as the great urban settlement of Mesoamerica with as many as 200,000 inhabitants. From A.D. 750 - 1350, following the abandonment of Teotihuacan, the Texcoco region presents a dispersed settlement pattern (in hamlets) with two regional centres: Huexotla and Coatlinchan.

Stage V (A.D. 1350 - 1519) is the final Preshispanic Period. During this stage we have the climax of ancient human occupation of the valley in terms of population size and density, intensity of land use, urban and political evolution and remodelling of the landscape. The Mexica culture of Tenochtitlan and the Acolhua culture of Texcoco become the paramount powers of the Central Mexican Highlands. Tenochtitlan maintains a core population of 150,000 to 200,000 inhabitants, and Texcoco approximately 30,000. The basin as a whole probably supported 800,000 to 1,200,000 inhabitants. All ecological areas which could support human populations are occupied: upper piedmont, great expansions of the alluvial plains, the swamps of the southern lakes with chinampa agriculture, and the Milpa Alta area of the upper piedmont (SANDERS, 1976; SANDERS et al., 1979; SANDERS, 1981).

Similar processes were at work in Tlaxcala (Fig.2), where hamlet life is established by agriculturists during the Tzompantepec Phase (1600 - 1200 B.C.). Nineteen hamlets of 10 to 25 residences in linear arrangements have been reported; characteristically as houses located on domestic terraces close to agricultural lands. In the Tlatempa Phase (1200 - 800 B.C.), large villages emerge (150 settlements are reported for the region, 100 of which are located in the Tlaxcala State, the majority of which are hamlets). Habitational and large agricultural terraces are constructed, and faced with cut tepetate. Sites average 80 residences, with the largest village containing 200 dwellings (GARCÍA COOK, 1981).

During the Texcolotzoc Phase (800-400/300 B.C.), the first proper towns emerge (five have been discovered). Great advances in irrigation technology led to sharp increases in agricultural production. Terraces become larger than those of earlier phases, with sloping or vertical walls entirely lined with cut tepetate. Sites such as Tlalancaleca can be considered as well as planned towns or small cities (GARCÍA COOK, 1981).

Based on the developments of previous phases, the Tezoquipan Phase (400/300 B.C. - A.D. 100) shows an impressive increment in population, now settled in rural hamlets and in about 20 towns and cities. There appears to be an early development of the "Classic" features, such as permanent agriculture, chinampas, irrigation, terraces, active commerce, hamlets built around ceremonial centres, urban zones related to the establishment of Teotihuacan and Cholula (GARCÍA COOK, 1985).

The Tenayecac Phase (A.D. 100 - 650) reflects the urban pull generated by the bipolar forces of Teotihuacan and Cholula, which has a profound effect in the Tlaxcala region in the form of a "ruralisation" of the population and an distinct evolution of local "cazicazgos" is evidenced. The Teotihuacan and Cholula spheres are connected by a "corridor" which runs from the northern area of Tlaxcala around the base of the Malinche volcano toward Cholula and beyond. Thus while suffering the hegemony of Teotihuacan, there was a certain participation of the region of Tlaxcala (GARCÍA COOK, 1978; 1985).

The demise of Cholula which must have had a great impact on the Teotihuacan metropolis, marks the beginning of the Texcalac Phase (A.D. 650 - 1100) in Tlaxcala, and the establishment of the Olmeca-Xicalanga polity at Cacaxtla. Subsequently, the arrival of the Teochichimecas sets the stage for the Tlaxcala Phase (A.D. 100 - 1519), in which this Nahua speakers set up political centres or "señorios" at Tepetecpaz, Ocotelulco, Tizatlan and Quiahuixtlan, as well as Tepeyanco, Atlhuetzla, Hueyotlipan, Tecoco, Tzompanzino, Xaltocan, Chiahuhtempan, Huiloapan and others forming a regional unity which remained independent from, albeit in conflict with, the Colhua Mexica / Alcolhua Empire which we know as Aztec Empire (GIBSON, 1952).
3.2. Prehispanic Water and Slope Management

Water management is defined as a deliberate system which results from significant human intervention on the landscape. Traditional agriculture in Middle America is characterized by a high input of human labour in the construction of irrigation systems in ancient and present times (WILKEN, 1987:148). The ancient farmers of Mesoamerica have left ample evidence in the archaeological record of their waterworks which include dams and canal irrigation systems, diverting of rivers, among other projects. Two such very important features from very early periods are the Teopantecuanitlan site dam on the Amacuzac and Mezcala Rivers in Guerrero State (ca. 1200 - 100 B.C.) (MARTINEZ DONJUAN 186:64) and the Massive Purron Dam in the Tehuacan Valley, Puebla State, built in four successive phases (ca. 700 B.C. - A.D. 250) (GARCIA COOK, 1985:31). Remains of canal irrigation systems have been found in Amazoc site in the Puebla Valley (ca. 750 B.C. - A.D. 750) (PRECOURT, 1983). Small reservoirs associated with terraced fields are first reported for Tlaxcala in the period ca. 800 - 300 B.C. In the Oaxaca Valley, the Xoxocotlan dam system, located below the site of Monte Albán, functioned from 550 - 150 B.C. (O'BRIEN et al., 1982:22).

In the early Classic Period there is evidence of water management systems in the sites of Cuicuilco, Texcoco (Amanalco), Teotihuacan (Cerro Gordo, Otumba, Tlajinga) in the Basin of Mexico, among many others (SANDERS, 1976; CHARLTON, 1977). In Puebla during this period there is evidence of a canal system in Amalucan as well as a relict canal system in Chilac in Tehuacan (GARCIA COOK, 1985).

During the Classic Period, evidence has been found of river and stream relocation and dam construction in Teotihuacan (ARMILLAS et al., 1956; SANDERS, 1981:130). The low lands of Teotihuacan region as well as the northwestern shore of Lake Xaltoca and Lake Texcoco are under floodwater and permanent irrigation agriculture as the principal food producing regions for the urban centre of Teotihuacan. The Puebla-Tlaxcala Valley witnesses an extension of agriculture in low lands in the form of camellones (chinampa type agriculture). Also, there is a cultivation of slopes of the piedmont through canal irrigation systems associated with terraces. At this time, there is evidence of strong competition between the Teotihuacan enclaves (the "Teotihuacan Corridor") and the local polities of the Bloque Nativitas and Bloque Tlaxcala to control agricultural lands, both seasonally rainfed and irrigated. During the Tezozooman phase slope and water management are well established. After GARCIA COOK (1985: 49; (translation by authors)): "The systems and agricultural techniques reach a climax. All forms of plant cultivation as well as forms of water control and distribution are known".

The last stage of Prehispanic period witnesses massive state directed waterworks and water control systems. In the Basin of Mexico there is generalized intensive agriculture on the entire landscape of a giant scale (SANDERS, 1981:192). The same can be said for the Puebla-Tlaxcala Valley where fertile lands were under intensive cultivation (GARCIA COOK, 1985:56-58), as well as for the Central Mexican Highlands as a whole.

The process of intensification of agriculture is a necessary measure to support the high population of the region in Prehispanic times. Estimates for the Basin of Mexico in the period immediately preceding the arrival of the Spanish range between 800,000 and 1,200,000 inhabitants (SANDERS, 1981:190), and over 10 million for the whole Central Mexican Highlands (BORAH 1989:217).

Agricultural intensification implies a maximization of slope management in a shift from extensive systems of sloping terraces (gradient heavily modified) to intensive systems of flat (bench) terraces in which the sloping hillside are radically modified to become level fields (WILKEN, 1987:13). The earthworks require massive labour input in the construction and maintenance of these systems. The vertical walls of the terraces must be constructed at the same time as the terrace is fashioned out of the hillside in order to maintain control over the slope and establish the proper base/top/height proportions during the design and building (WILKEN, 1987:120). Therefore, these intensive systems are not a product of accumulated effort. In addition, the artificial modification of hill slope to this degree requires costly maintenance in order to guarantee the stability of the system. According to WILKEN...
Maximizing terrace-bed space requires that rises be as steep as possible and, consequently, highly susceptible to degradation. Due to the formal architecture and design of these systems, they represent as a whole, an interlocking network of interdependent elements.

LAUER (1979) has undertaken an important study of environmental and cultural evolution of the Puebla-Tlaxcala Valley (Fig. 2). In his opinion, soil erosion in Prehispanic times is confirmed in the observation of Gullies Barrancas during two periods of the local archaeological sequence: Phase IV Tezoquipan (2000 yrs B.P.) and Phase VI Texcoloc (100 yrs. B.P.). These events correlate with expansion of the human settlements and the accumulation of human impact on the landscape of previous phases (Fig. 2). An important aspect of these two erosion events is that they occurred under distinct climatic conditions and they both represent a rapid degradation of the soils with the formation of exposed tepetate horizons (LAUER, 1979:46). The work of LAUER follows the previous work of COOK (1949) which correlates the extension of erosion process observed today on the landscape of the Central Mexican Highlands with processes triggered primarily during the Prehispanic period. This is based upon the calculation of the length of period of erosion, according to the amount of alluvial and slope-wash deposition. In this case the deposition is enormous, indicating a long period of erosion (COOK, 1949:86; HEINE, 1978).

3.3. Hispanic Colonial Management and its effects on Soil Erosion

3.3.1. Population and Agriculture

These authors do not consider other variables which must be considered before the causal relationship between erosion and activities of Prehispanic populations can be accepted.

There is an overall agreement among specialists that the Central Mexican Highlands were densely populated by A.D. 1519. The historical sources provide population figures in millions (over 11 million in 1519 according to COOK and SIMPSON, 1948) (Fig. 3). European contact causes a catastrophic drop in the native population, reaching a low of 1,500,000 by A.D. 1650, according to these authors. That is, the area experiences a demographic drop of 90% in the first 150 years of European contact, of which 60% of the population are lost in the first 80 years of Spanish presence on the continent. This depopulation is caused by a combination of factors, including cyclical epidemics of Old World diseases and deterioration of the indigenous economy related to the hardship of colonial regime.

![Figure 3. Population demographics in Central Mexico (Borah, 1989).](image-url)
In the Puebla-Tlaxcala Region, this population drop can be detected in a sharp decline in the number of maize related pollen in the palynological record found in cores taken from the Acuitlapilco Lake (OHNGEMACH and STRAKA, 1978: Figures 7 and 8). This is clear evidence in the almost complete abandonment of maize agriculture after A.D. 1520, which would be related to the catastrophic depopulation of the region.

The depopulation had direct implications on the landscape. The intensive agricultural systems described above are abandoned, leading to their rapid deterioration. Vacant lands, called "baldíos" proliferated, and became available for new economic activities based, primarily, on the introduction of small livestock, which grazed on the native grasses. By 1600, sheep covered the landscape (MELVILLE, 1983:50). Figure 4 illustrates the sharp increase in the number of sheep which accompanies the drop in the human population of this region.

![Graph](image)

**Escala en:**
- miles de blancos
- decenas de miles de bovinos
- centenas de miles de indígenas
- centenas de miles de ovinos

(1 blanco = 10 bovinos = 100 indígenas = 100 ovinos o caprinos)

Fig. 4. The take-over of the Central Mexican highlands by the pastoralist economy (Borah, 1989).

Of course, the decline of the native population brought about a sharp contraction in the native economy. Consequently, the agricultural population is increasingly found farming the low lands, at a lower labor cost than that associated with hill slope management and cultivation. Abandonment of the agricultural terrace systems and waterworks triggered a series of devastating events. In the absence of maintenance, a domino effect was unleashed on the hillsides, in which the deterioration of one element of the system, led to the destruction through erosion of entire systems, leading to the exposed tepetate situation of present day.

The policy of the colonial government of the early years was to grant lands to Spaniards in the newly conquered provinces. These were lands recently abandoned by the declining native population. In most cases, these were granted as "mercedes" for grazing and livestock. The Indian elite also participated in this process as a means of appropriating lands of the Indian communities for themselves, in direct competition with the land-grabbing activities of the Spanish (GIBSON, 1952; 1967:268; MELVILLE, 1983; BORAH, 1989).
In Tlaxcala, the major part of this new grazing economy was based on sheep and goat herding in the early years of the Spanish period. TRAUTMANN calculates a proportion of 67% sheep to 16% goats, the rest being bovine and porcine production (TRAUTMANN, 1981:175). The number of goats declined at the end of the XVI Century (TRAUTMANN, 1981). The early Spanish period also sees the expansion of pastoralist economy in Central Mexico. High stocking rates and increasing numbers of flocks over a very short time period, lead to the “saturation” of the ability of native pastures, in terms of grazing (MELVILLE, 1982:178). In some areas, 80-90% of the total surface area had been converted to pastoralism by this time (MELVILLE 1983:182). In Tlaxcala, it is reported that, by 1542, the Indians owned 300,000 head of sheep in an area of 6 square leagues which is a proportion so great that GIBSON, who was studying the documentation, felt that it was an error and should have read 30,000 (GIBSON, 1952). The latter number would render a total of 286 sheep/km² or a medium grazing rate for the period, according to MELVILLE, (1983).

The negative impact of overgrazing due to pastoralist activities in the XVI century cannot be overemphasized. Overgrazing in combination with the abandonment of intensive agricultural systems, due to the decline of the Indian population, triggered a negative feedback situation which precipitated radical environmental degradation in a period of fewer than 100 years. In addition, the Spanish presence caused a reorientation in urban settlement and economic demands. Their demand of charcoal for fuel in mining activities and in the cities, led to forest exploitation, which only worsened the situation on the natural landscape. Deforestation, denudation on soils, permanency of abandoned croplands and previously terraced hillsides to pasturelands, all underlie the degradation of the environment. Even the flora of the region was modified, as overgrazing produced the replacemement of the native grasses with thorny species, such as Agave spp., Yucca spp., Opuntia spp., Prosopis spp., Cynaria cardunculus, etc. These are the wild species most prominent in the area today.

The introduction of European crops also brought about an impact on the forests, with the possibility of cultivating introduced grains (GIBSON, 1967:311). This led to deforestation and related erosion processes. The acceleration of the processes of erosion is first mentioned by TORQUEMADA at the beginning of the XVII Century. This author mentioned that by this time, land previously devoted to agriculture had lost their topsoils exposing the tepetates (GIBSON, 1967:311; TORQUEMADA, 1975, III:424).

The process of soil erosion which was unleashed during this period is referred to as “extensive soil erosion” leading to the exposure of the hardpan layer of tepetates and gullying. The sheet erosion and gully or barranca formation have been mentioned in the literature (COOK, 1949). Nevertheless, the degree of deterioration of the landscape in the XVI Century due to European contact is seldom mentioned (MELVILLE, 1983). The present landscape in the Central Mexican Highlands, however, is directly related to the first years of the Spanish colonial system (XVI C), during which time they imposed a new agricultural regime upon the land. After GIBSON: “...great extensions of tepetate, feature so common on the landscape on the modern valley (of Mexico) were exposed very much before the end of the colonial period” (GIBSON, 1967:312, translation by the authors) and he gives a description of the damages caused by roving cattle especially in the months of August and September before harvest in the fields of the Indian small farmers (GIBSON, 1967). The real rates of erosion since the Spanish conquest have been poorly reported. However, a study by KIRKBY (1972) reveals the catastrophic dimension of the problem. He reports that the area of the Nochixtlan Valley in Oaxaca suffered from one of the highest rates of erosion in the world: 10 mm/yr for 500 yrs on a drainage area of 0,4 km² (KIRKBY, 1972:34).

3.3.2. The Colonial Road System and its Effects on the Landscape of Today

During his investigations in Tlaxcala, TRAUTMANN (1981) discovered remarkable correlations between the roads and the geomorphical and quaternary geological properties of the Tlaxcala landscape. It is evident that the barrancas which proceed radially down the volcano slopes and which
were cut into the old volcanic ashes (toba-sediments) had been sprung from the old hacienda roads which connected the upper parts of the fields with the haciendas.

The soil development in the toba-sediments, especially the morphogenesis of the tepetate is the reason for the intensive erosion at both sides of the Caminos Reales as far as they had been laid out in the toba-sediments. Because of the enrichment of silica the tepetate sometimes facilitated the construction of durable roads. The column polyedric aggregates of the tepetate which were abraded by the wheels of the carriages or by the steps of the draught animals collected the rain and thus deepened the track rills in every rainy season. This is one of the reasons of the beginning gully erosion which normally lead down to the next fossil soil and its respective tepetate so that during a few decades the roads were deepened for several meters. Still today the hardened subsoil of these roads gives the basis on which the precipitations flow off on the surface. These wounds in the landscape have always been exposed to erosion and enlarge every rainy season. Roads which are more than 40 meters wide like the above mentioned Caminos Reales are not very seldom.

3.3.3. Impacts of Forest Destruction and Agriculture

In the middle of the XVI century vast parts of the forests were needed as timber or firewood for the limekilns owing to the construction of the numerous monasteries and colonial cities. But the climax of forest destruction of this period is in the XVII century. The reasons are the foundation of the haciendas which extended their fields and pastures at the cost of the forests and forced the Indian population into the forests. Besides by the loss of land the indigenous population was forced to make their living by producing charcoal, selling firewood and resin (copal). Vague legal positions concerning the use of the forests encouraged the destructive lumbering. TRAUTMANN (1981) comes to the conclusion that the destruction of the forests advanced so rapidly that the lower forest limit of the Malinche volcano even in that time corresponded with the altitude of today. As a proof he mentioned that the oak varieties of this region had already been destructed at the end of the XVI century by charcoaling.

There are hardly any exact documents about the regions covered with forests at the time of the Spanish conquest. After OHNGEMACH & STRAKA (1978:193) pollen profiles taken from Acuitlapilco Lake which are dated between A.D. 1330 and A.D. 1650 show a 40% portion of Quercus. This fact allows the conclusion that this part of the Puebla-Tlaxcala region was covered with forests in which oak trees dominated. In the upper part of the pollen diagram the rate of Quercus is continuously surpassed by Alnus. Finally it is completely replaced in the last century by non-tree pollen among which maize dominates with 10-30%.

The extinction of the tree pollen is explained by a change of land use. An additional explanation is the amount of accumulated sedimentation of 500 cm at the lake bottom in only 400 - 500 years. This is due to forest destruction in the upper and middle slopes of the volcanoes and the following erosion. Because of the forest destruction considerable quantities of loose volcanic ashes are transported by the erosion down to the pediments of the volcano slopes as well as into the basins. It is reported that up to recent times the inhabitants in the villages on the pediments of the volcanoes have had great problems with the periodical sedimentations which they tried to stop with dams on both sides of the barranca mouths. But even nowadays, after heavy rainstorms it sometimes happens that these dams break and the sediments pour around on the fields covering the seeds with sand and gravel (WILKEN, 1987; WERNER, 1988a).

3.4. Post Colonial and Modern Impact

In colonial times the haciendas used their forests to provide themselves with timber, firewood and charcoal. Some haciendas sold more wood than maize (Trautmann 1981). Besides the forests served as pastures for the cattle of the Indian villages and the haciendas. During the XIX century the industrialization of the Puebla-Tlaxcala region based on steam engines demanded an increased need of
firewood. When in the second part of the XIX century the railway was introduced, the need of timber for railway construction and firewood for the locomotives increased once more (FABILA et al., 1955:67).

In the XX century the Mexican Revolution (tierra y libertad) destroyed the hacienda system and in the end of the thirties of this century the land was distributed by the government among the landless farmworkers. As one of the first consequences the pulque production decreased because the unskilled farmworkers were not able to produce and commercialize it. The terraces of the agave plantations deserted and were, some years later, transformed into large plots for the production of barley (beer production) which could easily be harvested by combine harvesters. This process has nearly been completed nowadays.

At the same time the population in the rural districts increased rapidly so that in the middle of the seventies population rates of about 5%/yr. were reported though there was an immigration into the big cities (Robichaux, 1986). Besides during the second phase of the industrialization in the middle of our century the demand of land rose because of the industrial settlements in the Puebla-Tlaxcala region. Great parts of the rural population had to leave their fields and went into the cities to make their living there; others transformed still existing forest regions into agriculturally used land. Often the second possibility was chosen with the well-known effects of soil erosion and landscape destruction.

For the last two decades the governments of the State of Tlaxcala in the Central Mexican Highlands have at least realized the effects of soil erosion. Government programs have been planned in order to recultivate the hardened subsoil horizons of old volcanic ash sediments (tepetate) exposed by erosion of the upper layers. Some of these ambitious programs have been executed. It is a pity to say that the well meant and expensive rehabilitation plans often fail because of the lack of knowledge of the correct use and management of these hardened soils. (WERNER, 1992).

4. Conclusions

The cultural history of the peoples of ancient Mesoamerica provides evidences that the fertile soils and ancient agricultural techniques were able to support high population densities during millennia before the Spanish conquest. That is to say, their agricultural production depended on massive water and earthworks; and the success of these intensive systems can be measured by the population densities of Prehispanic times. These densities has been maintained up to the time of the Spanish arrival. The archaeological record bears witness of the evolution of settlement and the expansion of the populations in the Central Mexican Highlands. This implies the evolution and adaptation of many different cultigens, agricultural techniques, and increasingly complex and sophisticated production systems. The impact of this human activity at that time on the landscape is undeniable. Nevertheless, while the archaeological record indicates a degree of complexity of agricultural systems, there is little evidence to support the notion of the deterioration of these systems in the period preceding European contact.

Unfortunately, the systems were extremely vulnerable in the absence of the labour force necessary for their land use and maintenance. The degradation of these Prehispanic systems and the introduction of a totally new agriculture by the Europeans is attested to, and much evidence exists which ties erosion processes to these changes. Evidence provided in the past which ties erosion to Prehispanic systems is faulted in the absence of clear dating of the processes observed on the landscape. Even the association of ceramic sherds and obsidian materials on the surface is insufficient evidence of causal relationships. We suggest that more attention and study will be focused on the acceleration of erosion in the Central Highlands due to the introduced species of plants and animals, and the apparent unwillingness to recognize the strengths of the Prehispanic soils and water management systems.

It is evident that the Indian civilization initiated the erosion by their agricultural land use before the Spanish conquest. But the transformation of the landscape was caused by the nature degradation during the last 400 years. At the end of the thirties of this century the social political results of the
Mexican Revolution caused changes in the way of living of the population of the Central Mexican Highlands and consequently the land use changed as well. The division into parcels of the hacienda land and their distribution among the small farmers was not at all successful. The constantly rising population rates of the Central Mexican Highlands needed more and more farm land to ensure their subsistence. Consequences were: the destruction of the forests to extend the fields proceeded followed by erosion of the loose volcanic ash soils down to the tepetate.

The Government has realized these processes very late and it is open to question whether the new programs for the recultivation of the tepetate will be successful. Most of them are inadequately planned and carried out for there are hardly any experiences of modern methods. The knowledges of Prehispanic times about recultivation of tepetate have been lost during the Colonial centuries, as discussed above.

Since Prehispanic times the people of the Central Mexican Highlands had an essential part on the morphodynamic process of soil erosion; but since the Spanish Conquest the new land management precipitated this process, destroying the soil, basis of their existence.

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A Tepetate Reclamation Program in the Mexico Watershed

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Abstract

A review is made of a proposal for a government project to reclaim tepetates in Central Mexico. The proposal is based on a research project that dealt with the classification, characterization and mapping of tepetates. The research project proposed a methodology for its reclamation, too.

A Benefit/Cost Analysis was made to support the need of this type of program. A more efficient use of natural, human and financial resources can be obtained when society is involved in the farmers problem. The analysis showed that the participation of farmers in this type of program would not only control environmental problems, such as erosion and sedimentation, but it would also improve their socioeconomic conditions.

The reclamation cost depends on who does the works and how it is made. When the works are done with government machines, and the operating costs are shared with the farmers, the cost for society becomes about one sixth of that done by private contractors. In the study area, 14 148 ha can be reclaimed for agricultural, range or forestland production. The expected yields, in terms of corn production, are above 1.0 ton/ha/yr or more, if irrigation is used. For rangeland, corn straw can be higher than 14 ton/ha/yr. In the case of forestland, certain species have higher yields when growing in tepetates than in soil, like Pinus montezumae.

Introduction

Tepetate is the local name for hardened layers of soils of volcanic origin that show up due to the removal of the surface soil by erosion. Those layers are mainly pyroclastic projections in the form of rain or flows that underwent decomposition (Zebrowski, 1992).

Tepetate lands are associated with low income farmers with a very reduced land tenure, and low investment capacity. Mismanagement of those lands, due to food and shelter needs, are enlarging the area; and as a result, the impoverishing of the owners increases, too, as well as the environmental effects that those badlands produce. Although the areas with tepetate are considered as source of pollution, due to the high sediment rates, and low productivity, almost no vegetation grows in tepetate lands, they have the potential for agricultural, range and forestland production. In the following paragraphs we are proposing a plan to reduce and control the situation above depicted.
The objective of the paper is to conclude the goals set for a research project developed by Colegio de Postgraduados, ORSTOM, University of Giessen, and the University of Tlaxcala, funded by the European Economic Community. The main goal was to develop a plan to reclaim tepetate lands. To do that, we first did (a) the characterization of tepetates, (b) a tepetate map, and (c) field tests of a reclamation program. Now, we are including a Benefit/Cost Analysis to show the feasibility of this type of program (Quantin, 1992).

Figure 1 shows the study area, located in Central Mexico, and covering an area of 1250 km².

Classification and characterization

Peña and Zebrowski (1992a) proposed a classification of this material, Table 1 shows it. The classification was based on earlier studies conducted in the area, a two-year survey combined with an intensive sampling, and laboratory analysis. Two main characteristics were for a field identification: (1) the type of layer, defined as T2, T3 and Ti, usually related to color, and (2) the presence or absence of carbonates.
Table 1. Classification developed by Peña and Zebrowski (1992a) for tepetates.

<table>
<thead>
<tr>
<th>Type</th>
<th>Key of the classification With Carbonates</th>
<th>Without Carbonates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation T3</td>
<td>T3+C</td>
<td>T3-C</td>
</tr>
<tr>
<td>Formation T2</td>
<td>T2+C</td>
<td>T2-C</td>
</tr>
<tr>
<td>Undeveloped</td>
<td>Ti+C</td>
<td>Ti-C</td>
</tr>
</tbody>
</table>

In general, it is possible to say that tepetates with carbonates (T3+C, T2+C, and Ti+C) are harder than those that have no carbonates; also, resistance and water dynamic studies (Peña et al., 1992) lead us to think that tepetates without carbonates behave as fragipans, while those with carbonates behave as duripans.

Chemical properties were defined by Etchevers et al (1992), while physical and mineralogical properties were described by Peña and Zebrowski (1992b).

Erosion Studies

In general, the surfacing of tepetates is the result of the mismanagement of the resources; in this case, vegetation. The soils overlaying tepetates are erodible, and the removal of the surface cover makes those soils susceptible to erosion. The soil losses for the overlaying soils were evaluated up to 13.84 ton/ha/yr, while those of tepetate as 6.134 ton/ha/yr. Soil losses were measured in runoff plots of 25x2 m in eight ecosystems in the Texcoco Watershed, inside the study area, during the period 1974-1981 (Table 2).

Table 2. Average Annual Soil Losses measured and adjusted, to correct differences in slope steepness using the Universal Soil Loss Equation, in eight ecosystems in the Texcoco Watershed (Arias and Figueroa, 1990).

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Average annual soil losses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>Pine Forest</td>
<td>0.034</td>
</tr>
<tr>
<td>Rangeland</td>
<td>0.025</td>
</tr>
<tr>
<td>Abies Forest</td>
<td>0.004</td>
</tr>
<tr>
<td>Upland agriculture</td>
<td>1.656</td>
</tr>
<tr>
<td>Tepetates</td>
<td>9.376</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.277</td>
</tr>
<tr>
<td>Oak Forest</td>
<td>0.005</td>
</tr>
<tr>
<td>Lowland agriculture</td>
<td>2.643</td>
</tr>
</tbody>
</table>

* Adjustment of slope steepness using the S factor of the Universal Soil Loss Equation.
In order to know if tepetates are erodible, the soil losses were compared with standards. One criterion used to define erosion levels is the "T value", or Tolerance Limits. It is based on the soil formation rates, which in general depends on the parent material and actual soil depth. The figures shown in Table 3 (modified from Logan, 1982), allow us to quantify the degree of erosion rates in the area.

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>Parent material</th>
<th>T Values (ton/ha/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;100</td>
<td>rock</td>
<td>X</td>
</tr>
<tr>
<td>50-100</td>
<td>rock</td>
<td>X</td>
</tr>
<tr>
<td>50-100</td>
<td>fragipan</td>
<td>X</td>
</tr>
<tr>
<td>25-50</td>
<td>rock</td>
<td></td>
</tr>
<tr>
<td>&lt;50</td>
<td>fragipan</td>
<td>X</td>
</tr>
<tr>
<td>&lt;25</td>
<td>rock</td>
<td></td>
</tr>
</tbody>
</table>

Since some tepetates are considered as fragipans, then the losses are within the limits (9.0 ton/ha/yr when soil depth is between 50-100 cm, and 6.7 ton/ha/yr when the fragipan is within 50 cm; which is the rule, in the average). For duripans (rock-like parent material) the limits are 11.2, 9.0, 4.5 and 2.2 ton/ha/yr when soil depth is deeper than 100 cm, 50-100, 25-50, and less than 25 cm, respectively. However, since the tepetate layers are about 30 cm deep, the tolerance levels should be 6.7 ton/ha/yr for soils over fragipans (tepetates without carbonates), and 2.2 ton/ha/yr for soils over duripans (tepetates with carbonates).

Since tepetate losses, measured in the field, were equal or higher than the tolerance limits, it is possible to conclude that tepetates are erodible; and therefore, care must be exercised when they are reclaimed.

Erosion studies for reclamation purposes

Erosion studies were conducted to test the methodology we were developing to propose tepetate reclamation. The methodology was supported with runoff plot experiments. An experimental site was set up in San Miguel Tlaixpan where runoff plots of 22.2 X 2 m were installed in order to make soil losses measurements, as well as runoff and rainfall rates, and soil moisture.

When tepetate was ripped following contour lines, the runoff rates and soil losses were the lowest, 1.95 ton/ha/yr (Table 4). The expected soil losses for the untreated plot (Blank) were 6.13 ton/ha (Arias and Figueroa, 1992), while the actual soil losses were below but within the expected range (5.09 ton/ha). The main reasons were roughness and preferential flow of water on the cracks formed by the ripper. The cracks held the excess water and no runoff was allowed since the furrow formed was 5-15 cm height, enough to hold the excess water. Furthermore, the aggregate size was the largest (D50=21 mm), compared with the tilled treatments (D50=0.78 mm), which means that more energy is required to splash material from those aggregates.
Table 4. Soil losses measured in runoff plots during the 1990 growing season (Arias et al, 1992).

<table>
<thead>
<tr>
<th>No</th>
<th>Treatment</th>
<th>plot size (m²)</th>
<th>Soil losses (ton/ha/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Blank</td>
<td>44</td>
<td>5.09</td>
</tr>
<tr>
<td>2</td>
<td>Rip</td>
<td>44</td>
<td>1.95</td>
</tr>
<tr>
<td>3</td>
<td>Rip+Till+Crop-Fur</td>
<td>44</td>
<td>5.00</td>
</tr>
<tr>
<td>4</td>
<td>Rip+Till-Crop-Fur</td>
<td>44</td>
<td>0.68**</td>
</tr>
<tr>
<td>5</td>
<td>Rip+Till-Crop-Fur</td>
<td>20</td>
<td>5.62</td>
</tr>
<tr>
<td>6</td>
<td>Rip+Till-Crop-Fur</td>
<td>10</td>
<td>5.66</td>
</tr>
</tbody>
</table>

Measurement errors in runoff collection

The following year (1991), when plowing and disk ing were performed without furrows in the same plot, the runoff rates and soil losses were the highest (40 ton/ha/yr), as can be seen in Table 5. In the same table, as a comparison, the soil losses were higher than in 1990, but within the expected range (blank 7.28 ton/ha/yr, expected 6.13 ton/ha/yr).

Table 5. Soil losses observed in 1991 (Arias et al, 1992).

<table>
<thead>
<tr>
<th>No</th>
<th>Treatments 1990</th>
<th>Treatments 1991</th>
<th>size (m²)</th>
<th>Soil losses (ton/ha/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Blank</td>
<td>Blank</td>
<td>44</td>
<td>7.28</td>
</tr>
<tr>
<td>2</td>
<td>Ripped</td>
<td>Till-Furr-Crop</td>
<td>44</td>
<td>44.61</td>
</tr>
<tr>
<td>3</td>
<td>Rip+Till-Crop-Fur</td>
<td>Till+Furr-Crop</td>
<td>44</td>
<td>1.60</td>
</tr>
<tr>
<td>4</td>
<td>Rip+Till-Crop-Fur</td>
<td>Till+Furr-Crop</td>
<td>44</td>
<td>1.41</td>
</tr>
<tr>
<td>5</td>
<td>Rip+Till-Crop-Fur</td>
<td>Till+Furr-Crop</td>
<td>20</td>
<td>1.18</td>
</tr>
<tr>
<td>6</td>
<td>Soil (rangeland)</td>
<td>Till+Furr-Crop</td>
<td>44</td>
<td>1.27</td>
</tr>
<tr>
<td>7</td>
<td>Soil (rangeland)</td>
<td>Till+Furr-Crop</td>
<td>44</td>
<td>1.86</td>
</tr>
</tbody>
</table>

Therefore, if subsoiling is to be performed without ant erosive works, it better be following contour lines, instead of crossed ripping; while if erosion control practices, like bench terraces, are considered, and economics does not play a major role, then cross ripping and maximum tillage, to obtain the optimum particle size distribution, can be applied since the first year.

Tepetate Mapping

About 11 % of Mexico's surface have hardened layers that limit the agricultural production of the country. Three main types of hardened layers are included in that extension. Although only 1.9 % represents what are called Duripans (Guerrero et al, 1992), that area has the highest population density.
Peña and Zebrowski (1992c) surveyed the study area and the results are shown on Table 6, according to the classification of Table 1.

Although there are only 14,148 ha with different levels of erosion, and 3,097 ha have been reclaimed, there are still 26,296 ha that are still covered with soil, and if the actual trend continues, they will also become a problem for society.

Table 6. Aerial distribution of Tepetate types in the eastern part of the Mexico Watershed (Peña and Zebrowski, 1992c).

<table>
<thead>
<tr>
<th>Surface (ha)</th>
<th>T3-C</th>
<th>T2-C</th>
<th>Ti-C</th>
<th>T3+C</th>
<th>T2+C</th>
<th>Ti+C</th>
<th>Subtotal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Erosion</td>
<td>1750</td>
<td>1042</td>
<td></td>
<td>1516</td>
<td></td>
<td></td>
<td>4308</td>
</tr>
<tr>
<td>Severe Erosion</td>
<td>589</td>
<td>541</td>
<td></td>
<td>1267</td>
<td></td>
<td></td>
<td>2397</td>
</tr>
<tr>
<td>Partial Erosion</td>
<td>1346</td>
<td>1072</td>
<td></td>
<td>5025</td>
<td></td>
<td></td>
<td>7443</td>
</tr>
<tr>
<td>No Erosion</td>
<td>2324</td>
<td>9737</td>
<td>3863</td>
<td>10372</td>
<td></td>
<td></td>
<td>26296</td>
</tr>
<tr>
<td>Reclaimed</td>
<td></td>
<td></td>
<td></td>
<td>3097</td>
<td></td>
<td></td>
<td>43541</td>
</tr>
</tbody>
</table>

Tepetate reclamation

Tepetate reclamation was practiced in prehispanic times. The clods were broken by maze blows, and maguey (Opuntia spp) ashes were used as fertilizer to compensate the low nutrient content (Williams, 1972). In modern times, the mechanical energy is provided by heavy machinery, to rip the hardened layer, and agricultural tractors, to prepare the seedbed; and commercial fertilizers (manure is strongly recommended) are applied to insure a reasonable yield.

Tepetate reclamation depends on the land slope and the projected use. The main activities can be separated in: (1) land reshaping, that depends on the land slope and projected land use, (2) land preparation, that depends on the land use, and (3) fertilization, depending on economics.

Land reshaping is mainly performed with heavy machinery (usually 250 HP or more) equipped with a ripper. In the average, the ripping goes between 0.30 to 0.60 m depth, depending on the strength of the material and the moisture content. If the land slope is steep, it is recommended to build bench terraces. Although crossed subsoiling can be made, it increases the cost, and if the land is not protected with antierosive practices, it becomes more susceptible to high erosion rates.

In the case of reforestation or rangeland improvement, reshaping can be made with hand labor, too. Although hand labor can be more expensive, when funds are scarce and time is not a constraint, combination of ditches with revegetation by hand is an alternative with less money investment, when performed by the farmers with small land tenure.

Land preparation follows the same routine as any agricultural activity. Improvement of soil porosity for better water and air flow is accomplished with plowing (primary tillage), and seedbed preparation is usually
done with disking (secondary tillage). The objective is to have a particle size distribution that optimizes water and air flows, and less impedance for seed emergence. To obtain the optimum particle size distribution, it usually requires several steps of the agricultural implements.

If the projected land use is either for forest or range production, plowing is only performed following contour lines, with the objective of increasing the water retention. Lister plowing is a good land preparation for rangelands, as well as for reforestation, although cattle movement is restricted.

Fertilization is usually accomplished with commercial fertilizers or manure, depending on availability and economics. Organic fertilizers are strongly recommended because they will improve soil fertility and development, whenever economics does not play a limiting factor.

Cost Benefit Analysis for a Reclamation Program

Tepetate reclamation is a very expensive process. However, the environmental and socio-economical problems associated with those badlands arouse a question about the involvement of society in these types of projects. The following is a brief analysis to justify the involvement of the government in a reclamation project.

Tepetate lands despite being unproductive, they are a source of pollution, since sediments, besides causing silting problems in hydraulic structures, affect wildlife, especially river or lake fauna. Therefore, the economy of a region is negatively affected.

Reclamation Benefits

In the following analysis, fauna is not considered directly, since it depends on the vegetation; therefore, with this omission, reclamation benefits are only analyzed as land productivity restoration.

Land productivity restoration. Although rangeland productivity is a very important component in the present analysis, data are missing to include this economic activity, but since many secondary agricultural products are used for cattle raising, it is included in croplands.

Croplands. An experiment analyzed the corn yield of tepetate and soil in the 1991 growing season. Although the grain yield in soil is significantly larger than that of reclaimed tepetate, the yields are higher than the regional average (less than 1.0 ton/ha) as can be seen in Table 7. It also shows that the straw yields are not significantly different. Since livestock is one of the main activities in the area, it has a significant economic importance.

<table>
<thead>
<tr>
<th>No</th>
<th>Treatments</th>
<th>size (m²)</th>
<th>Corn yield grain (ton/ha)</th>
<th>straw</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tepetate</td>
<td>Blank</td>
<td>44</td>
<td>---</td>
</tr>
<tr>
<td>2</td>
<td>Tepetate</td>
<td>Til-Fur-Crop</td>
<td>44</td>
<td>---</td>
</tr>
<tr>
<td>3</td>
<td>Tepetate</td>
<td>Til+Fur-Crop</td>
<td>44</td>
<td>---</td>
</tr>
<tr>
<td>4</td>
<td>Tepetate</td>
<td>Til+Fur+Crop</td>
<td>44</td>
<td>1.24</td>
</tr>
<tr>
<td>5</td>
<td>Tepetate</td>
<td>Til+Fur+Crop</td>
<td>20</td>
<td>1.74</td>
</tr>
<tr>
<td>6</td>
<td>Soil</td>
<td>Til+Fur-Crop</td>
<td>44</td>
<td>---</td>
</tr>
<tr>
<td>7</td>
<td>Soil</td>
<td>Til+Fur+Crop</td>
<td>44</td>
<td>2.78</td>
</tr>
</tbody>
</table>

Tepetate development as a substrate for crop production is time dependent, and several researchers have found that the crop yield increases with time, after the reclamation process. It is believed that within a five year period, the crop yield difference, between reclaimed tepetate and soil, is close to zero (Navarro and Zebrowski, 1992). Therefore, reclaimed tepetate can be considered as soil for agricultural purposes in about five years under rainfed agriculture.

When tepetates are irrigated, the difference in crop yield is less. The average corn yield in a nearby irrigated area, Distrito de Riego 063 Tula, Hidalgo, México, is 4.0 ton/ha. The substrate is mainly reclaimed tepetate and the irrigation source is Mexico City sewage water. The average crop yields in this irrigation district are higher, despite the substrate, because of the hyperfertilized water.

Forestland. In the case of forest production, Arias et al (1990 and 1992) analyzed the productivity of reforestation in tepetates. The results (Table 8) showed that *Pinus montezumae* develops better in tepetate than in soil, with an average annual increase in volume of 0.80 m³/ha/yr, while for soils that overlays tepetate the best option is *Pinus seudostrobus*, with figures of 3.46 m³/ha/yr.


<table>
<thead>
<tr>
<th>Species</th>
<th>Average Annual Increase in Volume, AAIV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tepetate</td>
</tr>
<tr>
<td><em>Cupressus lindleyi</em></td>
<td>0.46</td>
</tr>
<tr>
<td><em>Pinus montezumae</em></td>
<td>0.80</td>
</tr>
<tr>
<td><em>Pinus radiata</em></td>
<td>0.19</td>
</tr>
<tr>
<td><em>Pinus michoacana</em></td>
<td>0.50</td>
</tr>
<tr>
<td><em>P. seudostrobus</em></td>
<td>3.46</td>
</tr>
<tr>
<td><em>P. ayacahuite</em></td>
<td>0.49</td>
</tr>
</tbody>
</table>
The information above presented confirms the benefits for society of a tepetate reclamation program.

Reclamation Works Cost

The main concern for society is how much it will need to support a regional program. Usually, society, through the government, subsidizes this type of plans. However, how it can be done in an efficient way?

Several government institutions have started programs to reclaim highly eroded lands using government's machinery. Sánchez (1992) analyzed the costs of a reclamation program, based on used machinery and 1991 prices (3 000 $/USDLS). Accessory services (topographic units, supervision, and others) were not included in the analysis, just machine and driver costs.

The cost for the government can vary from 142.45 to 1 086.45 USDLS. Table 9 describes the fluctuation in terms of the way the reclamation program is supported. If the reclamation is performed by private contractors, the average price, depending on the type of machinery is about 700 USDLS/ha, when machines are rented, the cost is above 1000 USDLS, but when the costs are shared by the government and the farmers, the cost for the government can be as low as 142.45 USDLS/ha.

It depends on (1) who performs the works: private or government agencies, (2) the ownership of the machines: rented or owned (for the government owned is called Direct Administration), and (3) who pays the operating costs (fuels, driver fees, and minor repair works on the machine): total government or shared with the farmers (agreements).

Table 9. Unit costs per alternative of tepetate reclamation with used machinery (Sánchez, 1992).

<table>
<thead>
<tr>
<th>Type of Machine</th>
<th>Run by private companies</th>
<th>Run by the governments agencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-4</td>
<td>573.93</td>
<td>1009.49</td>
</tr>
<tr>
<td>D-6</td>
<td>761.92</td>
<td>1045.44</td>
</tr>
<tr>
<td>D-7</td>
<td>789.18</td>
<td>1086.45</td>
</tr>
<tr>
<td>D-8</td>
<td>732.44</td>
<td>1033.98</td>
</tr>
</tbody>
</table>

In general, it is cheaper when the works are performed by the government (columns 5 vs 2), when the machines are owned (columns 2 vs 3), and when costs are shared with the farmers (columns 3 vs 4, and 5 vs 6). The participation of farmers, besides being the cheapest alternative, insures the possible success of the program.
Cost-Benefit Analysis

Although the benefits and costs of a reclamation program were already discussed before, a cost-benefit analysis was performed accounting for the benefits (to society) as the cost of erosion.

Erosion costs

To analyze a reclamation program and the way it can be implemented, erosion costs were calculated according to a methodology proposed by Arias (1990), where Erosion costs are the accumulation of on site and off site effects. On site effects are valued as productivity losses (crop, range or forest production), while off site effects are valued as corrective works (water treatment, cleaning and sediment control structures construction). The mathematical formulation is:

\[ Ce = Con + Coff \]

where \( Ce \) is cost due to erosion ($), \( Con \) is cost due to on site effects ($), and \( Coff \) is cost due to off site effects ($).

On site cost is calculated solely on the basis of production decrease in terms of money losses, according to the following equation:

\[ Con = P \times CV \times \sum_{i=1}^{n} (A \times i) \]

where \( i \) is the degree of productivity loss due to erosion (fraction), \( A \) is the Area with a degree of productivity loss (ha), \( P \) is the potential productivity (ton/ha), and \( CV \) is the crop value ($/ton).

Off site effects are considered as point source problem, and the calculations were made in terms of the volume of sediment deposited that may affect a water treatment facility (the cost of contaminants treatment), the reduction of the capacity of a reservoir (the price of water that is displaced due to sediments), or the cost of construction of a check dam to retain the sediment volume. That reasoning is treated in the following equation.

\[ Coff = S \times [T + \min(Cwat, Cdam)] \]

where \( S \) is the sediment volume (m\(^3\)), \( T \) is the unit price for the water treatment due to any excess of a contaminant ($/m\(^3\)), \( \min \) is an expression for the minimum of, \( Cwat \) is the water price ($/m\(^3\)), and \( Cdam \) is the unit cost of a check dam ($/m\(^3\)).

The analysis was based on the following assumptions:

(1) The degree of actual erosion is considered on aerial coverage; it means total erosion is 100% eroded, severe erosion means 67% area eroded, partial erosion means 33% area eroded, and No erosion means 0% eroded; also, reclaimed land is not accounted in the analysis.
Productivity degree is correlated with the degree of actual erosion, and the same percentages are related to the four erosion classes. Total erosion means 100% productivity loss, Severe erosion means 67% productivity loss, Partial erosion means 33% productivity loss. The potential productivity for the land is 2 ton/ha of corn, or equivalent in any other crop, grass, or tree.

The value of corn was set as 200 USD/ton (according to 1993 prices in Mexico).

The sediment volume was calculated according to the soil losses measured in the runoff plots corrected for a sediment delivery ratio, set as 10%.

Sediment cost was only evaluated assuming a check dam is built to retain sediments. The unit cost ($/m³) was calculated based on the construction of a 3750 m³ check dam whose cost was 10 000 $; therefore, the unit cost is 2.67 $/m³ (approximately 0.89 USD/m³, based on 1992 prices).

Table 10 shows the calculations for the cost of erosion when applying the equations for the study area of the EEC funded project. The first column shows the type of erosion, the second column shows the area covered for each type of erosion, the third column shows the productivity loss assumed, column fourth is the “on site” cost (productivity losses), fifth column shows the volume of sediment expected, given the soil losses (6.13 ton/ha/yr) and a sedimentation rate of 10%, the sixth column shows the check dam cost, and the last column the cost for each type of erosion. The total is 3 353 308.67 USLDS. Most of the cost is due to the productivity loss (close to 100%), or "on site" effects.

<table>
<thead>
<tr>
<th>Erosion Class</th>
<th>Area (ha)</th>
<th>Productivity fraction</th>
<th>C on site (USDLS)</th>
<th>Sediment volume (m³)</th>
<th>C check dam (USDLS)</th>
<th>C total (USDLS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Erosion</td>
<td>4308</td>
<td>0</td>
<td>1723200</td>
<td>2021.446</td>
<td>2695.262</td>
<td>1725895</td>
</tr>
<tr>
<td>Severe Erosion</td>
<td>2397</td>
<td>0.33</td>
<td>642396</td>
<td>753.5799</td>
<td>1004.773</td>
<td>643400.8</td>
</tr>
<tr>
<td>Partial Erosion</td>
<td>7443</td>
<td>0.67</td>
<td>982476</td>
<td>1152.52</td>
<td>1536.693</td>
<td>984012.7</td>
</tr>
<tr>
<td>No Erosion</td>
<td>26296</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Reclaimed</td>
<td>3097</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>43541</td>
<td></td>
<td>3348072</td>
<td>5236.727</td>
<td>5236.727</td>
<td>3353309</td>
</tr>
</tbody>
</table>

The reclamation costs for the whole area depends on who owns the machinery, and the association between the government and the farmers. If the program is performed entirely by the government, it would cost 6 130 666 USLDS (column 4 in Table 11). If the machinery is rented and the expenses are paid by the farmers, it would be more expensive, 6 882 074 USLDS (column 5 in Table 11). The best alternative is when the machinery is owned by the government and the operating costs are paid by the farmers through an agreement, since the cost is 1 192 301 USLDS (column 6, Table 11), close to 1/6 of the higher expense.
Table 11. Reclamation costs for the partial, severe or total erosion area with tepetates in the Mexico Watershed.

<table>
<thead>
<tr>
<th>Erosion Class Area</th>
<th>Aerial Contribution (ha)</th>
<th>Private Contractor (fraction)</th>
<th>Rented mach. &amp; Govt. mach. &amp; Agreement</th>
<th>Agreement</th>
<th>Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(USDLS)</td>
<td>(USDLS)</td>
<td>(USDLS)</td>
<td>(USDLS)</td>
<td>(USDLS)</td>
</tr>
<tr>
<td>Total Erosion</td>
<td>4308</td>
<td>0</td>
<td>3155357</td>
<td>3542095.04</td>
<td>613658.80</td>
</tr>
<tr>
<td>Severe Erosion</td>
<td>2397</td>
<td>0.33</td>
<td>1176293</td>
<td>1320466.39</td>
<td>228767.39</td>
</tr>
<tr>
<td>Partial Erosion</td>
<td>7443</td>
<td>0.67</td>
<td>1799015</td>
<td>2019512.17</td>
<td>349875.26</td>
</tr>
<tr>
<td>No Erosion</td>
<td>26296</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Reclaimed</td>
<td>3097</td>
<td>0</td>
<td>6130666</td>
<td>6882073.59</td>
<td>1192301.45</td>
</tr>
</tbody>
</table>

This analysis proves that the involvement of society, through government agencies, and farmers would make a positive effect on the solution of this type of programs. It would not only solve the societal problems of erosion and sediment rates, but also it would improve the regional economy by increasing the area for agriculture, range or forestland production.

Literature Cited


Hydrodynamique, Erodabilité et Conservation des Sols Volcaniques Indurés d’Amérique Latine (Equateur, Mexique et Nicaragua): Impact du Matériau Originel et Effet de la Réhabilitation Agricole


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Abstract.
Studies on indurated volcanics soils, which cover large areas of Latin America, have been conducted by ORSTOM in association with local institutes such as : MAG (Ministerio de Agricultura y Ganaderia) in Ecuador, some universities among which CPM (Colegio de Postgraudados de Montecillo) in Mexico and DIRENA (Dirección de los Recursos Naturales y del Ambiente) in Nicaragua. Important lessons concerning the behaviour of these soils towards erosion by water and their suitability for an agricultural rehabilitation emerged from these studies, which have been carried out under simulated rainfalls (1 m²), on runoff plots (6 - 1000 m²) and on catchment basins of various areas (1 ha - 15 km²). When the natural material is concerned, the process of induration plays a major role: permeability and soil losses are low while runoff coefficients are higher than 70 %. When this indurated material is recovered for agricultural production, the management is difficult because of a nitrogen and phosphorus deficiency, and eventually significant soil loss (> 20 t/ha/yr), concerning especially the aggregates < 2 mm. The experiments carried out in Ecuador and Mexico proved that these two constraints could be overcome, leading to a successful agricultural rehabilitation.

Introduction.

Dans ces trois pays, on constate donc une relation étroite entre le développement des sols indurés, l’extension des paysages dégradés et la croissance de l’exode rural. L’objectif des programmes vise à répondre à cette problématique: d’une part en évaluant l’impact hydrodynamique des sols indurés avant et après ameublissement, d’autre part en étudiant des possibilités de réhabilitation de la fertilité du matériau ameubli en milieu paysan ou d’actions de reboiselement sur bassins-versants. Les essais sont réalisés sur petites et grandes parcelles expérimentales (de 6 à 1000 m²) en Equateur et au Mexique, sur bassins-versants de différentes tailles (1 ha à 15 km²) au Nicaragua et ont donné lieu aussi à des campagnes de simulation de pluies en Equateur et au Nicaragua.
L'objet de cet exposé est de rendre compte des résultats majeurs issus de ces essais. Les uns concernent l'ensemble des facteurs hydrodynamiques causes de l'érosion, les autres se réfèrent aux aménagements anti-érosifs en milieu paysan et sur bassins-versants qui sont nécessaires pour assurer une réhabilitation et une gestion durables de ces sols.

I. OBJET D'ÉTUDE

1. Les horizons des sols volcaniques indurés.

1.1. Localisation.

En Equateur, les cangahuas sont localisées dans les régions centre et nord du bassin intrandin où s'est déposée la majeure partie des projections pyroclastiques émises par d'imposants stratovolcans tels le Chimborazo (6310 m) ou le Cotopaxi (5900 m). Il s'agit donc d'une cendre fine, andésitique ou dacitique, et indurée par la présence d'un encroûtement calcaire. Elles occupent 20 % des terres volcaniques du bassin (3000 km², environ) et sont situées entre 2000 et 2800 m (climat subaride, 600 mm/an); soit, entre deux caños sur les interfluves plats du bassin, soit en position de transition sur les piémonts de versants et glacis-terrasses (De Noni et al. 1986). Les cangahuas paraissent en altitude lorsque le climat devient plus humide: on observe alors des sols bruns argileux a smectites (2800-3200 m) puis sur les hautes terres, jusqu'à 4000-4400 m, les sols noirs a allophanes. Lorsqu'elles n'affleurent pas, les cangahuas sont coiffées par des sols bruns vertiques ou par des sols sableux, ponceux et pulvérulents. En profondeur, les cangahuas sont interstratifiées avec d'autres pyroclastites, notamment des ponces blanches et recouvertes localement par des paléosols (De Noni, Derrau, 1979).

Au Nicaragua, les "Talpetates" occupent une superficie de 2500 km² et sont localisés à l'ouest de l'océan Pacifique entre les lacs Managua et Nicaragua. Ce sont des tufs pyroclastiques altérés (cendres d'andésite basaltique "palagonitisées") provenant de l'explosion phréato-magmatique de la caldeira de Masaya, il y a 2000 ans environ (Prat, Quantin, 1992). Les talpetates, dont l'épaisseur varie de quelques centimètres à plus d'un mètre, sont recouverts, avant décapage par l'érosion, par d'autres sols: sols bruns andiques dans les zones basses de piedmont (climat tropical sec avec 6 mois sans pluie) et andosols en altitude (900 m) où règne un climat tropical humide (3 mois secs).

Au Mexique, les "Tepetates" ont été étudiés sur les versants occidental et oriental de la Sierra Nevada qui sépare les bassins de Mexico (Texcoco) et de Tlaxcala. Les sols sont dérivés de dépôts volcaniques pyroclastiques, cendres rhyolitiques ou dacitiques très siliceuses et alcalines (Quantin, 1992). Ils sont distribués en climotoposéquences, entre 2200-2400 m et 4000 m d'altitude où l'on observe successivement d'amont en aval: andosols, sols bruns eutrophes, sols bruns vertiques et sols bruns subarides à croûte calcaire (Peña, Zebrowski, 1992 et Werner, 1992). Sur les piémonts et glacis, en climat à saison sèche marquée, les sols comportent deux ou plusieurs horizons indurés. Sur la partie supérieure et moyenne des piémonts, les tepetates sont friables à l'état humide et ont un comportement de "fragipan". Au bas des piémonts et sur les glacis, l'induration est calcaire et les sols demeurent durs (horizons pétrocalciques). Les tepetates sont interstratifiés dans une succession de dépôts volcano-sédimentaires. Ils sont recouverts actuellement en surface par un dépôt sablo-limoneux et en profondeur par 3 paléosols superposés. Dans la région de Texcoco, les tepetates occupent plus de 400 km², soit près de 40 % de la surface totale.

1.1.2. Propriétés physiques et chimiques majeures.

Ces sols se caractérisent par des contraintes physiques importantes dues à leur compacité et à leur dureté permanente. On distingue cependant des différences de comportement d'un pays à l'autre. Au Nicaragua, les talpetates présentent des horizons moyennement compacts (densité...
apparaît de l’ordre de 1 g/cm³) et une porosité totale pouvant atteindre 65 % du poids sec (Prat, Quantin, 1992). La texture argilo-limoneuse des horizons (porosité texturale de 10-15 %) et le nombre important de vides formés par l’empiètement des microlithes (porosité structurale de 55-60 %) expliquent en grande partie ces valeurs élevées. La capacité de rétention en eau est donc importante mais en cas de précipitations abondantes, l’horizon sature et sa duréte diminue permettant ainsi l’érosion par rigoles et ravines (Prat, 1989).

En Equateur et au Mexique, les sols indurés sont plus compacts (densités apparentes, respectivement de 1.7 g/cm³ et de 1.45 g/cm³) et plus durs. La cangahua et le tepetate pétrocalcique, qui se caractérisent par des encroûtements calcaires et une teneur en argile inférieure à 15%, présentent une porosité totale (25-30%) et une capacité de rétention en eau (< 20-30%) faibles. En revanche, le tepetate-fragipan, moins calcaire et plus argileux, a une porosité totale supérieure à 40% (microporosité > 30%) et une réserve d’eau utile pour la plante d’au moins 10% en volume. La duréte augmente avec la présence de calcaire, elle est maximale à l’état sec (Miehlich, 1984); les valeurs de résistance à la pénétration sont élevées sur cangahua et tepetate pétrocalcique, de l’ordre 100 et 200 kg/cm² (Nimlos 1990; Peña, Zebrowski, 1992). Elles baissent à moins de 20 kg/cm² sur tepetate-fragipan. Il résulte de ces propriétés que la conductivité hydraulique est lente: de 5 à 15 mm/h au champ en Equateur, au Mexique, en laboratoire, de 2 à 10 mm/h sur tepetate calcaire et de 0,3 à 0,5 mm/h sur tepetate-fragipan.

La stabilité structurale des fragments grossiers est bonne (> 2 mm). Les expérimentations réalisées au Mexique, au champ et au laboratoire, montrent que l’agrégat optimum a un diamètre de 3,4 à 2,4 mm. Pour cette classe, 98% des agrégats sont stables, la vitesse d’infiltration est maximale et sans effet de colmatage, la capacité de rétention en eau (= 29% en poids et 39% en volume) est élevée et comparable à un sol argilo-limoneux. Les fragments fins (< 2 mm) sont par contre très instables. La rapidité de dispersion dépend cependant du taux de matière organique comme le montrent les observations réalisées au laboratoire en Equateur sur des petits échantillons de cangahua, disposés sur un tamis de 2 mm et sur lesquels on fait tomber des gouttes d’eau. Pour deux échantillons dont les teneurs de matière organique varient de 0,4% à 1,02%, il faut 2 fois plus de gouttes de pluie pour détruire les agrégats (Caujolle-Gazet et Luzuriaga, 1986).

Ces sols présentent aussi des propriétés chimiques particulières. La capacité d’échange cationique est en général élevée sur ces sols indurés: de 15 à 25 mè/100 g au Mexique et en Equateur, voir même supérieure sur les talpetates du Nicaragua, entre 20 et 40 mè/100 g. Les teneurs en base échangeables sont importantes comme le montrent les dosages, exprimés en mè/100 g, effectués en Equateur sur le calcium (9,5 à 14), le magnésium (4,5 à 11) et sur le potassium (0,8 à 1,9) ainsi qu’au Mexique sur les mêmes éléments, Ca (7 à 18), Mg (6 à 10) et K (0,8 à 1,2) (Custode, De Noni et al. 1992, Quantin, 1992). Sur tous les tepetates, les réserves minérales en potassium sont très importantes (2 à 3%) ainsi que leur disponibilité sous forme échangeable (0,6 à 0,8%). Le pH varie de neutre à légèrement basique pour ces sols. L’alcalinité augmente avec la teneur en calcaire (> 5%): on note des ph compris entre 8,5 et 9 sur cangahua et tepetate pétrocalcique.

En revanche, les sols indurés sont fortement carencés en matière organique, < 0,3%, en azote, < 0,04%, et en phosphore total et assimilable, < 3 ppm (Etchevers et al. 1991, a et b).

1.2. Les stations d’étude.

1.2.1. En Equateur.

L’ORSTOM et le Ministère équatorien de l’Agriculture et de l’Elevage (MAG) ont installé et suivi, de 1986 à 1992, un réseau d’une quarantaine de parcelles de ruisseaux regroupées en 10 stations principales. Celles-ci sont situées dans les Andes et recoupent, sur 800 km environ du nord au sud, différentes situations agricoles en conditions témoin et améliorées. Parmi ces situations, la station de Tumbaco correspond à une cangahua ameublie pour la culture du maïs. On se trouve ici dans le bassin de Quito (2650 m) au pied du versant est du volcan Iñaló. L’horizon
induré se trouve à 30-50 cm de profondeur, le sol meuble en surface provient en grande partie du défonçage de la cangahua. On observe localement cependant quelques témoins résiduels du sol noir originel à smectite. La station est composée de 3 parcelles de ruissellement: une parcelle en culture traditionnelle (maïs) et une Wischmeier de 100 m² chacune (20 m x 5 m), et une parcelle améliorée de 1000 m² (50 x 20 m) dotée de bandes enherbées isohypses (De Noni et al., 1990). Par ailleurs, des simulations de pluies ont été réalisées à côté de la station sur cangahua induré et ameublie (Custode, De Noni et al., 1992).

1.2.2. Au Mexique.

Le programme mexicain s'est déroulé dans le cadre d'un contrat CEE (TS2-A-212-C). Il a regroupé deux projets: l'un dans la région de Mexico (vallée de Texcoco) mené par le Colegio de Postgraduados de Montecillo (CPM) et l'ORSTOM; l'autre dans la région de Tlaxcala à la charge de l'Université de Giessen (UG) et un consortium de l'Université de Tlaxcala (UAT) et de Services du Gouvernement de cet Etat. L'étude expérimentale de l'érosion et de régénération de la fertilité a porté sur le tepetate de type fragipan qui présente les meilleures propriétés physiques et chimiques (Quantin, 1992).

Dans la région de Texcoco, les observations ont été effectuées sur une seule station située à San Miguel Tlaixpan (2650 m d'altitude) sur le piémont ouest de la Sierra du Tlaloc-Telapón. Le site est constitué par des parcelles de type Wischmeier, de 22 m de long par 2 m de large et sur une pente de 8 à 9 %. En 1990, les mesures ont été effectuées sur 6 parcelles de ruissellement (tepetate nu témoin et tepetates remaniés par rippage et pulvérisage). En 1991, le dispositif de la station a été revu et distribué en 7 parcelles: 5 sur tepetate et 2 sur sol non érodé, avec introduction sur chaque type de sol d'une culture de maïs. Hormis les mesures de l'érosion et du ruissellement (août-septembre 1991 et mai-octobre 1992), d'autres mesures ont été effectuées sur les propriétés physiques du tepetate (porosité, vitesse d'infiltration, humidité), sur l'évolution des états de surface et de la fonte des agrégats et sur l'évaluation du rendement du maïs. En 1992, un petit bassin versant de 1800 m² a été équipé, puis en 1993, ce sont 6 autres parcelles de tepetate rippé qui ont été aménagées en terrasses (Prat et al., 1993; Marquez et al. 1994).

L'autre site expérimental est dans la région de Tlaxcala. Il est formé par trois stations, El Carmen, Matlalohcan et Tlalpan. La situation est voisine de celle du site précédent: altitude de 2500-2600 m, pente de 8-9 % et régime climatique "ustic" avec 6 mois de saison sèche. De la même manière, le comportement d'un tepetate nu et fragmenté, avec ou sans culture de maïs, est comparé à celui d'un sol. Seules diffèrent les quantités de pluies et surtout les valeurs d'érosivité correspondantes. Les essais sur la productivité agricole des tepetates ont été réalisés sur les stations de El Carmen et Tlalpan (Marquez et al., in Quantin, 1992).

1.2.3. Au Nicaragua.

L'ORSTOM et la DIRENA (Direction des Ressources Naturelles et de l'Environnement) ont fait une étude intégrée du bassin-versant du lac de Managua dont l'un des objectifs est l'analyse des relations entre l'érosion hydrique et les systèmes de culture. Ce bassin-versant, d'une superficie de 850 km², est délimité au sud par une Sierra volcanique et au nord par le lac Managua. En moins de 30 km, on passe de 60 m à plus de 900 m d'altitude, du climat tropical à saison sèche au climat tropical perhumide. Dans ce cadre, des observations ont été réalisées à l'échelle de plusieurs petits bassins-versants (1 ha à 15 km²) ainsi que localement sur des zones où l'érosion est significative. Parmi celles-ci, une attention particulière a été portée aux zones de piémont (glacis, bas et haut piémont) où les sols se caractérisent par la présence de talpetate. Les données disponibles se réfèrent au bassin-versant du Municipio "Los Altos de Santo Domingo", situé à 5 km au sud-est de Managua. Elles sont constituées par des mesures de ruissellement obtenues sous pluies simulées et d'humidité à la sonde à neutrons (Prat, 1989,1991 et 1992).

2. METHODES D'ETUDE
2.1. Régime et érosivité des pluies.

Cet aspect concerne l'Equateur et le Mexique où pour interpréter les résultats issus des parcelles de ruissellement il est nécessaire de déterminer ce type d'information (De Noni et al., 1990 et 1992, Quantin, 1992). Les hauteurs de pluies et les intensités correspondantes ont été mesurées avec des pluviographes. Sur les enregistrements pluviographiques, chaque pluie est découpée en segments de pente constante permettant ainsi de déterminer le début, la fin et la quantité d'eau en mm de la partie de pluie considérée. Ensuite, les données sont organisées par classes d'intensité et de fréquence d'occurrence.

Les observations effectuées en Equateur montrent que les appareils de rotation journalières ou mensuelles sont plus précis que ceux de rotation hebdomadaires car ils permettent d'identifier sur les enregistrements, outre les classiques intensités maximales (IM) en 30 minutes, des IM de 15 à 5 minutes. Dans plusieurs cas, les relations entre les intensités et les pertes en terre ont été meilleures avec les IM15.

Seules quelques pluies d'intensités remarquables sont responsables de plus de 60% de l'érosion totale. L'érosivité des pluies est donc un facteur déterminant. Elle est calculée conventionnellement selon la formule établie aux USA par le Service de Conservation des Sols (Wischmeier et Smith, 1978) où pour chaque événement on utilise le coefficient E.I30. E est l'énergie cinétique, I30 l'intensité moyenne pendant 30 minutes, le résultat étant exprimé en système métrique international (MJ/ha x mm/heure).

2.2. Mesures du ruissellement et de l'érosion.

Quelle que soit la surface des sites expérimentaux, le ruissellement a été calculé à partir du volume mesuré dans les cuves de sédimentation situées au pied des parcelles de ruissellement (Equateur et Mexique, De Noni et al. 1990, Quantin, 1992) et des enregistrements limnigraphiques sur les petits bassins-versants du Nicaragua (Prat, 1989). Les poids de terre sont évalués par pesées dans les cuves ou fosses de sédimentation et exprimés en poids sec (kilo. ou tonne) par hectare (ha) et pour une période déterminée. Pour de petites parcelles, de 6 à 44 m² au Mexique et de 100 m² en Equateur, ce type de mesure permet de relier un prélèvement à une pluie.

La méthode se complique lorsque les mesures sont effectuées sur des surfaces plus grandes, hormis sur bassins-versants où les hydrologues, qui possèdent une longue expérience en la matière, savent dimensionner correctement les fosses de sédimentation et les déversoirs correspondants. Sur les grandes parcelles de ruissellement, de 500 à 1000 m², face au caractère aléatoire des événements on ne peut conseiller que de surdimensionner le dispositif de récupération des eaux et des terres. C'est ainsi qu'en Equateur, les plus grandes parcelles (1000 m²) ont été équipées d'une série de 4 cuves avec partiteurs représentant un volume total proche de 75 m³. Durant les 5 années d'observation, aucun débordement n'a été constaté. Les prélèvements ont été réalisées manuellement et après chaque pluie. Cette méthode est certes contraignante mais sûre. L'utilisation d'un système mécanique de prélèvement par échantillonnage telle la roue de "Coshocton" permet en principe d'alléger le protocole de mesures mais peut aussi causer des problèmes importants si son installation est imparfaite comme le montre l'exemple mexicain.

2.3. Mesures hydrodynamiques.

2.3.1. La simulation de pluie.

En Equateur et au Nicaragua, le simulateur utilisé est l'appareil mis au point à l'ORSTOM par Asseline et Valentin (1976). Il est composé d'une tour pyramidale de 4 m de haut au sommet de laquelle est fixé un système d'aspiration électronique doté d'un gicleur calibré. Ce dernier est animé d'un mouvement pendulaire dont l'énergie est fournie par une batterie et il est alimenté...
régulièrement en eau, à pression constante (0.6 bars). Il est ainsi possible en faisant varier l’angle de balancement de créer au sol, sur une parcelle de 1 m² de surface, des averses dont l’intensité est proche de celle des pluies naturelles (de 15 à 150 mm/h).

En fonction des buts recherchés et des conditions climatiques locales, les protocoles suivants ont été utilisés : en Equateur, les simulations ont duré 30 minutes pour des intensités de : 20 mm/h (plusieurs fois par an), 40 mm/h (fréquence bi-annuelle) et 60 mm/h (fréquence médiane). Entre chaque essai les temps de ressuyage sont de : 24 heures entre la première et la seconde pluie, 5 heures entre la seconde et la troisième pluie (Custode, De Noni et al., 1992);
- au Nicaragua, les intensités testées sont de fréquence annuelle (de 40 à 60 mm/h durant 15 à 30 minutes, quinquennale (90 mm/h durant 30 minutes) et décennale (120 mm/h durant 15 minutes). Chaque parcelle a reçu 2 pluies simulées à 24 heures d’intervalle (Prat, 1989, 1992).

2.3.2. Régime hydrique.


2.3.3. Evolution des états de surface.

Par ailleurs, des expérimentations de laboratoire ont été réalisées sur 7 classes de taille d’agréagat obtenu après fragmentation contrôlée. Différents tests ont été appliqués sur ces agrégats : stabilité à une pluie simulée, capacité de rétention en eau, vitesse d’infiltration, porosité, fonte des agrégats par effet “splash” et par ruissellement (Quantin, 1992).

3. RESULTATS.

3.1. Régime des pluies et érosivité.

3.1.1. Régime général.

Dans la Sierra équatorienne, le climat est équatorial à 2 saisons des pluies (septembre à novembre puis de mars à mai) séparées par une petite saison sèche qui correspond à l’hiver de Noël et une vraie saison sèche estivale qui s’étend de mi-juin à août. Les conditions générales sont comparables à celle de Mexico : gradient positif de pluie avec l’altitude et gradient négatif des températures mais les micro-climats sont particulièrement accusés. Les neiges éternelles sont atteintes au dessus de 4800 m d’altitude.
La cangahua s’observe entre 2200 et 2900 m (au-dessus elle perd son induration) ; ces conditions correspondent à une moyenne annuelle de pluies comprise entre 500 et 800 mm et une température...
moyenne annuelle de 13 à 16 °C avec des variations mensuelles qui ne dépassent pas 1 °C autour de ces moyennes. Le régime hygrothermique est ustic-isomésic.

Le climat de la région de Mexico et de Tlaxcala est un climat intertropical différencié en raison de l'altitude (2200 à 5465 m) et d'effets de versants; les températures moyennes mensuelles varient peu : seulement 6°C au cours de l'année (Quantin, 1992).

De la vallée de Mexico au sommet de la Sierra Nevada, on distingue quatre zones climatiques caractérisées par une pluviosité croissante (totaux annuels et répartition) des températures de plus en plus froides et un régime hygrothermique passant de l'ustic-isomésic au cryic caractérisé par de fortes différences de températures diurnes. Il gèle et neige surtout en hivers.

Les tepetates sont présents seulement dans l'étage bas entre 2200 et 2800 m d'altitude; la température est comprise entre 15 et 11 °C; la pluviométrie moyenne annuelle oscille entre 600 et 900 mm; la région appartient à la zone intertropicale nord définie par des pluies estivales de 6 mois (mai à novembre) dont 2 à 1 mois subhumides et 4 à 5 mois subarides (décembre à mars). Le régime hygrothermique est ustic-isomésic. Il s'agit donc d'un climat tempéré à pluies d'été et 6 mois de saison sèche hivernale à peine plus froide.

Au Nicaragua, la zone concernée par les talpetates s'étend depuis la côte ou le lac de Managua jusqu'à 1000 m d'altitude. Le climat est tropical sec (moins de 1000 mm) près de la côte puis tropical humide sur les reliefs (1600 mm). En dessous de 500 m où les talpetates sont le mieux représentés, la température moyenne annuelle est élevée 27 à 29 °C avec de faibles variations des moyennes mensuelles. La saison des pluies est estivale, légèrement bimodale et dure 6 mois avec un maximum en mai et un autre en septembre; les autres 6 mois sont subarides. Le régime hygrothermique est ustic-hyperthermic (Prat et al. 1992).

3.1.2 Variabilité interannuelle des pluies.

On remarque qu'au Mexique l'irrégularité est inverse au nombre de jours de pluies.

En Équateur, dans les bassins intracordillères (Pourrut et al., à paraître) ont montré que pour des totaux annuels de pluies inférieurs à ceux de Mexico, la variabilité interannuelle est moyenne. Dans le tableau ci-après sont données la valeur moyenne de la pluie ainsi que les valeurs décennales et centennales calculées à partir des données existantes.

<table>
<thead>
<tr>
<th>Irrégularité interannuelle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tulcán</strong> k₃ = 1.76*</td>
</tr>
<tr>
<td>100 années sèches = 500 mm</td>
</tr>
<tr>
<td>10 années sèches = 646 mm</td>
</tr>
<tr>
<td><strong>Ibarra</strong> k₃ = 1.77</td>
</tr>
<tr>
<td>100 années sèches = 380 mm</td>
</tr>
<tr>
<td>10 années sèches = 466 mm</td>
</tr>
<tr>
<td><strong>QUITO-OBSERVAT.</strong> k₃ = 1.59</td>
</tr>
<tr>
<td>100 années sèches = 570 mm</td>
</tr>
<tr>
<td>10 années sèches = 947 mm</td>
</tr>
<tr>
<td><strong>AMBATO</strong> k₃ = 1.91*</td>
</tr>
<tr>
<td>100 années sèches = 260 mm</td>
</tr>
<tr>
<td>10 années sèches = 341 mm</td>
</tr>
<tr>
<td><strong>LOJA</strong> k₃ = 1.55</td>
</tr>
<tr>
<td>100 années sèches = 530 mm</td>
</tr>
<tr>
<td>10 années sèches = 645 mm</td>
</tr>
</tbody>
</table>

* Coefficient d'irrégularité interannuelle (k₃ = quotient des valeurs décennales humides et sèches).
Ce sont des valeurs moyennes à comparer avec $K_3 > 2.5$ sur la côte et $K_3 < 1.3$ en Amazonie où ce coefficient est particulièrement faible.

De cette étude on peut également faire ressortir que la variabilité est d'autant plus forte que les périodes sèches sont marquées et que les totaux pluviométriques moyens sont faibles. Cette observation est tout à fait conforme à la situation observée au Mexique: le quotient $P$ annuel et nombre d'évènements pluviaux est un bon indicateur de la variabilité.

Au Nicaragua, la position régionale des zones à talpetate et l'existence d'une saison sèche font conclure à une forte variabilité interannuelle dans les parties basses.

### 3.1.3. Variabilité stationnelle.

La variabilité des précipitations est importante d'un site à l'autre comme le montre l'exemple mexicain (Quantin, 1992). Cependant, quelle que soit l'ampleur de cette variabilité, d'un site à l'autre ou entre les trois pays considérés, on peut noter une relative similitude de comportement vis à vis de l'érosion : l'érosion est toujours le fait de quelques pluies.

En Equateur, sur 5 années d'observation, on a mis en évidence que dans ce pays où les intensités sont faibles à moyennes, quelques événements majeurs ($IM_{15}$ pouvant atteindre 80 mm/h et $IM_{30}$ de 40 à 55 mm/h) sont responsables de plus de 85% de l'érosion (De Noni, Nouvelot et al., 1984, De Noni, Viennot et al., 1990 et 1992).

Il en est de même au Mexique. On observe, en effet, que 1 à 2 pluies moyennement érosives à El Carmen, 2 pluies fortement érosives et 3 pluies moyennement érosives à Tlalpan enfin, 1 pluie fortement érosive et 3 pluies moyennement érosives à Matlalohcan causent à elles seules 60 à 80% de l'érosion totale. Les pluies fortement érosives sont celles où $I_{30} > 50$ mm/h. Dans le tableau ci-dessous sont récapitulées ces observations:

<table>
<thead>
<tr>
<th>Station</th>
<th>Pluie H mm</th>
<th>E. I30</th>
<th>Alm N jours</th>
<th>U. Am</th>
<th>Lal</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Carmen</td>
<td>779</td>
<td>120</td>
<td>234</td>
<td>261</td>
<td></td>
</tr>
<tr>
<td>Matlalohcan</td>
<td>775</td>
<td>96</td>
<td>429</td>
<td>418</td>
<td>330</td>
</tr>
<tr>
<td>Tlalpan</td>
<td>803</td>
<td>112</td>
<td>357</td>
<td>330</td>
<td></td>
</tr>
</tbody>
</table>

Au Nicaragua, les données disponibles sont ponctuelles pour l'instant et estimées sur bassins-versants. On constate, également, que l'action de l'érosion régressive en ravines est en relation avec des pluies exceptionnelles, par leur intensité et leur durée. Ainsi au niveau de la zone basse (glacis de piémont), la pluie du 16 mai 1985, d'une hauteur de 216 mm en 90 minutes a provoqué la formation d'une ravine de 100 m de long, de 20 m de large et de 3 m de profondeur, soit 6000 tonnes de terres arrachées. Sur des bassins cultivés, des pluies plus normales, de l'ordre de 100 mm, provoquent des taux d'érosion de 35 t/ha (Prat, 1989).

### 3.2. Mesures du ruissellement et de l'érosion.

#### 3.2.1. Sols indurés non ameublis.

Les mesures effectuées au Mexique, dans la province de Mexico, à San Miguel Tlaixpan sur tepetate nu, font ressortir la très forte valeur du coefficient de ruissellement 83 à 92% pour les 4 principales pluies soit une moyenne de 88.5% et des pertes en terre de 5 t/ha pour chacune des 2 années d'observation sur parcelles Wischmeier contre 12 t/ha sur un petit bassin versant de 1800 m² (Prat et al., 1993; Marquez et al. 1994).

A Tlaxcala les 3 sites montrent des ruissellements importants (65 à 70%) et des valeurs d'érosion faibles (6 à 10 t/ha) sauf à Tlalpan où elles atteignent 30 t/ha.
En Equateur grâce à la simulation de pluie on a pu mesurer le ruissellement et évaluer la charge solide des sédiments. On a ainsi obtenu des coefficients de ruissellement de 80% pour une intensité de 20 mm/h et de 91% pour une intensité de 60 mm/h. Ces valeurs se stabilisent rapidement et dans tous les cas en moins de 10 minutes. Dans ces conditions la charge solide du ruissellement est nulle, ce qui est conforme aux observations.

En conclusion, c'est toujours sur sol nu induéré, quelle que soit l'intensité de la pluie, que l'on observe les plus forts ruissellement: selon la dureté de l'induration et l'état de décapage de cette surface l'érosion est variable. Si la perte en terre est limitée, les ruissellements engendrent en aval une érosion régressive qui peut conduire à des catastrophes, les pertes en terre se chiffrant alors en centaines de tonnes.

<table>
<thead>
<tr>
<th>Sol antique, nus</th>
<th>année</th>
<th>CR</th>
<th>E t/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Miguel Tlaixpan</td>
<td>Texcoco-Mex.</td>
<td>90-91</td>
<td>69</td>
</tr>
<tr>
<td>El Carmen</td>
<td>68</td>
<td>6.9</td>
<td></td>
</tr>
<tr>
<td>Matlolohcan</td>
<td>Tlaxcala-Mex.</td>
<td>90-91</td>
<td>69</td>
</tr>
<tr>
<td>Tlaixpan</td>
<td>67</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Tumbaco</td>
<td>Quito-Equat.</td>
<td>Simulat.</td>
<td>85</td>
</tr>
</tbody>
</table>

Simulat. = par simulation de pluie

3.2.2. Sols indurés ameublis.

3.2.2.1. Sols non cultivés.
Ils correspondent aux trois essais suivants:

- **sols rippés ameublis en gros éléments**: cette opération correspond à un rippage avec un engin lourd à chenilles de type "D8" qui laisse en surface une forte proportion de gros éléments (de 0.5 à 5 cm) de forme anguleuse.

<table>
<thead>
<tr>
<th>Sous sols, nus</th>
<th>année</th>
<th>CR</th>
<th>E t/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Miguel Tlaixpan</td>
<td>Texcoco-Mex.</td>
<td>90-91</td>
<td>-</td>
</tr>
<tr>
<td>Matlolohcan</td>
<td>Tlaxcala-Mex.</td>
<td>90-91</td>
<td>32</td>
</tr>
<tr>
<td>Tumbaco</td>
<td>Quito-Equat.</td>
<td>Simulat.</td>
<td>0</td>
</tr>
</tbody>
</table>

Simulat. = par simulation de pluie

A San Miguel Tlaixpan, dans le bassin de Texcoco, le ruissellement n'est pas connu mais il est logique de considérer qu'il est faible et comparable aux résultats obtenus à Tumbaco. Dans cette station la simulation de pluie a montré que le sol superficiel couvert de gros "éléments structuraux" ne commençait à ruisseler qu'après 45 minutes sous une pluie de 100 mm/h. Cet événement a une probabilité très faible ; en effet il dépasse largement la pluie décennale qui est seulement de 55 mm/h pour cette même durée de 45 minutes! A Matlolohcan, le ruissellement comme l'érosion sont élevés en relation avec des pluies très érosives.

Un important taux d'éléments structuraux grossiers superficiel réduit l'effet cinétique des pluies la formation de la croûte de battance est retardée : le ruissellement et l'érosion restent faibles

- **sols rippés puis labourés (ameublis et émiettés)**: ces traitements correspondent à un rippage suivi d'un ou plusieurs pulvérisages poussés qui éliminent presque tous les gros éléments afin d'obtenir un bon lit de semences.

Dans des conditions que l'on pourrait considérer comme favorables aux cultures, on observe des coefficients de ruissellement très élevés 23 à 70% selon les stations et des érosions pouvant dépasser 100 t/ha ce qui constitue des valeurs excessives.
A la station de Tumbaco sur une parcelle de type Wischmeier qui reproduit cet état de surface, le coefficient de ruissellement annuel est relativement modéré mais l'érosion est importante puisqu'elle oscille entre 70 et 120 t/ha/an selon les années. Les plus fortes valeurs d'érosion ont toujours été obtenues dans ces conditions. Les pertes en suspension représentent 30% du total. Les coefficients de ruissellement annuels et mensuels restent modérés mais ils peuvent sous quelques pluies atteindre 90% et donner lieu à des érosions exceptionnelles. Les mois les plus pluvieux : octobre, novembre et de mai qui ont des coefficient de ruissellement ne dépassant pas 35% donnent lieu à des érosions importantes. Au mois d'août, les rares précipitations accompagnées de chutes de grêle très localisées donnent lieu à des coefficients de ruissellement particulièrement forts. Sur le tableau ci-après on notera l'absence de corrélation entre la pluie, le coefficient de ruissellement et l'érosion.

<table>
<thead>
<tr>
<th>Station</th>
<th>Année</th>
<th>CR %</th>
<th>E t/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Miguel Tlaixpan</td>
<td>90-91</td>
<td>45</td>
<td>5-22</td>
</tr>
<tr>
<td>El Carmen</td>
<td>90-91</td>
<td>34</td>
<td>77</td>
</tr>
<tr>
<td>Matlolochan</td>
<td>90-91</td>
<td>69</td>
<td>9.3</td>
</tr>
<tr>
<td>Tlaxcala</td>
<td>90-91</td>
<td>43</td>
<td>128</td>
</tr>
<tr>
<td>Quito</td>
<td>86-91</td>
<td>23</td>
<td>92</td>
</tr>
</tbody>
</table>

Lorsqu'il y a diminution de la taille des éléments structuraux ceux ci deviennent plus fragiles; il y a formation d'une croûte de battance qui favorise le ruissellement. Les grosses pluies donnent lieu à des phénomènes d'érosion intense.

- **sols rippés, pulvérisés et billonnés**: le billonnage conjugué à un rippage gomme les effets catastrophiques du pulvérisage : à San Miguel Tlaixpan, le ruissellement reste assez élevé (CR de 12%), mais l'érosion qui est de l'ordre de 1 t/ha est très faible; cependant l'expérience montre que cette stabilité a des limites. Au delà de 50 mm/h pendant 30 mn les billons ne résistent plus à la pression dans le billon. A Tumbaco, la première pluie (52 mm) de la saison 86-87 a donné lieu à une érosion de 19 t/ha sur un sol fraîchement pulvérisé où les billons se sont rompus en cascade.

<table>
<thead>
<tr>
<th>Station</th>
<th>Année</th>
<th>CR %</th>
<th>E t/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Miguel Tlaixpan</td>
<td>90-91</td>
<td>12</td>
<td>1</td>
</tr>
</tbody>
</table>

3.2.2.2. Sols indurés ameublis et cultivés
Deux types d'essais ont été considérés:

- **sols rippés, labourés, billonnés et avec maïs**: cette modalité a été étudiée dans le bassin de Texcoco à San Miguel Tlaixpan, dans la province de Tlaxcala et à Tumbaco en Equateur.
Les ruissellements sont faibles à modérés, l'érosion est moyenne mais peut prendre des valeurs relativement élevées lorsque sous l'action de fortes pluies les billons se rompent; ce phénomène s'amplifie quand le temps de culture augmente.
- sols rippés, labourés, billonnés avec mesures conservatoires et maïs : grâce aux parcelles de Tumbaco, on peut se faire une idée de l’efficacité du billonnage complété par des ouvrages conservatoires : ici des bandes enhérbées isoïques espacées de 10-15 m. D’autres essais ont montré que sur une même pente de 20%, les terrasses progressives les murets constitués de blocs de cangahua ont un rôle comparable.

<table>
<thead>
<tr>
<th>Sols solés, labourés, billonnés avec mesures conservatoires, maïs</th>
<th>CR</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Miguel Tlaixpan, Texcoco-Mex. 90-91</td>
<td>5</td>
<td>1.2</td>
</tr>
<tr>
<td>El Carmen Tlaxcala-Mex. 90-91</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>Tlaxpan 90-91</td>
<td>15</td>
<td>2.6-26</td>
</tr>
<tr>
<td>Tumbaco Quito-Equat. 86-91</td>
<td>8.5</td>
<td>19</td>
</tr>
</tbody>
</table>

Dans ces conditions le ruissellement et l’érosion sont minimaux : respectivement 1.5 à 9% selon les années et moins de 1 t/ha de suspension.

3.3. Les mesures hydrodynamiques.

3.3.1. Simulations de pluies.

**En Equateur**, les essais ont été effectués sur cangahua naturelle à nu et sur cangahua défoncée à la pioche (Custode, De Noni et al., 1992). Les agrégats sont grossiers (> 2 mm) et irréguliers. Cette situation simule la reprise du matériau pour la culture telle qu’elle se pratique traditionnellement. Sur cangahua nue, les coefficients de ruissellement sont forts comme sur le tepetate mexicain: de 80% pour une intensité de 20 mm/h et de 91% pour une intensité de 60 mm/h. Ces valeurs s’obtiennent rapidement et dans tous les cas en moins de 10 minutes. En revanche, la charge solide du ruissellement est nulle ce qui diffère des observations effectuées sur parcelles de tepetate. Il semblerait donc que les cangahuas équatorriennes des bassins intra-andins soient plus résistantes à l’érosion. Sur cangahua défoncée, le ruissellement et l’érosion sont nuls pour tous les essais. Pour le moins la première année, avant qu’intervienne la fonte des agrégats, la cangahua est relativement stable.

**Au Nicaragua**, les simulations de pluies ont permis de mettre en valeur l’action du travail et du degré de couverture du sol contre l’érosion. Comme en Equateur, c’est sur le sol superficiel à talpetate, compacté et nu, que le ruissellement est le plus fort: pour une intensité de 65-70 mm/h durant 90 minutes et une pluie utile de 100 mm, la lame ruisselée est supérieure à 30 mm sur sol sec et à 40 mm sur sol saturé. L’introduction d’une couverture sur le sol permet de réduire considérablement ces valeurs. Ainsi des morceaux ou des blocs de talpetate, de la même façon qu’une bonne couverture végétale ou de débris organiques, contribuent à protéger efficacement le sol contre l’érosion. Les éléments grossiers de talpetate, outre leur texture argileuse qui retient l’eau, absorbent l’énergie des gouttes de pluie et freinent le ruissellement par la rugosité qu’ils créent en surface. Par exemple, pour un sol couvert à plus de 80% par de la végétation, des débris de maïs ou des morceaux de talpetate, la lame ruisselée est inférieure à 5 mm. En revanche, un sol profond, labouré fraîchement et nu est très érodible. Son comportement est proche du sol superficiel nu: la lame ruisselée est de l’ordre de 20 mm sur sol sec et dépasse également 40 mm sur sol saturé (Prat, 1989, Prat et al. 1992).
3.3.2. Régimes hydriques.

La porosité globale du tepetate est supérieure à 40%; elle augmente à près de 60% par suite du labour. On constate cependant qu'elle se réduit progressivement au cours de la saison des pluies pour redescendre à 50% par effet de la fonte des agrégats et du tassement. De la même façon, la vitesse d'infiltration, qui s'est élevée de 1 mm/h à 100 mm/h sur les billons et à 50 mm/h dans les sillons, a régressé à 10 mm/h sur les bilons et à 2 mm/h seulement dans les sillons (Quantin, 1992).

Le régime d'humidité d'un tepetate cultivé est comparable à celui d'un sol argilo-sableux normal. Dans un tepetate pulvérisé à la façon locale, l'humidité atteint le point de flétrissement pendant la saison sèche. Pour une pulvérisation plus fine (agrégalets < 2 mm), le sol maintient une réserve utile pour la plante durant toute l'année. En revanche, pour un tepetate naturel à nu, l'humidité demeure en dessous du point de flétrissement une grande partie de l'année.

Au Nicaragua, la réserve en eau est plus importante encore (> 50% du volume du sol). Dans ces conditions, le talpetate se comporte comme un sol limono-argileux (Prat, 1992). La plante peut ainsi continuer de s'alimenter correctement durant la saison sèche. En outre, les observations montrent que le horizont induré ne ralentit pas la progression du front d'humectation, du moins pour des pluies peu érosives. Pour de fortes pluies, la progression de ce front est tout de même ralentie provoquant une accélération du ruissellement et une érosion des horizons de surface.

3.3.3. Évolution des états de surface.

- il y a toujours formation d'une croûte, d'abord structurale sur le billon (effet splash de la pluie) puis de dépôt dans le sillon, quand l'infiltration est assez lente pour entraîner une érosion superficielle du billon;
- cette évolution est progressive au cours de la première période du cycle culturel (du semis au premier sarclage). Elle s'accélère par la suite du fait de la réduction de la taille des agrégats et de l'accroissement de l'érosivité des pluies. La taille des agrégats joue donc un rôle important: ce sont ceux plus petits que 2 mm qui fondent rapidement et déclenchent le processus d'encroûtement. En comparaison, le processus est plus rapide sur le sol labouré en la fonte des agrégats presque totale, entrainant la formation d'une croûte de dépôt plus épaisse et plus intense;
- sur tepetate labouré et non billonné, la croûte se généralise, le ruissellement s'accélère et il se développe une érosion linéaire en griffes. La présence de billons permet de maîtriser complètement le ruissellement et l'érosion, pour le moins dans les conditions climatiques observées en 1990-91. Mais on peut craindre que les billons soient inefficaces pour des pluies plus érosives (> 30 mm/h).

4. INTERPRETATION ET DISCUSSION.

4.1. Les sols indurés en conditions naturelles: un environnement fragile et instable.

Le rôle premier de l'induration et en second lieu de l'environnement naturel (montagnes volcaniques, climat-végétation) font que les sols à horizons indurés constituent un milieu propice à l'érosion hydrique.

4.1.1. le rôle premier de l'induration.

En règle générale, ces horizons indurés n'affleurent qu'après le décapage du sol meuble qui les coiffe. Progressivement, les horizons de surface disparaissent par érosion hydrique et laissent
affleurer de larges plages indurées. Dans tous les cas, l'induration modifie les conditions d'infiltration et de régime hydrique. Il en résulte une faible perméabilité (conductivité hydraulique de l'ordre de 1 mm/h en laboratoire au Mexique et de 5 à 15 mm/h au champ en Equateur) qui bloque la percolation de l'eau. Les coefficients de ruissellement sont donc élevés : ils provoquent une érosion en nappe sur l'horizon induré et une reprise d'érosion sur les sols proches non indurés. En Equateur comme au Mexique, si les pertes en terre sont inférieures à 10 t/ha/an, les coefficients de ruissellement dépassent 70%, voire 80 à 90% lors de fortes pluies.

Le comportement des talpetates du Nicaragua est quelque peu différent. Le talpetate est plus perméable mais aussi plus sensible à l'érosion en ravines et en rigoles.

4.1.2. L'environnement naturel.

L'influence des reliefs volcaniques n'est pas négligeable. La dénivellation relative entre le pied des versants et le sommet des volcans est impressionnante: 1000 m au Nicaragua, de l'ordre de 2000 m au Mexique, près du double en Equateur. En général, les horizons indurés se trouvent en zone de piémont où se concentre et agit efficacement le ruissellement après avoir pris naissance, à l'amont, sur des versants réguliers et pentus (40-70%).

L'incidence du climat intervient aussi, d'une part sur la répartition de la végétation et d'autre part sur l'érosivité des pluies. En Equateur, des simulations de pluies d'intensité faible (20 mm/h durant 30 minutes) ont montré que le régime permanent est atteint en moins de 10 minutes et que le ruissellement dépasse 80%. La circulation de l'eau est d'autant plus efficace que la couverture végétale est discontinue, ce qui est généralement le cas dans les zones à horizons indurés. Ils sont peu à très mal couverts, si ce n'est la présence de plantes xérophytiques dans des zones privilégiées d'atterrissage.

Aux contraintes physiques imposées par l'environnement, s'ajoutent des contraintes chimiques qui s'expriment par une forte carence en azote et phosphore. Ces sols constituent donc en l'état naturel un milieu quasi stérile, impropre à l'agriculture.

4.2. Les sols indurés en conditions de réhabilitation : une érosion active et maîtrisable, une exploitation productive et durable.

Les essais de réhabilitation sont plus avancés au Mexique où on utilise de puissants tracteurs pour riper et pulvériser les horizons indurés. En Equateur, hormis quelques travaux mécanisés subventionnés par l'Etat, la méthode manuelle au pic est la plus employée. Les études menées dans ces 2 pays sur parcelles de ruissellement montrent qu'en pulvérisant l'horizon induré, on crée de nouvelles conditions d'hydrodynamique et d'érodibilité.

En effet, lorsque ces sols sont travaillés superficiellement, la compétence du ruissellement augmente et les pertes en terre sont importantes. L'érosion augmente en fonction de la diminution de la taille des agrégats (< 2 mm) et l'érosivité des pluies devient le facteur prédominant.

4.2.1. Sur matériau rippé non billonné.

Au Mexique et en Equateur, quelle que soit la profondeur du labour, on constate, par rapport au sol induré originel, une relation étroite entre les valeurs du ruissellement, les pertes en terre élevées et quelques pluies érosives qui provoquent la fonte des agrégats. Sur tepetate et sur cangahua cultivés, le ruissellement varie selon l'érosivité des pluies de 10-20% à 30-40% et les pertes en terre sont importantes, de 70 à 130 t/ha/an.
4.2.2. Sur matériau rippé et billonné.

Le billonnage réduit le ruissellement et freine l'érosion lorsque l'intensité des pluies est faible. Pour des pluies plus érosives, ces valeurs augmentent et atteignent des valeurs trop élevées: 10 à 15% de ruissellement et de 20 à 40 t/ha/an en Equateur et au Mexique. Au Nicaragua, on note les mêmes tendances: au delà de 15% de pente, les billons sont crevés par le ruissellement et l'érosion en griffes est active. Dans ces conditions, le billonnage n'est efficace que combiné avec d'autres méthodes conservatoires, d'autant plus que dans les trois pays le sol est fortement destructuré par les pratiques culturelles. Au dessous de 2 mm, les agrégats se transforment rapidement en une croûte imperméable.

4.2.3. Sur matériau rippé, billonné et avec ouvrages conservatoires.


C'est pour éviter ce type de problème qu'en Equateur il a été décidé de lutter contre l'érosion en utilisant des ouvrages simples et proches des traditions locales, du type micro-barrages perméables évoluant progressivement en pseudo-terras. Des enquêtes socio-agricoles ont permis d'identifier des matériaux autochtones qui pourraient constituer l'architecture de ces ouvrages. C'est ainsi que nous avons été conduits à tester des bandes herbeuses de 1 m de large et de petits murets en blocs de cangahua (de 0.4 à 0.6 m de haut initialement), l'ensemble étant disposé de manière isohygrique avec un espace de 10 à 12 m entre ouvrages. Le coût estimé à l'hectare est bas, moins de 100 US$. Durant les 5 années d'observations, on a constaté une diminution importante de l'érosion: ruissellement compris entre 1.5 et 4%, pertes en terre inférieures à 5 t/ha/an (De Noni et al., 1992). Ces valeurs faibles permettent d'envisager une mise en valeur des sols rippés que confortent les essais menés au Mexique sur la fertilité. L'équipe mexicaine a montré, en station et au laboratoire, que les carences originelles de ces sols en azote et phosphore pouvaient être corrigées par une fertilisation adaptée à la plante, soit minerale (N 60 à 120 et P 60) soit organique (fumure). Ces essais ont permis d'obtenir des rendements satisfaisants: presque normaux dès la première année pour le blé, l'orge, le haricot et la vesce; plus tardifs, à partir de la 2ème voire la 3ème année pour le maïs ou la fève (Quantin, 1992, Marquez et al., 1992, Baez et al., 1994, Chora et al., 1994).

Les études menées en Equateur, au Mexique et au Nicaragua sont très complémentaires et permettent d'énoncer, grâce à une meilleure connaissance du comportement hydrodynamique et de l'érodibilité des sols indurés, quelques principes relatifs à une gestion mieux adaptée et plus durable des paysages volcaniques. Il ressort de cette analyse comparative que:

- les sols indurés sont très sensibles au ruissellement en conditions naturelles. Avant d'entreprendre des projets de réhabilitation, il est nécessaire d'abord de contrôler la circulation de l'eau qui met en danger la stabilité des zones bordières;
- il est possible, après ripillage, de corriger par des amendements adaptés les carences chimiques. Il est ainsi envisageable d'obtenir des rendements corrects;
- pour que la productivité soit durable, il est nécessaire d'installer sur les parcelles des ouvrages conservatoires car l'horizon rippé devient très érodible;
- le coût global des opérations est cependant très élevé pour de petits propriétaires qui sont les plus concernés. Le rôle de l'Etat semble nécessaire pour pouvoir concrétiser à l'échelle régionale des projets de ce type.
Littérature citée


Baez, A., Prat, C., Marquez Ramos, A. et Chora, A., 1994 - Premiers résultats d’essais agronomiques visant à la réhabilitation agricole du tepetate t3 (Texcoco, Mexique) : I. Cas de l’orge et de la vesce. Dans ce volume.


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Pourrut, P. et al. 1994 (à paraître). L'homme et l'eau, Ed. ORSTOM.


Fertilidad de los Suelos Volcánicos Endurecidos: Características Químicas y Microbiológicas de los Tepetates de México

Abstract. The social and economic importance of the indurated volcanic soils, particularly in Latin-America, is well documented. These soils are common in Mexico, Nicaragua, Colombia, Ecuador, Peru, and Chile where local names (tepetates, talpetates, cangahua, sillares, terteles, fierrillo) are used. They have been also described in Japan (masa, kora, nigatsuchi). A common condition of most indurated volcanic soils developed under dry climate is an extreme fragility and low fertility, which make them scarcely productive or non-productive at all. Previous work has shown that physical and chemical amelioration of these materials is possible. Improvement of both soil physical conditions and availability of some plant nutrients, mainly, nitrogen and phosphorus, are paramount in this process. Increasing the organic carbon content and the microbial activity are also important steps in achieving higher productivity.

The indurated volcanic soils in low rainfall areas present chemical characteristic related to soil fertility which differ from soils developed under somewhat more humid conditions. The latter contain much less CaCO₃ than those developed in arid or semiarid conditions. This difference makes the pH, and the Ca, Mg and K content lower than in the former. The low availability of phosphorus is a common feature in all indurated volcanic soils, as well as, the moderate to high level of exchangeable potassium.

The organic matter, and consequently nitrogen and carbon, are practically non-existent in the indurated volcanic soils of semi-arid and arid regions when in natural conditions. Although, high values have been reported in the soils developed in more humid conditions. A prime concern in the rehabilitation of these soils is to achieve an increment of the organic carbon and the microbial activity. Both roturation of the hardened material and addition of organic matter produce an increase in the oxygen consumption, an index of the microbial activity, and an increase in the population of bacteria, actinomycetes and fungi.

The productivity of indurated volcanic soils becomes equal to that of normal soils once the constraining factors (physical and chemical) have been removed.
Introducción. La importancia económica y social de los suelos volcánicos endurecidos está bien documentada. Estos materiales han sido objeto de numerosos estudios, particularmente en la región del Pacífico de todo el continente americano (cf. Zebrowski et al., 1992). En el caso particular de México, una parte importante de ellos se localiza en zonas de altura, con gran presión demográfica, con escasez de tierra de producción, lo cual justifica los esfuerzos tendientes a su habilitación para la agricultura (Quantín, 1992a). Una situación similar debe haber ocurrido con los suelos volcánicos endurecidos de Japón, ya que prácticamente todos ellos fueron recuperados y actualmente se encuentra en producción (Yamada et al., 1994). En Ecuador se hacen esfuerzos por ampliar la superficie cultivada de suelos que presentan esta característica (Vera y López, 1992).

Una tarea prioritaria en la habilitación o rehabilitación de estos suelos, lo constituye el conocimiento de su fertilidad actual, así como la forma de optimizar el abastecimiento de los nutrimentos esenciales y reducir los efectos nocivos de ciertas substancias, para que los cultivos que en ellos se establezcan alcancen los rendimientos máximos posibles. Estos últimos rendimientos son determinados por un marco físico (factores edafológicos y climáticos) impuesto por la ubicación geográfica del lugar donde se sitúan. A pesar de que la importancia de la fertilidad de los suelos en la nutrición de los cultivos es de sobra conocida, el fenómeno ha sido poco estudiado en el caso los suelos volcánicos endurecidos, y en particular en los de América Latina. La mayor parte de la escasa información con que se cuenta proviene de trabajos hechos con otros propósitos, especialmente de clasificación y génesis de los suelos volcánicos endurecidos.

Los suelos volcánicos endurecidos se presentan en una gran diversidad de situaciones geográficas, clima, materiales parentales, son cementados por diversos agentes y han sido sometidos a diversos usos y sistemas de manejo en el pasado, todo lo cual, sin duda, influye en las fertilidad actual y potencial y en las propiedades químicas relacionadas con la nutrición de los cultivos, y hacen difícil establecer un patrón característico único para todos ellos.

Los diversos tipos de suelos volcánicos endurecidos. Los depósitos de tefras que presentan capas endurecidas, son comunes en el llamado Cinturón de Fuego del Pacífico (Quantín, 1992a; Zebrowski, 1992). De estos se han originado los materiales que concitan nuestro interés.

En América Latina los suelos volcánicos endurecidos se denominan localmente de varias maneras, pero estos nombres no son consistentes en cuanto al origen y tipo de material. En México se conocen como tepetates (Ruiz, 1987), en Nicaragua se les denomina talpetates (Rodríguez y Acuña, 1992; Prat y Quantín, 1992), en Ecuador se les llama cangahua (Vera y López, 1992), en Perú a ciertos flujos de cenizas volcánicas riolíticas pedocementadas se les nombra localmente sillares (Nimlos y Zamora, 1992), finalmente en el extremo sur del continente, en Chile, se presentan ciertos materiales volcánicos endurecidos en las regiones desérticas que se llaman terteles (W. Luzio. Comunicación personal) y en las regiones mediterráneas y húmedas de ese país se encuentran: un duripán fuertemente cementado o toba y un horizonte plácido cementado con hierro y materia orgánica, denominado localmente fierrillo, respectivamente (Besoain et al., 1992; Luzio y Saaavedra, 1992; Luzio et al., 1992). En Japón, también se tienen materiales volcánicos endurecidos que reciben nombres locales, como masa, kora, nigatsuchi y suelos volcánicos que presentan horizontes plácticos (Yamada et al., 1994). La gran diferencia entre estos últimos materiales y los que se encuentran en América Latina, con excepción de los fierrillos, es el elevadísimo contenido de carbono orgánico del primer horizonte (en general, mayor de 10%).
Los suelos volcánicos endurecidos y la problemática de la producción. En México Central y en Ecuador se encuentran grandes extensiones de materiales volcánicos endurecidos, pobres en carbono orgánico, que por su extrema fragilidad frente a la erosión y la profunda influencia que en ellos han ejercido los sistemas de manejo inadecuados (tala irracional del bosque nativo y prácticas agronómicas degradantes) han aflorado a la superficie, provocando un daño ecológico, social y económico nada despreciable. En contraste, en Perú, en los suelos volcánicos de la parte alta se han construido terrazas, llamadas andenes, que aparentemente se cultivan desde tiempos pretéritos (Nimlos y Zamora, 1992), sin que hayan sufrido mayor deterioro o su estabilidad se encuentre amenazada en el manejo actual. Una experiencia similar se ha observado en el estado de Tlaxcala en México, donde aún se conservan terrazas construidas en tepetates, que datan de época prehispánica (González, 1992). Lo anterior indica que, bien manejados, los suelos volcánicos endurecidos pueden representar un recurso de producción atractivo. Un caso similar a los anteriores, lo presenta el fierillo del Sur de Chile, material que se encuentra en su mayoría bajo una cubierta de pastos naturales, y no tiene serios problemas de erosión, aunque sí de drenaje (Besoaín et al., 1992). Otros suelos endurecidos, como los sillares y los tertules, se ubican en climas de baja precipitación, donde no se practica la agricultura, por lo que no son amenazados por procesos de degradación inducida (Nimlos y Zamora, 1992). Los suelos volcánicos endurecidos de Japón han sido, por el contrario, casi todos recuperados y se encuentran cultivados con pastos, maíz, papas, bosques, etc. (Yamada et al., 1994).

La recuperación y la incorporación de los suelos volcánicos endurecidos a un sistema de agricultura sostenible, ha requerido (y requerirá) de una remediación integral en la cual se consideren tanto el mejoramiento de las propiedades físicas (particularmente aquellas tendientes a establecer una zona de enraizamiento, una capacidad de almacenamiento de agua, y una porosidad adecuadas), como de las microbiológicas (en especial, el asegurar la presencia de una fuente de carbono rápidamente disponible que permita un aumento sustancial de la actividad microbiana, para que los residuos metabólicos de ésta contribuyan al mejoramiento de las propiedades físicas y nutricionales) y químicas (en particular, de aquellas relacionadas con la nutrición de los cultivos). En el caso específico de los suelos hidromórficos, también se ha considerado aspectos relacionados con el drenaje.

Los resultados de los estudios relacionados con la remediación física y prácticas agronómicas de los tepetates de México y los avances logrados en este aspecto son abundantes y se encuentran publicados (cf. Zebrowski et al., 1992). Estos incluyen roturación, nivelación, construcción de terrazas, construcción de bordos en los cuales se siembra nopal o maguey, surcos en contorno, reforestación, cultivos de rotación, cultivos en franjas, incorporación de altas cantidades de materia orgánica (estiércol de bovino o gallinaza) y de fertilizantes químicos para mejorar su nivel nutrimental e iniciarlos en la producción agrícola, así como estudios en relación a sus propiedades físicas y químicas, los cuales son fundamentales en el proceso de rehabilitación del tepetate (Avila, 1963; Cajuste et al., 1987; Cruz et al., 1992; Delgadillo et al., 1989; Etchevers et al., 1992; Oleschko et al., 1992; Pacheco, 1979; Rey, 1979; Zebrowski, 1992). Sin embargo, el conocimiento de las características químicas y microbiológicas de los suelos volcánicos endurecidos, así como las prácticas de fertilidad más adecuadas para su rehabilitación, son escasos para lograr una agricultura de tipo sostenible.

Los bajos niveles de ciertos elementos esenciales para el crecimiento y desarrollo de la planta que exhiben algunos suelos volcánicos endurecidos requieren de la aplicación de fertilizantes químicos y abonos orgánicos. El conocimiento de la dinámica de los nutrientes carenciales es necesario en el diseño de tales prácticas.
Los microorganismos juegan un papel fundamental en la nutrición de las plantas en los agroecosistemas. Esto se debe a sus múltiples actividades metabólicas, como son: la fijación de CO₂, la transformación de la materia orgánica y síntesis de humus. Los procesos de la fijación de nitrógeno atmosférico (N₂) y nitrificación hacen disponible este elemento a las plantas (Guzman y Ferrera-Cerrato, 1990). En cuanto al fósforo se libera por la solubilización de las rocas y es eficientemente traslocado a las plantas por la simbiosis micorríca que se establece (Jean, 1987). En las zonas perturbadas esta dinámica se ha alterado en forma dramática hasta dar como resultados suelos marginales (como los tepetates) que por su difícil manejo e infertilidad, requieren diferentes estrategias para incorporarlos a la producción (Ferrera-Cerrato, 1991). En México existen pocos trabajos relacionados con el estudio de la microbiología dentro del proceso de rehabilitación de los suelos volcánicos endurecidos; se han realizado algunas medidas parciales de evaluación de la actividad microbiana en tepetates no cultivados (Gómez et al., 1990; González, 1987; Matías et al., 1992; Palacios et al., 1991), las que se comentaran a continuación.

Del análisis de los pocos resultados disponibles se concluye que no es posible lograr la incorporación de los suelos volcánicos endurecidos a la agricultura, solamente mediante un mejoramiento de las condiciones químicas y microbiológicas, sin mejorar primero sus características físicas. Las primeras han recibido mucho menor atención que las últimas. Se conocen algunas características químicas de los materiales volcánicos endurecidos, que se revisan a continuación, y que se intenta ligarlas con la fertilidad actual y potencial de estos suelos. Así mismo se incluye información poco conocida relacionada con aspectos microbiológicos y el uso de los microorganismos en su remediación.

Algunas características generales de los suelos volcánicos endurecidos. Es probablemente en México donde los suelos volcánicos endurecidos, llamados extensivamente tepetates, han sido estudiados en mayor detalle en los últimos años, gracias a una colaboración franco-germano-mexicana, financiada por la ex-Comunidad Económica Europea (cf. Zebrowski et al., 1992). Las particularidades de estos suelos ya habían despertado el interés de otros científicos, quienes, investigaron algunas de sus características (Miehlich, 1984 y 1991; Ruiz, 1987). Los tepetates aflorados ya habían sido utilizados en producción agrícola por siglos, después de ser rehabilitados con tecnologías primitivas (Hernández, 1987). En el presente trabajo se hará particular alusión a los resultados de los estudios conducidos en México, por lo que es conveniente establecer algunas bases sobre los tepetates y su nomenclatura.

En ese país se ha determinado que los materiales que dieron origen a los tepetates más comunes (cf. Zebrowski et al., 1992) son depósitos de cenizas volcánicas finas (cineritas riolíticas), parcialmente alteradas a arcillas y llimo muy fino, producto de erupciones volcánicas muy violentas (Quentin et al., 1992). Estos materiales se han denominado como tepetates del tipo t2 y t3, en concordancia con dos series estratigráficas (T2 y T3) descritas por Heine (1978) y Miehlich (1991). Los principales minerales primarios observados en láminas delgadas de los tepetates son: vidrios riolíticos, plagioclases, horblenda y magnetita, además de un poco de hiperstenio y augita y pequeñas cantidades (trazas) de cuarzo y cristobalita, los cuales presentan diversos grados de alteración (Hidalgo et al., 1991). Previamente Valdez (1970) había descrito la presencia de limonita y hematita, en tanto que Pacheco (1979) y Rey (1979) indicaron haber detectado albita, andesina (una plagioclasa sódica) y ortoclasa.

En la fracción fina de un tepetate de la parte central de México, Hidalgo et al. (1992) observaron la presencia de haloisita y esmectita con diversos grados de cristalización y en diversas proporciones. Estos autores señalan que, en general, la esmectita es más abundante en el tepetate t2 y la haloisita en el t3. Por su parte, Rey (1979), al examinar la fracción arcillosa de los
tepetates, observó la presencia de illita y montmorillonita interestratificadas, así como de material amorfo. Cajuste y Cruz (1987a) señalaron que estos materiales amorfos son principalmente geles de sílice.

La presencia de sílice en el plasma matricial de ciertos tepetates es evidente, así como en la fracción arcillosa. Hidalgo et al. (1992) la atribuyeron a una alteración primaria de los vidrios volcánicos. Estos autores también observaron una silificación secundaria de los argilanes, la cual se debería a un proceso pedológico, pero que no explica totalmente la cementación de los mismos. Oleschko et al. (1992) establecieron que los tepetates de la parte alta de México presentan micromorfológicamente una fábrica con revestimientos de arcilla halosíntica mezclada con sílice, que sin duda juega un papel importante como agente cementante. La silificación incipiente de las cineritas alteradas en estos suelos hace pensar que la mayoría de los tepetates de México Central puedan considerarse como fragipanes, y por lo tanto susceptibles de recuperarse para la producción agrícola. En contraste con este proceso de endurecimiento, se tiene que otros tepetates de este país, particularmente los ubicados en las partes más bajas de las topo-climosecuencias (clima sub-árido), presentan carbonatación. Esta carbonatación puede estar uniformemente distribuida en el material o puede formar láminas que penetran las fisuras y los tubos biológicos (Quantin, 1992). Los sillares de Perú y los terétles de Chile corresponderían mejor con esta clase de suelos volcánicos endurecidos. Finalmente, los mecanismos de endurecimiento de ciertos suelos volcánicos de Japón y el sur de Chile, están dominados por óxidos de hierro y materia orgánica (Besoain et al., 1992; Yamada et al., 1994).

Características químicas asociadas con la fertilidad de los suelos volcánicos endurecidos. El análisis de las características químicas de estos materiales, que se relacionan con su fertilidad, debe ser abordado considerando dos situaciones: (1) la de los suelos que sobreyacen a horizontes volcánicos endurecidos, que pueden ser derivados de esos materiales o haber sido transportados, pero que tienen una capa de al menos 20-30 cm donde las raíces de las plantas pueden crecer sin mayores dificultades, y y por extensión se denominan suelos volcánicos endurecidos; y, (2) los materiales volcánicos endurecidos propiamente tales, que no han sido cultivados en tiempos recientes, pero que tienen cierto potencial productivo agrícola, una vez superadas las restricciones físicas que presentan.

La mayoría de las propiedades químicas de los suelos volcánicos endurecidos han sido determinadas con el propósito de apoyar diversas hipótesis de trabajo (Avila, 1963; Besoain et al., 1992; Cajuste y Cruz, 1987; Custode et al., 1992; Delgadillo et al., 1989; Etchevers et al., 1992a; Luzio y Saavedra, 1992; Luzio et al., 1992; Prat y Quantin, 1992; Peña y Zebrowski, 1992; Rey, 1979; Rossignol et al., 1992; Sánchez, 1981; Valdez, 1970; Yamada et al., 1994). El primer autor conoce pocos trabajos realizados ex profeso para caracterizar químicamente los diversos tipos de materiales volcánicos endurecidos (Etchevers et al., 1992a; Peña y Zebrowski, 1992; Yamada et al., 1994) y para estudiar la fertilidad de los mismos (Cajuste y Cruz, 1987; Cruz et al., 1992; Etchevers et al., 1992b y 1992c).

En el Cuadro 1 se presentan algunas características químicas seleccionadas de perfiles de varias partes del mundo, que poseen horizontes derivados de materiales volcánicos endurecidos, que fueron reportados en algunas de las referencias arriba indicadas, y que no necesariamente corresponden a las capas endurecidas, sino más bien a los suelos sobreyacentes a éstas donde se pueden cultivar plantas.
Cuadro 1. Comparación de Características Químicas de Horizontes Volcánicos Endurecidos.

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Los datos presentados, por razón de brevedad, sólo consideran aquella porción del perfil que puede ser colonizada por las raíces. Las principales conclusiones que se derivan del análisis de esa información son las siguientes: las características químicas de los perfiles de suelos volcánicos endurecidos se pueden dividir, de acuerdo con la ubicación de éstos, en dos grandes grupos: aquellas de suelos desarrollados en un clima con una estación seca en el año y las de los que se formaron en condiciones de humedad relativamente elevada. Entre ambos grupos hay diferencias principalmente de pH, materia orgánica y bases intercambiables. Los desarrollados en climas con estación seca presentan, en general, una reacción neutra a alcalina; en contraste, aquellos situados en zonas tropicales o frías, con pluviometría elevada y con fuerte influencia volcánica en épocas relativamente recientes, como lo son Xalapa (México), sur de Chile (Quillén) y Japón, la reacción es ligeramente ácida a ácida. Los primeros son suelos, que poseen bajos niveles de materia orgánica y nitrógeno, cantidades medias a altas de potasio intercambiable, contenidos bajos de fósforo extractable en bicarbonato de sodio (éstos aumentan en función de la cantidad de fertilizante fosfatado aplicado o años de cultivo, como lo veremos más adelante) y, en general, niveles altos de calcio, magnesio y potasio intercambiables. Los segundos, por lo contrario, tienen niveles de materia orgánica elevados a muy elevados (más altos mientras mayor es la pluviometría y las características ándicas del suelo), y bajos niveles e bases intercambiables. Sólo un estudio, conducido en un tepetate con alto contenido de carbonato de calcio (Cajuste y Cruz, 1987), hace referencia a los bajos niveles de micronutrientes en estos suelos, particularmente de manganeso y zinc. Etchevers et al., (1992b) también reportaron deficiencia de un micronutriente (hierro) en plantas cultivadas en un tepetate calcáreo sometido a una extracción acelerada de nutrientes.

Los resultados anteriores, sin embargo, no reflejan claramente la situación de las capas endurecidas de estos suelos. Las características químicas de dichas capas (caso de los tepetates) se pueden apreciar mejor en el Cuadro 2, tomado del trabajo de Etchevers et al. (1992a), el cual se refiere exclusivamente a las capas volcánicas endurecidas encontradas en la región altiplánica mexicana, pero que se supone son parecidos a las de los suelos endurecidos desarrollados en condiciones similares. Las características químicas de los tepetates de referencia (horizontes endurecidos) t2, t3 y ti (tepetates indefinidos), clasificación que se relaciona con el origen del material parental como ya se indicó, muestran algunos contrastes. En general, los valores promedio de pH en agua fueron menores en los tepetates con bajo contenido de carbonato (7.8 y 7.5) que los tepetates con alto nivel de carbonato (8.4 y 8.8), lo cual es congruente con la teoría. Las concentraciones de CaCO₃ en los seis primeros tepetates del tipo t3 del Cuadro 2, fueron consideradas como bajas, ya que presentaron, en promedio, 2.7% de este material; los t3 (7 y 8) se clasificaron en el campo como tepetates con alta proporción de CaCO₃. Pero el análisis de laboratorio del segundo sólo arrojó un contenido de 2.1% de CaCO₃. Esto se debe a que dicha capa contiene CaCO₃ en forma laminar y probablemente la muestra analizada no fue representativa de la situación general observada en el campo. En contraste, el tepetate 7 tiene el CaCO₃ mezclado con la matriz del suelo, lo cual se refleja en el resultado del análisis. La diferencia entre tepetates con bajo y alto nivel de CaCO₃ se reflejó en el examen morfológico de campo, también se manifiesta en los t2 (9 a 12). Las medias de ambos tipos fueron 1.7 y 4.6%, respectivamente. El porcentaje de CaCO₃ en los tepetates clasificados como indefinidos (ti), es decir en aquellos en que no existe seguridad de que pertenezcan al tipo t2 o t3, varió de 1.9 a 5.5%. Las altas concentraciones de CaCO₃ contribuyen a explicar las características de dureza que exhiben estos materiales, así como las deficiencias de micronutrientes observadas por Cajuste y Cruz (1987) y Etchevers et al. (1992b) en los tepetates cultivados. La dureza de los tepetates con bajo contenido de CaCO₃ estaría mejor explicada por un proceso de silificación (Hidalgo et al., 1992) o por la presencia de arcillas haloísicas mezcladas con sílice (Olechko et al., 1992).
arcillas haloisiticas mezcladas con sílice (Oleschko et al., 1992).

Cuadro 2. Algunas características químicas de los tepetates aflorados empleados como referencia.

<table>
<thead>
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<th>No.</th>
<th>Tepetate</th>
<th>campo</th>
<th>CaCO₃</th>
<th>CaCO₃</th>
<th>pH campo</th>
<th>pH agua</th>
<th>KC11N</th>
<th>% N</th>
<th>% P</th>
<th>Ca ppm</th>
<th>Mg ppm</th>
<th>K ppm</th>
<th>Na ppm</th>
<th>CIC cmol/kg</th>
<th>PSB ppm</th>
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<td>8.1</td>
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<td>T</td>
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<td>22.9</td>
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</tbody>
</table>

1 (Etchevers et al., 1992a).
2 SC=tepetates con bajo contenido de CaCO₃ determinado morfológicamente; CC= tepetates con alto contenido de CaCO₃.
3 T=Trazas

Los porcentajes de N total en las capas endurecidas (tepetates) son extraordinariamente bajos y se deben a la ausencia casi absoluta de residuos orgánicos. Tal situación es una de las principales limitantes para el establecimiento de plantas superiores en estos materiales. La habilitación de los tepetates para el establecimiento de cultivos agrícolas debe considerar, en forma especial, el incremento de la materia orgánica y el nitrógeno, mediante adiciones de estiércoles, abonos verdes y fertilizantes nitrogenados. La respuesta a estas prácticas ha sido documentada en numerosos trabajos (Ruiz, 1987; Zebrowski et al., 1992) y en los trabajos realizados por el grupo de estudios de microbiología del suelo Colegio de Postgraduados de México, mismos que se reportan más adelante en este trabajo.

El P extractable (Olsen), un índice de disponibilidad del P del suelo para las plantas, es prácticamente inexistente en todas las capas endurecidas, lo cual evidentemente dificulta el establecimiento de cualquier cultivo agrícola, de no corregirse dicha situación oportunamente. Tal comportamiento ha sido atribuido por Etchevers et al. (1992c) a los bajos niveles de P total más que a reacciones de adsorción rápida o lenta. Al igual que el N, el P debe ser adicionado al suelo, hasta alcanzar niveles compatibles con los requerimientos de los cultivos. Debido a las características adsorbtivas de estos materiales, es posible alcanzar dichos niveles en el corto plazo y con adición de cantidades moderadas de fertilizantes fosfatados de alta solubilidad (Etchevers et al., 1992c).
En general, la capacidad de intercambio de cationes (CIC) de los tepetates t3, es mayor que la de los t2 (30.7 vs 23.1 cmolkg\(^{-1}\)) y aseguran una buena capacidad de almacenamiento de bases intercambiables. En este aspecto los ti se semejan más a los t2 que a los t3 (media 23.5 cmolkg\(^{-1}\)). Hidalgo et al. (1992) indican que la halloysita es la arcilla dominante en la fracción fina de los t3, mientras que en los t2b es la esmectita.

Las concentraciones de Ca, Mg, K y Na extraíbles en acetato de amonio IN pH7 son, en general, superiores en los t3, que en los t2. Es obvio que los niveles de este Ca estén estrechamente asociados con los porcentajes de CaCO\(_3\) presente en los tepetates. Las concentraciones de Ca extraíble en los t3 varían de 6.7 a 45.3 cmolkg\(^{-1}\), con una media de 20.0 cmolkg\(^{-1}\), en tanto que en los t2 de bajo nivel de carbonato, el rango es de 7.2-8.7 cmolkg\(^{-1}\), con una media de 7.7 cmolkg\(^{-1}\). Los ti, con una excepción (K 22), se sitúan entre 11.4 y 18.8 cmolkg\(^{-1}\). El Mg extraíble, al igual que el Ca, es más elevado en los t3 (6.0-11.9 cmolkg\(^{-1}\)) que en los t2 (6.1-8.5 cmolkg\(^{-1}\)). Los ti tienen en promedio menos Mg que los t3 (7.2 cmolkg\(^{-1}\)) pero una mayor variabilidad (4.5-10.5 cmolkg\(^{-1}\)). Llama poderosamente la atención los elevados porcentajes de K intercambiable que presentan los tepetates. Estos varían entre 0.5 y 3.4 cmolkg\(^{-1}\), siendo mayores en los t3 que en los t2. Dichas cantidades son muy superiores a los requerimientos de los cultivos. La fuente de este K no es clara, ya que la mayoría de los minerales de la fracción gruesa descrito en estudios previos no contienen este elemento (Hidalgo et al., 1991; Pacheco, 1979; Rey, 1979; Valdez, 1970). Quantin (P. Quantin. 1994. Comunicación personal) atribuye estos altos niveles a la alteración de vidrios volcánicos ríolíticos, ricos en potasio. Los niveles de Na intercambiable también son altos (0.6-2.7 cmolkg\(^{-1}\)) y probablemente se derivan de minerales, como la andesina, descritos por Pacheco (1979) y Rey (1979) y de otras plagioclasas y vidrios volcánicos.

En el Cuadro 3 se presenta un compendio de algunos parámetros químicos de interés para el estudio de la fertilidad, correspondientes a las capas superficiales de suelos sobreyacentes a horizontes endurecidos y de tepetates aflorando, de un estudio morfopedológico realizado por Peña y Zebrowski (1992) en el altiplano del centro de México. Los últimos obviamente no tienen en su condición actual ningún uso agrícola, en cambio algunos de los primeros sostienen una vegetación natural o son cultivados precariamente. En general, las conclusiones que se obtienen del análisis del anterior cuadro son las mismas señaladas para los Cuadro 1 y 2. Estos datos refuerzan la idea que la situación de la fertilidad en los suelos sobreyacentes y los horizontes endurecidos prácticamente tales, difieren; consecuentemente, también lo hacen el manejo de ambos tipos de materiales con fines de producción agrícola.

En resumen se puede señalar que las restricciones químicas de los suelos sobreyacentes a los tepetates y de los tepetates propiamente tales, pueden subsanarse en forma relativamente simple con las tecnologías de fertilidad de suelos actualmente vigentes. El mayor problema se presentaría en aquellos materiales que contienen altos niveles de CaCO\(_3\) en la parte superior del perfil o en suelos que al habilitarse para el cultivo, las capas de este material ubicadas en profundidad, pudieran traerse a la superficie. En ambas situaciones existe potencialidad para que se presenten problemas en el abastecimiento de micronutrientes. La elevación de la materia orgánica y los niveles de fósforo son medidas sine qua non para el éxito de la producción agrícola.
Cuadro 3. Características Químicas de Suelos sobre *Tepetates* o de *Tepetes* en México

<table>
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<th>Prof.</th>
<th>pH</th>
<th>C (%)</th>
<th>N (%)</th>
<th>P</th>
<th>Ca (ppm)</th>
<th>Mg (ppm)</th>
<th>K</th>
<th>Na</th>
<th>B1</th>
<th>CIC</th>
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</tr>
<tr>
<td><strong>Suelos de la serie T2 sobre serie T3. prof. a medios. algo vérticos. arcill. a franco arcill. poco CaCO₃</strong></td>
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Cuadro 3: Continuación

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**Media**

| 7.7       | 1.05  | 0.07| 6.1 | 13.76| 4.83 | 0.62 | 0.24 | 19.5 | 15.6 | 100 |

**Tepetates (2) Aflorando, sin CaCO3**

| P-30.5K   | 7.3   | 0.15| 0.05| 0.0  | 8.68 | 6.26 | 1.29 | 1.15 | 17.4 | 21.3 | 82  |
| P-33.5K   | 7.8   | 0.20| 0.05| 0.0  | 7.29 | 5.14 | 0.97 | 0.86 | 14.3 | 17.6 | 83  |

**Media**

| 7.5       | 0.17  | 0.05| 0.0  | 7.98 | 5.70 | 1.13 | 1.00 | 15.8 | 19.5 | 83  |

**Tepetates (2) Aflorando, alto contenido CaCO3**

| A-13      | 8.9   | 0.36| 0.07| 0.0  | 41.42| 10.54| 2.56 | 1.01 | 55.5 | 26.6 | 100 |

**Media**

| 8.15      | 0.13  | 0.03| 0.0  | 11.01| 6.60 | 2.19 | 1.87 | 21.7 | 32.6 | 70  |

**Tepetates (3) Aflorando, sin CaCO3**

| P-13K     | 7.9   | 0.08| 0.02| 0.0  | 15.67| 10.04| 2.35 | 2.66 | 30.7 | 39.5 | 78  |
| P-26,10K  | 7.6   | 0.16| 0.02| 0.0  | 12.13| 7.90 | 2.61 | 0.92 | 23.6 | 44.4 | 53  |
| P-27,Kb   | 7.6   | 0.12| 0.02| 0.0  | 6.39 | 4.82 | 1.31 | 0.96 | 13.5 | 19.8 | 68  |
| P-30,11K  | 8.1   | 0.24| 0.07| 0.0  | 6.39 | 4.82 | 1.31 | 0.96 | 13.5 | 18.8 | 72  |
| P-35,11K  | 7.6   | 0.08| 0.02| 0.0  | 14.47| 9.48 | 3.38 | 3.87 | 31.2 | 40.6 | 77  |

**Media**

| 7.76      | 0.13  | 0.03| 0.0  | 11.01| 6.60 | 2.19 | 1.87 | 21.7 | 32.6 | 70  |

**Tepetates (3) Aflorando, moderado contenido CaCO3**

| K12       | 8.1   | 0.15| 0.02| 0.0  | 11.38| 8.15 | 1.54 | 1.77 | 22.8 | 25.0 | 92  |
| P-28,8K   | 8.2   | 0.12| 0.02| 0.0  | 13.57| 6.67 | 1.49 | 0.89 | 22.6 | 25.6 | 88  |

**Media**

| 8.15      | 0.13  | 0.02| 0.0  | 12.47| 7.1  | 1.51 | 1.33 | 22.7 | 25.3 | 90  |

**Tepetates (3) Aflorando, alto contenido CaCO3**

| K7        | 8.8   | 0.16| 0.02| 0.0  | 45.28| 11.93| 1.20 | 1.34 | 59.8 | 27.6 | 100 |
| K15a      | 8.9   | 0.36| 0.07| 0.0  | 41.42| 10.54| 2.56 | 1.01 | 55.5 | 26.6 | 100 |

\(^1\) Peña y Zebrowski, 1992.

Situación del fósforo y el potasio en suelos volcánicos endurecidos. La situación del fósforo y el potasio y los factores que se relacionan con su dinámica, en capas endurecidas sin cultivar, cultivadas por periodos que van de 1 a 16 años y en suelos de referencia, ubicados en áreas adyacentes a los anteriores, ha sido estudiada por Etchevers et al. (1992c) para los suelos volcánicos endurecidos de la región altiplánica central del México. No se conocen otros trabajos sobre el tema.

En el Cuadro 4 se presentan algunas características químicas de las capas endurecidas que se relacionan con esas dinámicas. Como se señaló anteriormente los llamados tepetates se han
La concentración promedio de fósforo Olsen inicial en los tepetates sin cultivar varía entre 2.4 y 3.0 ppm P. Estos valores indican que la cantidad de fósforo disponible en el material original es baja. Ello se explica, en parte, porque el fósforo total es bastante inferior a los niveles considerados como normales en suelos cultivados. En cambio, los tepetates cultivados muestran concentraciones de fósforo disponible un poco más elevadas (4.2 a 6.4 ppm P), lo cual refleja las adiciones de fertilizante que periódicamente se hacen en estos suelos. La acumulación de fósforo es mayor a medida que aumentan los años que un tepetate ha estado cultivado. Los tepetates cultivados sólo durante 1 año presentan concentraciones de fósforo extraíble Olsen menores a 3 ppm, en cambio en aquellos suelos cultivados por más de 10 años este índice varía de 5 a 11 ppm. Como comparación se tienen los niveles de fósforo extraíble que se pueden alcanzar después de más de 30 años de cultivo en los suelos asociados (17 a 37 ppm P Olsen), los cuales se consideran muy superiores a las necesidades actuales de los cultivos. Algunos tepetates presentan niveles de este nutriente preocupantemente elevados, debido a aplicaciones de fertilizante fosfatado en dosis, como las reportadas por Delgadillo et al. (1989), que pudieran llegar a provocar desórdenes nutrimentales.

Los valores de Kpo (un índice de las reacciones rápidas de adsorción de fósforo) nos señalan que los tepetates derivados de t3 mantienen, después de 24 horas, aproximadamente un 60% del fósforo aplicado en el "pool" lável y que este valor es aún mayor en el caso de los tepetates derivados de t2 (71%). En general, los tepetates t2 y t3 que han sido cultivados presentan valores de Kpo ligeramente inferiores a los no cultivados, en tanto que el de los suelos es aún más bajo (56%), señalando una reactividad ligeramente superior, que pudiese atribuirse al aporte periódico de cenizas volcánicas que han recibido en los últimos siglos. Al comparar los Kpo de los tepetates con los medidos en suelos de la zona se puede decir que estos valores son relativamente altos (Cruz, 1990; Galvis, 1990) y que el fenómeno de adsorción rápida en los tepetates no representa un mayor problema en las prácticas de fertilización fosfatadas.

El fenómeno de la difusión de fósforo intrapartícula en los tepetates, mismo que se mide por el coeficiente (Kp 1año) de una ecuación potencial que se ajusta a la función de decaimiento del "pool" lável del suelo, es de pequeña monta. Los valores de este coeficiente varían entre 0,06 y 0,08 en los tepetates del estado de Tlaxcala y son un poco más elevados en los del estado de México. Los resultados anteriores permiten concluir que el fósforo aplicado tiene en estos suelos un efecto residual relativamente prolongado, ya que su tasa de adsorción lenta es relativamente baja.

El potasio extraíble (con una mezcla de ácidos concentrados) de los tepetates sin cultivar fue bastante uniforme (aproximadamente 5 cmolkg⁻¹), sin observarse diferencias apreciables entre las zonas; éste fue inferior en los tepetates cultivados y aún más bajo en los suelos aledaños. Estos valores son sorprendentemente bajos y representan sólo una fracción del potasio total. Tisdale et al. (1985) señalan que la concentración media de potasio total en los suelos es de aproximadamente 1.2%, con un rango de 0.5 a 2.5%.

El potasio no intercambiable (HNO₃ 4M en caliente) fue mayor en los tepetates t3 que en los t3, denotando seguramente las diferencias en el material parental de ambas series. Los tepetates cultivados, aún por corto plazo mostraron una disminución significativa de potasio no intercambiable. Estos datos señalan que el sistema potasio en los tepetates es un poco inestable y que debe ser observado con mayor detenimiento para evitar un empobrecimiento irreversible debido a las prácticas de cultivo.

El potasio intercambiable en los tepetates t3 sin cultivar, cultivados y en los suelos de referencia fue 1.10, 0.75 a 0.94 y 0.42 a 0.42 cmolkg⁻¹, respectivamente. Estos valores son muy superiores a los reconocidos como límites críticos para un gran número de cultivos (0.15 a 0.30 cmolkg⁻¹).
formado a partir de materiales piroclásticos de diferentes edades, mismos que presentan características químicas distintas. El tratamiento y estudio indicado se hizo en función de los materiales parentales que dieron origen a las capas endurecidas.

Cuadro 4. Características Químicas Relacionadas con la Dinámica del P y el K en Tepetates de México.  

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<td></td>
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<td></td>
</tr>
<tr>
<td>Tepetate (x)²</td>
<td>0</td>
<td>170</td>
<td>0.58</td>
<td>0.72</td>
<td>5.28</td>
<td>1.53</td>
<td>1.09</td>
<td>0.44</td>
<td>0.54</td>
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<td></td>
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<td>210</td>
<td>1.6</td>
<td>0.55</td>
<td>0.76</td>
<td>5.37</td>
<td>1.41</td>
<td>0.89</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>180</td>
<td>4.4</td>
<td>0.60</td>
<td>0.67</td>
<td>5.12</td>
<td>1.60</td>
<td>1.00</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>230</td>
<td>4.7</td>
<td>0.60</td>
<td>0.68</td>
<td>5.12</td>
<td>1.41</td>
<td>0.83</td>
<td>0.30</td>
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<tr>
<td></td>
<td>4</td>
<td>220</td>
<td>4.9</td>
<td>0.55</td>
<td>0.73</td>
<td>4.60</td>
<td>1.23</td>
<td>0.85</td>
<td>0.31</td>
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<tr>
<td></td>
<td>5</td>
<td>230</td>
<td>4.8</td>
<td>0.68</td>
<td>0.69</td>
<td>5.63</td>
<td>1.54</td>
<td>0.90</td>
<td>0.35</td>
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<td>10</td>
<td>230</td>
<td>13.3</td>
<td>0.61</td>
<td>0.89</td>
<td>5.12</td>
<td>1.95</td>
<td>1.20</td>
<td>0.56</td>
</tr>
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<td></td>
<td>15</td>
<td>230</td>
<td>11.2</td>
<td>0.56</td>
<td>0.80</td>
<td>4.86</td>
<td>1.72</td>
<td>0.90</td>
<td>0.40</td>
</tr>
<tr>
<td>Tepetate (x)</td>
<td>1 a 15</td>
<td>219</td>
<td>6.4</td>
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<td>0.74</td>
<td>5.12</td>
<td>1.55</td>
<td>0.94</td>
<td>0.37</td>
</tr>
<tr>
<td>Suelo Ref. (x)</td>
<td>≥ 30</td>
<td>330</td>
<td>37.2</td>
<td>0.59</td>
<td>0.66</td>
<td>4.10</td>
<td>1.53</td>
<td>0.83</td>
<td>0.57</td>
</tr>
<tr>
<td><strong>t2, Tlaxcala, México</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Tepetate (x)</td>
<td>0</td>
<td>110</td>
<td>2.7</td>
<td>0.72</td>
<td>0.73</td>
<td>5.88</td>
<td>2.67</td>
<td>1.45</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>110</td>
<td>3.2</td>
<td>0.72</td>
<td>0.79</td>
<td>5.12</td>
<td>2.01</td>
<td>1.20</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>120</td>
<td>5.2</td>
<td>0.61</td>
<td>0.64</td>
<td>5.12</td>
<td>2.56</td>
<td>1.45</td>
<td>0.57</td>
</tr>
<tr>
<td>Tepetate (x)</td>
<td>1 a 4</td>
<td>115</td>
<td>4.2</td>
<td>0.67</td>
<td>0.72</td>
<td>2.29</td>
<td>1.33</td>
<td>0.55</td>
<td>0.39</td>
</tr>
<tr>
<td><strong>t3, San Miguel Tlaixpan, México</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tepetate (x)</td>
<td>0</td>
<td>165</td>
<td>2.4</td>
<td>0.64</td>
<td>0.56</td>
<td>4.86</td>
<td>1.77</td>
<td>1.10</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>200</td>
<td>4.3</td>
<td>0.63</td>
<td>0.55</td>
<td>3.84</td>
<td>1.56</td>
<td>0.98</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>180</td>
<td>5.2</td>
<td>0.60</td>
<td>0.72</td>
<td>5.37</td>
<td>1.13</td>
<td>0.52</td>
<td>0.13</td>
</tr>
<tr>
<td>Tepetate (x)</td>
<td>9 a16</td>
<td>190</td>
<td>4.8</td>
<td>0.61</td>
<td>0.64</td>
<td>4.61</td>
<td>1.35</td>
<td>0.75</td>
<td>0.20</td>
</tr>
<tr>
<td>Suelo Ref. (x)</td>
<td>≥ 30</td>
<td>340</td>
<td>16.8</td>
<td>0.53</td>
<td>0.44</td>
<td>3.84</td>
<td>0.90</td>
<td>0.42</td>
<td>0.15</td>
</tr>
</tbody>
</table>

(1): x es el promedio de varias observaciones.

Las concentraciones de fósforo total de todos los tepetates y suelos asociados fueron muy inferiores a las que normalmente se encuentran en los suelos cultivados (450 a 1100 ppm, según Tisdale et al., 1985). Los tepetates t2 y t3 sin cultivar contienen 110 y 168 ppm P, respectivamente. Los tepetates t3 cultivados mostraron concentraciones de este elemento superiores a los tepetates sin cultivar. Esto último es explicable en razón de las aplicaciones periódicas de fertilizantes fosfatados a que son sometidos los terrenos de cultivo por los agricultores. Dicha situación no fue evidente en el caso de los t2, debido a los escasos años transcurridos desde su recuperación. Los bajos porcentajes de fósforo explican la escasez de fósforo disponible y la respuesta a la aplicación de fertilizante que reportan los campesinos (Etchevers et al., 1992a).
de lo cual se infiere que en el corto plazo este nutriente no se presentará un problema de abastecimiento para los cultivos. Sin embargo, los suelos de referencia, cultivados por más de 30 años, tienen concentraciones de potasio intercambiable menores que los tepetates sin cultivar o cultivados, hecho que debe ser destacado por las implicaciones para la predicción de la capacidad de sumistro futura de este elemento.

Las concentraciones de potasio soluble en agua en los tepetates fueron, en general, elevadas en relación al potasio intercambiable (aproximadamente 30%). La concentración de potasio soluble en los tepetates cultivados fue inferior a la observada en los tepetates no cultivados, lo cual fue atribuido a la exportación de este elemento por las cosechas y a la escasa o nula aportación de potasio como fertilizante en la explotación de los tepetates.

La capacidad tampón de potasio de los tepetates, medida a través del estimador cK, presentó valores de 0.35 a 0.71. En contraste, el cK de los suelos de referencia alcanzó valores de 0.30 a 0.43. Estos cK indican un poder tampón de potasio superior al esperado, el que puede ser explicado por la presencia de materiales arcillosos del tipo 2:1 y una fijación específica.

En resumen los estudios de laboratorio confirman las observaciones realizadas en estudios biológicos, referente a la escasez de fósforo y la abundancia del potasio en los tepetates, la primera debida a la escasa presencia de minerales fosfatados naturales y la segunda a un elevado grado de intemperismo de los vidrios volcánicos riolíticos ricos en potasio. La adición de fertilizantes fosfatados en los tepetates cultivados ha determinado un aumento gradual del fósforo disponible, condición que ha sido permitida por la baja reactividad de estos materiales y un elevado efecto residual de los correctores.

La microbiología en la rehabilitación de los tepetates. Con el fin de conocer el papel que ejercen los microorganismos en la recuperación de los suelos volcánicos endurecidos (tepetates) el grupo de estudios de microbiología el suelo del Colegio de Postgraduados en México, ha experimentado con un manejo agroecológico de los mismos, teniendo como base el uso de materia orgánica y la inoculación con diferentes microorganismos de reconocida capacidad para participar en la nutrición de las plantas tales como: la endomicorriza vesículo-arbuscular, que capta y trasloca fósforo y otros nutrimentos, así como Azospirillum sp. y Rhizobium, que participan en la fijación de nitrógeno. En estos trabajos se ha colocado especial énfasis en el recuento del número total de bacterias, actinomicetos y hongos presentes en los tepetates, para lo que se ha empleado el método de dilución en placa, frecuentemente usado en estudios microbiológicos, así como la medición del consumo de oxígeno. También se verificó la sobrevivencia de Rhizobium y Azospirillum sp. en tepetates sembrados con frijol, haba, veza y maíz previamente inoculados. Los resultados que aquí se presentan son preliminares, pero indicativos del proceso de rehabilitación del tepetate. En el Cuadro 5 se observa que el número de los diferentes tipos de microorganismos observados en los tepetates sometidos a rehabilitación cambió con el manejo. Por ejemplo, sólo con la roturación, el número de microorganismos fue mayor que en el material no roturado y las poblaciones microbianas se vieron incrementadas, después de las primeras lluvias, en los tratamientos que recibieron adición de materia orgánica.
Cuadro 5. Efecto de la roturación y la incorporación de materia orgánica en la población microbiana total del tepetate¹.

<table>
<thead>
<tr>
<th>Tepetate</th>
<th>Bacterias</th>
<th>Actinomicetos</th>
<th>Hongos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sin roturación</td>
<td>2.23x10⁴</td>
<td>11.8x10³</td>
<td>6.57x10¹</td>
</tr>
<tr>
<td>Con roturación</td>
<td>5.97x10⁴</td>
<td>19.6x10³</td>
<td>12.9x10¹</td>
</tr>
<tr>
<td>Sin materia orgánica²</td>
<td>9.89x10⁴</td>
<td>34.9x10³</td>
<td>17.3x10¹</td>
</tr>
<tr>
<td>Con materia orgánica²</td>
<td>2.49x10⁶</td>
<td>13.5x10⁴</td>
<td>6.51x10¹</td>
</tr>
<tr>
<td>Testigo: Suelo agrícola adyacente</td>
<td>4.59x10⁷</td>
<td>2.11x10⁵</td>
<td>39.6x10¹</td>
</tr>
</tbody>
</table>

²Tepetate roturado con humedad debido a las primeras lluvias.

Un indicador de la fertilidad del suelo es el consumo de oxígeno, la evolución de CO₂ ó la evaluación de otros productos del metabolismo. Para dicho estudio se usó un respirómetro. La metodología empleada se presentó en el trabajo de Matías et al., (1991). Los resultados muestran que hubo mayor actividad respiratoria en el tepetate roturado que sin roturar (Fig. 1). Se observó que la adición de materia orgánica indujo un efecto modificador en la respiración de los microorganismos en el tepetate, siendo ésta mayor en las parcelas que recibieron materia orgánica, que las que no lo recibieron, pero sin llegar a superar la actividad respiratoria del suelo agrícola (Fig. 2).

Fig. 1. El consumo de oxígeno por los microorganismos presentes en el suelo agrícola, tepetate sin roturar y tepetate roturado en Talpan, Mpio. de Hueyotlipan, Edo. de Tlaxcala. (Determinación durante 15 min.).

Fig. 2. Consumo de oxígeno por la población microbiana en tepetate con y sin materia orgánica en Talpan. (Determinación durante 15 min.).
Las cepas de *Rhizobium leguminosarum* tienen una resistencia a antibiótico de 1000 μg/ml de kanamicina y *Azospirillum* sp. resistencia a 500 mg/ml de espeptomicina y 500 mg/ml de estreptomicina (Alvarez, 1991).

En relación a la producción de amonio, se observó que la incorporación de veza o del rastrojo del policultivo, con y sin previa incorporación de materia orgánica, tuvo un efecto significativo en la actividad amonificante y nitrificante de la microbiota del tepetate. Al inicio del ensayo los tratamientos de veza sin materia orgánica y veza con materia orgánica presentaron mayor contenido de amonio que los otros tratamientos. En el transcurso de la incubación, los tratamientos con veza pero sin materia orgánica (VSMO), sin materia orgánica pero con incorporación del rastrojo del policultivo (PSMO) y con materia orgánica e incorporación de rastrojo del policultivo (PCMO), se observó un incremento en el contenido de amonio, el que presentó un pico de máxima producción a los 5 días, pero posteriormente el amonio declinó hasta los valores similares a los observados al inicio, mientras que en los tratamientos: *tepetate* sin materia orgánica (TSMO) y *tepetate* con materia orgánica (TCMO), la concentración de éste permaneció constante y con valores bajos durante todo el período de incubación.

Al término del período de incubación el contenido total de nitrógeno inorgánico y el porcentaje respectivo de amonio y nitrito fue el siguiente: TSMO = 25.6 ppm de N (37.4% NH₄⁺ y 62.6% NO₃⁻), PSMO = 35.2 ppm de N (25.5% NH₄⁺ y 74.5% NO₃⁻), TCMO = 42.1 ppm de N (32.1% NH₄⁺ y 67.9% NO₃⁻), PCMO = 43.1 ppm de N (10.9% NH₄⁺ y 89.1% NO₃⁻), VSMO = 63.8 ppm de N (9.8% NH₄⁺ y 90.2% NO₃⁻) y VCMO = 99.1 ppm de N (7.5% NH₄⁺ y 92.5% NO₃⁻). La comparación de estos resultados con los que se han reportado para otras regiones con condiciones ambientales diferentes, permiten apreciar que el *tepetate* presenta una respuesta favorable a la incorporación de materiales orgánicos. Así por ejemplo, Saffigna et al. (1989) observaron en muestras de suelo provenientes de un Vertisol con 1.24% de carbono orgánico y 0.102% de N, que después de 10 días de incubación, las muestras del sistema de labranza convencional produjeron 26.4 y 30.2 ppm de N sin y con manejo de rastrojo respectivamente, mientras que las muestras provenientes de labranza cero los valores correspondientes fueron 25.1 y 32.8 ppm de N sin y con manejo de rastrojo, respectivamente.

Es prematuro llegar a conclusiones con los datos que se tienen hasta el momento, pero podría indicarse que en la rehabilitación del *tepetate* el manejo del agroecosistema redundará en una recuperación más acorde con el ambiente, tendiente a una producción orgánica que facilite el equilibrio natural del sistema, para finalmente llegar a establecer una producción sostenida.

**Conclusión.** Los suelos volcánicos endurecidos presentan características químicas asociadas a su fertilidad, que dependen del régimen hídrico del área donde se ubican. En general, todos los suelos volcánicos endurecidos que se desarrollaron en climas áridos y semi-áridos presentan pH alcalino, contenidos medibles de CaCO₃, concentraciones de Ca, Mg y K extractables en acetato de amonio 1N pH 7 relativamente elevadas, pero niveles de nitrógeno y carbono orgánico muy bajos. En contraste, los suelos desarrollados en condiciones de humedad elevada tienen pH neutros a ácido y concentraciones de cationes intercambiables bajas, pero altos porcentajes de carbono y nitrógeno orgánico. Una característica de ambos tipos de suelos es su baja disponibilidad de fósforo, situación atribuida en el caso de los de regiones secas a la presencia de cantidades incipientes de fósforo total en el suelo y no a reacciones de adsorción, en tanto que en los de regiones húmedas se han reportado niveles altas de capacidad de fijación de este elemento.
La presencia del cultivo y su manejo indujeron cambios importantes en el tepetate. La mayoría de las muestras fueron tomadas de tepetate adherido a la superficie de la raíz de los cultivos (denominándosele suelo tepetatoso rizosférico de maíz, frijol, haba y veza) y una muestra de tepetate sin materia orgánica y sin cultivo. Los efectos de la rizósfera de cada cultivo se presentan en el Cuadro 6. Se observó un notorio efecto de la adición de materia orgánica en el incremento de la población microbiana de la rizósfera, en comparación con las parcelas que no recibieron este insumo; los datos de cada tratamiento se comparan con los obtenidos en un tepetate colectado a distancia (25 cm de los cultivos) y con otro tomado de la parcela que no recibió materia orgánica ni se cultivó.

Cuadro 6. Efecto rizosférico del maíz, frijol, haba y veza en la población microbiana total del tepetate a los 50 días después de la siembra¹.

<table>
<thead>
<tr>
<th>Materia Orgánica</th>
<th>Cultivo</th>
<th>Bacterias</th>
<th>Actinomicetos</th>
<th>Hongos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sin</td>
<td>Maíz</td>
<td>31x10⁶</td>
<td>7.0x10⁴</td>
<td>1.9x10⁴</td>
</tr>
<tr>
<td></td>
<td>Frijol</td>
<td>98x10⁶</td>
<td>30x10⁴</td>
<td>1.5x10³</td>
</tr>
<tr>
<td></td>
<td>Haba</td>
<td>16x10⁷</td>
<td>1.4x10⁵</td>
<td>2.5x10³</td>
</tr>
<tr>
<td></td>
<td>Veza</td>
<td>54x10⁶</td>
<td>8.2x10⁴</td>
<td>1.9x10³</td>
</tr>
<tr>
<td></td>
<td>A distancia</td>
<td>32x10⁵</td>
<td>9.3x10⁴</td>
<td>8.8x10²</td>
</tr>
<tr>
<td>Con</td>
<td>Maíz</td>
<td>16x10⁷</td>
<td>8.0x10⁵</td>
<td>5.8x10³</td>
</tr>
<tr>
<td></td>
<td>Frijol</td>
<td>16x10⁷</td>
<td>11.0x10⁵</td>
<td>1.9x10³</td>
</tr>
<tr>
<td></td>
<td>Haba</td>
<td>38x10⁷</td>
<td>1.3x10⁵</td>
<td>6.3x10³</td>
</tr>
<tr>
<td></td>
<td>Veza</td>
<td>20x10⁷</td>
<td>1.8x10⁵</td>
<td>4.7x10³</td>
</tr>
<tr>
<td></td>
<td>A distancia</td>
<td>63x10⁶</td>
<td>8.6x10⁵</td>
<td>4.7x10³</td>
</tr>
<tr>
<td>Sin</td>
<td>Sin</td>
<td>49x10⁵</td>
<td>12.5x10⁴</td>
<td>1.5x10²</td>
</tr>
</tbody>
</table>

También se evaluó la sobrevivencia de Rhizobium leguminosarum biovar phaseoli en la rizósfera del frijol y Azospirillum sp. en la de maíz (Cuadro 7). Las dos cepas empleadas fueron marcadas con antibióticos para facilitar su detección. Los resultados obtenidos nos permiten visualizar que a los 50 días de inoculación de las plantas, los microsímbiontes se encontraron completamente establecidos en la rizósfera de los dos cultivos.

Cuadro 7. Sobrevivencia de Rhizobium leguminosarum y de Azospirillum sp. en tepetate rizosférico de la asociación de frijol y maíz, a los 50 días después de la siembra.

<table>
<thead>
<tr>
<th>Materia Orgánica</th>
<th>Rhizobium</th>
<th>Azospirillum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sin</td>
<td>8.9x10⁴</td>
<td>1.18x10⁴</td>
</tr>
<tr>
<td>Con</td>
<td>1.4x10⁴</td>
<td>2.84x10⁴</td>
</tr>
</tbody>
</table>
La roturación hecha de acuerdo a parámetros técnicos determinados y la adición de materia orgánica, antes de establecer un cultivo han permitido incrementar la capacidad de almacenamiento de agua y de suministro de nitrógeno. La adición de fertilizante fosfatado es imprescindible en estos suelos. La cantidad de estos materiales requerida para alcanzar concentraciones de fósforo disponible en el suelo ligeramente superiores a los niveles críticos, no son muy elevadas, gracias a que los parámetros que determinan la dinámica del fósforo a corto y mediano plazo, son relativamente bajos. La adición anual de pequeñas dosis de fertilizante fosfatado (40 kg P₂O₅/ha) se refleja en una acumulación de este.

La adición de materia orgánica, junto con dosis moderadas de fertilizante nitrogenado permite, mantener un suministro adecuado de nitrógeno para el crecimiento de los cultivos. La materia orgánica promueve, junto con la roturación, una mayor actividad microbiana reflejada en el aumento del consumo de oxígeno y el un aumento del número total de bacterias, actinomicetos y hongos. Se espera que los residuos orgánicos, así como aquellos subproductos de la actividad microbiana, contribuyan a un mejoramiento más rápido de las características físicas y químicas relacionadas con la fertilidad de estos suelos.

Con el propósito de complementar el conocimiento que actualmente se tiene sobre la fertilidad de los suelos volcánicos endurecidos, es necesario realizar estudios particularmente sobre la dinámica del nitrógeno, así como una mejor estimación de las potencialidades de abastecimiento de micronutrientes. En cuanto a la investigación aplicada es preciso definir las dosis de fertilización que se requiere para cada condición de producción específica (tipo de cultivo, de suelo y condiciones climáticas). Los suelos volcánicos de las regiones húmedas deben estudiarse más detalladamente, ya que la información que se tiene de ellas es escasa.

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La réhabilitation agricole des sols volcaniques indurés et érodés en Equateur et au Mexique

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Abstract. Hardness and compactness as well as organic matter and available phosphorus deficiencies of the indurated eroded volcanic soils are severe constraints upon plant growth and limitations for agriculture development. Nevertheless these soils, respectively known in Mexico and Ecuador as tepetate and cangahua, are reclaimed by mechanized or manual subsoiling and ploughing as well as by an appropriate fertilization. According to the country and the farmers conservation works are or not used.

The history of this indurated soils reclamation as well as the balance of its costs are presented for both countries.

The results concerning the tepetates soils reclaiming show that yields, after few years of cultivation, are close to those obtained on non indurated soils. But the profit of these reclaiming works is depending in fact on the crop benefices which are usually low in these countries.

Résumé. La réhabilitation agricole des sols volcaniques indurés et érodés, connus sous les noms respectifs de cangahua et de tepetate en Equateur et au Mexique, était réalisée de façon traditionnelle par les populations préhispaniques. Elle a été intensifiée depuis une vingtaine d’années dans ces deux pays.

Cette réhabilitation implique une correction des niveaux d’azote et de phosphore, toujours très bas dans ces matériaux, par une fumure adéquate, ainsi qu’une amélioration de leurs caractéristiques physiques défavorables. Leur dureté et leur compacité induisent en effet une mauvaise macroporosité et donc une capacité de rétention en eau et une aération déficientes pour les plantes. Ces défauts sont corrigés par le défoncement des matériaux jusqu’à obtention d’agrégats suffisemment petits. Les zones ainsi travaillées sont sensibles à l’érosion et des mesures de conservation doivent être prises.

En Equateur, à part quelques essais de défoncement mécanisés, la plupart des travaux sont réalisés manuellement à l’aide du pic. L’élaboration de terrasses n’est pratiquée que dans le cadre de rares projets gouvernementaux.

Au Mexique la réhabilitation des tepetates est à l’heure actuelle presque toujours mécanisée. Le défonçage est réalisé au moyen de puissants tracteurs (D5 à D8) qui effectuent un sous-solage à 80 cm de profondeur, suivi de passages de pulvérisateur à disques. L’édification de terrasses n’est réalisée que dans le cadre de projets financés par les Etats. Le paysan se contente, après le défonçage du sol, de faire réaliser des bordures de terres limitant l’érosion.

Les coûts des travaux de réhabilitation sont toujours très élevés, souvent plus élevés pour les manuels que pour les mécanisés: le défonçage mécanisé, seul, est compris entre 800 à 1200 $/ha, le manuel entre 5000 et 6000 $/ha. Le défonçage, conjointement à la mise en terrasses, est estimé de 1500 à 1900 $/ha, mécanisé, et de 2000 à 3000 $/ha, si ce n’est beaucoup plus, lorsqu’ils sont manuels, ce qui fait s’interroger sur la rentabilité, elle même fonction de la productivité, de telles opérations.
Les suivi agronomiques effectués sur des tepetates et des sols non indurés au Mexique ont montré que la productivité des tepetates, relativement élevée dans le cas de la culture du blé, dès la première année de mise en culture, est faible dans le cas du maïs en première année, mais s'accroît régulièrement avec le temps de mise en culture, pour être, au bout de 4 à 5 ans, sensiblement égale à celle des sols agricoles. La rentabilité des opérations de réhabilitation des sols indurés est en fait fortement liée au choix de la culture et fonction du prix de vente de chacune d'entre elles.

**Mots clés:** Sols volcaniques indurés, Tepetate, Cangahua, Mexique, Equateur, Réhabilitation, Productivité, Coûts, Rentabilité.

**Introduction.** Les sols volcaniques indurés existent dans de nombreux pays d'Amérique Latine. Dans les zones relativement sèches l'utilisation intensive de ces sols, sans mesures de protection adéquates, a provoqué l'érosion de la couche arable mettant à découvert les horizons indurés. Les zones érodées couvrent ainsi d'importantes surfaces notamment en Equateur et au Mexique où ces formations sont connues respectivement sous les noms de cangahua et tepetate. La récupération agricole de ces formations est nécessaire tant d'un point de vue écologique que dans le but d'augmenter les surfaces cultivables dans ces zones à forte densité de population. Elle pose néanmoins des problèmes techniques qui ont été résolus de différentes manières dans les pays concernés afin d'assurer une productivité et une rentabilité suffisante à ces opérations.

**1 - Rappel de quelques caractéristiques des sols volcaniques indurés.**

**11 - Morphologie et nature des matériaux.** Les sols volcaniques indurés sont caractérisés par une superposition de couches meubles présentant généralement une structure de sol et de couches plus dures, massives. Cette alternance résulte, dans la plupart des cas, d'une succession de dépôts pyroclastiques provenant d'éruptions de type phréato-pléniennes. Celles-ci comportent un dépôt de flux, à l'origine des horizons indurés, suivi d'une retombée de cendres fines, à partir desquelles se sont formés les horizons plus meubles. Le flux, consolidé au moment de son dépôt, l'est également par des processus pédologiques secondaires: accumulation d'argile, de silice, ou de calcaire dans les zones les plus sèches. Ce schéma de formation vérifié au Mexique (Quantin, 1992) et au Nicaragua (Prat et Quantin, 1992), semble également être applicable en Equateur.

**12 - Caractéristiques physiques.** La dureté originelle des horizons indurés, particulièrement néfaste à leur mise en valeur, est néanmoins liée à leur degré d'humidité. Miehlich (1984) a montré que les tepetates du Mexique sont d'autant plus résistants à la pénétration qu'ils sont plus secs. Nimlos (1990), Peña et Zebrowski (1992) ont montré que la présence de carbonate de calcium augmente la dureté des matériaux (Fig. 1). Ainsi les tepetates non ou peu calcaire ont un comportement de "fragipan": à l'état sec ils sont peu résistants à la pénétration (< 20 Kg/cm²) et friables; à l'état humide ils sont plastiques et se déforment sans éclat d'où l'avantage de les émietter à l'état sec malgré l'effort supplémentaire demandé. Les tepetates encroutés de calcaire ont un comportement de "duripan" et présentent, autant à l'état sec qu'à l'état humide des valeurs de résistance à la pénétration comprises entre 100 et 200 Kg/cm². Ils sont particulièrement difficiles à rompre. La porosité présente également des caractéristiques défavorables à la mise en valeur de ces matériaux. Bien que la porosité totale soit supérieure à 40%, la macroporosité (pores > à 10 μm) est souvent inférieure à 5%. Il en résulte une mauvaise perméabilité et une aération insuffisante pour le bon développement des racines.
Figure 1. Résistance des tepetates, évaluée avec un pénétromètre à cône, en fonction de l'humidité et de la richesse de l'échantillon en carbonate de calcium.

La texture est très variable suivant la nature et le degré d'altération des matériaux, mais les teneurs en éléments fins sont loin d'être négligeables. Les taux d'argile varient de 7 à 54%, ceux de limons de 9 à 58% (Tableau 1), ce qui est favorable à la rétention de l'eau tout comme à la création d'une structure secondaire utile aux plantes.

Tableau 1. Texture des horizons indurés

<table>
<thead>
<tr>
<th>Lieu</th>
<th>Argile fin</th>
<th>Argile grossier</th>
<th>Limon fin</th>
<th>Limon grossier</th>
<th>Sable fin</th>
<th>Sable grossier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecuateur(1)</td>
<td>12,5</td>
<td>27,3</td>
<td>16,9</td>
<td>19,1</td>
<td>2,4</td>
<td>2,4</td>
</tr>
<tr>
<td>Chuspiaco 1</td>
<td>16,3</td>
<td>33,7</td>
<td>21,6</td>
<td>23,9</td>
<td>4,4</td>
<td>4,4</td>
</tr>
<tr>
<td>Chuspiaco 2</td>
<td>21,9</td>
<td>38,9</td>
<td>27,9</td>
<td>30,9</td>
<td>7,6</td>
<td>7,6</td>
</tr>
<tr>
<td>Chuspiaco 3</td>
<td>23,3</td>
<td>22,5</td>
<td>15,3</td>
<td>25,9</td>
<td>6,3</td>
<td>6,3</td>
</tr>
<tr>
<td>Tumbaco</td>
<td>9,2</td>
<td>16,9</td>
<td>13,0</td>
<td>10,9</td>
<td>15,1</td>
<td>15,1</td>
</tr>
<tr>
<td>Cangahua</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Méxique(2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t2 peu calcaire</td>
<td>25 à 42</td>
<td>13 à 42</td>
<td></td>
<td></td>
<td>22 à 60</td>
<td></td>
</tr>
<tr>
<td>t3 peu calcaire</td>
<td>31 à 54</td>
<td>11 à 25</td>
<td></td>
<td></td>
<td>24 à 53</td>
<td></td>
</tr>
<tr>
<td>calcaire, encrouté</td>
<td>7 à 9</td>
<td>9 à 12</td>
<td></td>
<td></td>
<td>80 à 82</td>
<td></td>
</tr>
</tbody>
</table>

(1) in Custode et al, 1992
(2) in Quantin, 1992
13 - Caractéristiques chimiques. Les horizons indurés présentent quelques caractéristiques favorables à leur mise en culture:
- la capacité d'échange effective est relativement élevée, entre 15 et 25 me/100 g.
- les teneurs en bases échangeables sont toujours élevées surtout en calcium et magnésium. Celles en potassium sont importantes. Peña et Zebrowski (1992) notent que les teneurs en cet élément sont plus élevées dans les horizons indurés que dans les sols cultivés non indurés. L'alimentation des plantes en Ca, Mg et K ne pose donc pas de problème sur ces matériaux.

Le pH est généralement légèrement basique d'où l'intérêt d'employer des fertilisants tendant à abaisser sa valeur.

Par contre ces matériaux sont fortement carencés en azote et phosphore. Les teneurs en phosphore sont faibles dans les matériaux bruts, non cultivés, mais Etchevers et al. (1992 a) ainsi que Navarro et Zebrowski (1992) ont montré que les teneurs en cet élément augmentent, par suite de l'application régulière d'engrais phosphaté, dans les matériaux remis en culture. Tous les horizons indurés ne contiennent que des traces de carbone et d'azote. Le carbone est fortement minéralisé (C/N voisin de 5). Il n'y a donc ni humus ni azote disponible pour les plantes.

Les rares études microbiologiques réalisées sur ces matériaux montrent que la micro-faune et la micro-flore sont quasiment nulles. En particulier Alvarez et al. (1992) montrent que les teneurs en bactéries, actinomycètes et champignons sont beaucoup plus élevées dans le sol agricole que dans un tepetate du Mexique (Tableau 2).

<table>
<thead>
<tr>
<th>Microflore dans le sol et le tepetate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bactéries</strong></td>
</tr>
<tr>
<td>Tepetate</td>
</tr>
<tr>
<td>Sol</td>
</tr>
</tbody>
</table>

2 - Réhabilitation (mise en valeur). Elle nécessite la correction des facteurs physiques, chimiques et biologiques qui limitent la croissance des végétaux et donc la reforestation ou la mise en culture de ces matériaux.

21 - Différentes étapes de la réhabilitation

211 - Amélioration des caractéristiques physiques. Elle a pour but la création d'un volume utile à la plante et fait appel à un défonçage de l'horizon induré suivi d'un émiettement des blocs afin de créer une structure optimum.

Le défonçage est réalisé de différentes façons.
- Les méthodes manuelles, à l'aide du pic, étaient traditionnellement employées chez les aztèques et les incas; elles ne sont pratiquement plus utilisées de nos jours au Mexique, mais sont encore fréquentes en Equateur chez le petit agriculteur (De Noni et al, 1992).
L'emploi d'explosifs a été utilisé, surtout expérimentalement, tant en Equateur qu'au Mexique mais n'est plus pratiqué actuellement.
- Les méthodes mécanisées font appel à de puissants tracteurs (D5, D7 ou D8) qui rompent l'horizon induré au moyen d'un sous-solage. La longueur des dents, généralement de 80cm, exceptionnellement de 1,2m, conduit à une profondeur effectivement sous-solée de 40-50 cm dans le premier cas et de 60-70 cm dans le second. Bien qu'il soit plus facile de réaliser le sous-solage à l'état humide, son efficacité, qui se traduit par la fracturation des horizons, est meilleure à l'état sec.

Le sous-solage aboutit à la formation de blocs de tailles très variées (10 à 40cm), peu propices à la germination des plantes, qui doivent donc être rompus jusqu'à obtention d'agrégats de taille optimum. Cet émiettement des blocs se fait généralement au moyen de plusieurs passages de pulvérisateur à disques; l'emploi de rouleau à pieds de mouton afin de casser les blocs et de compacter légèrement le sol a également été pratiqué tant au Mexique (Camargo et Acosta, 1987) qu'en Equateur (communication personnelle de Ing. Marcial Nuñez). Mais tous les essais ont été menés de façon empirique sans qu'aucune norme pratique soit dégagée.

La taille optimum des agrégats est elle-même difficile à définir. Elle doit être telle que la rétention en eau soit maximum et que l'érosion soit minimum. Braunack et Dexter (1989) indiquent que la taille des agrégats doit être comprise entre 2 et 8 mm pour que l'aération ainsi que la capacité de rétention en eau soient correctes. Martinez et García (1990) ont montré qu'une taille moyenne des agrégats de 2 mm, obtenue après émiettement des tepetates, assure une bonne capacité de rétention en eau, une stabilité structurale maximum et une érodibilité minimum. Néanmoins l'érodibilité de ces matériaux fractionnés reste élevée; Jérome (1992) a observé une fonte progressive des agrégats de 2 mm et moins qui favorise l'encroûtement superficiel, le ruissellement et l'érosion, Custode et al (1992) notent des pertes en terre atteignant 92 t/ha/an sur des parcelles de cangahua sous-solées et émiettées, avec une pente de 20%. Des mesures anti-érosives s'imposent donc.

212 - Mesures de conservation. Elles ont pour but de rompre la vitesse de l'eau et de favoriser son infiltration. Elles mettent en œuvre des méthodes manuelles ou mécanisées.

2121 - Méthodes manuelles
- Confection de replats dans la pente: Cette méthode a été employée au Mexique pour des travaux de reforestation. Les replats sont effectués à l'aide du pic et de la pelle sur des pentes pouvant dépasser 50%. C'est une méthode particulièrement recommandée dans l'aménagement des têtes de vallons (Pimentel, 1987).
- Elaboration de "Zanjas trincheras": Ces travaux sont fréquents au Mexique avant la reforestation de versants érodés. Ils consistent en la confection de tranchées de 40x40x500 à 700cm disposées souvent en quinconce. La terre évidée est disposée en petits talus à l'aval de la tranchée, les plantations sont effectuées sur ces talus. L'eau de ruissellement s'accumule dans les tranchées, ce qui favorise son infiltration et diminue donc l'érosion.
- Construction de petites terrasses: Méthode traditionnelle au Mexique où les aztéques, depuis les temps reculés, avaient coutume de construire des terrasses planes de 10 à 20m de large limitées souvent en aval par des bordures de terre au pied desquelles de petits fossés (cajetes), à l'égal des "zajjas trincheras", diminuaient l'érosion en favorisant l'infiltration de l'eau (Gonzalez, 1992). En Equateur la réalisation manuelle de terrasses, qui semble avoir été abandonnée durant l'époque.
coloniale, revoit actuellement le jour chez le paysan de faibles ressources économiques grâce à l’initiative de certains programmes de conservation. Les blocs de cangahua, dégagés au cours de la réalisation de la terrasse, sont disposés sous forme de mur de soutien de la terrasse. Des essais de terrasses à formation continue sont actuellement en cours de réalisation, tant au niveau expérimental (mesure de l’érosion) que chez le paysan où cette méthode est diffusée (De Noni et al., 1992). Ceux-ci dressent de petits murets en blocs de cangahua pour retenir la terre qui, s’accumulant avec le temps, conduisent à la formation de terrasses.

La construction manuelle de terrasses a pratiquement été abandonnée au Mexique au profit des méthodes mécanisées.

2122 - Méthodes mécanisées. Toutes ces méthodes nécessitent l’emploi de tracteurs et comportent toujours un sous-solage.

Bien que celui-ci puisse être l’unique opération pratiquée, il ne peut être considéré comme une mesure efficace de conservation car, si l’infiltration de l’eau est effectivement favorisée la première année, le sol se colmate rapidement et la partie ameublie du matériau est érodée.

- Sous-solage et bordures de terre
Le sous-solage peut être associé à la confection de bordures, édifiées au moyen de la pelle du tracteur, qui retiennent le sol érodé. Ce système revient donc à construire progressivement la terrasse en effectuant des sous-solages successifs au cours des ans. Au Mexique il est pratiqué par les paysans qui n’ont pas les moyens de réaliser des investissements plus importants.

- Sous-solage et élaboration de terrasses
La construction des terrasses est réalisée simultanément avec le sous-solage. La forme des terrasses dépend de leur utilisation future, reboisement ou culture, ainsi que de la pente du terrain, les terrasses les plus larges étant sur les pentes les plus faibles.

Sur pente forte, en général reboisée, les terrasses ont 4 à 5 m de large; elles peuvent être à plat ou avec une contre pente pouvant atteindre 5%.

Sur pente plus faible les terrasses atteignent une vingtaine de mètres de large; elles sont le plus souvent planes ou possèdent une pente de 1 à 2% vers l’aval. Au Mexique il est coutume de les limiter par des bordures de terre dressées avec la lame du tracteur.

Une telle construction de terrasses permet d’avoir immédiatement la terrasse avec sa forme définitive sur laquelle l’érosion est minimum. Elle est toutefois onéreuse et les terrasses ne sont généralement réalisées, essentiellement au Mexique, que dans le cadre de grands projets de récupération des terres érodées.

- Sous-solage et banquettes alternées
Le sous-solage étant effectué les bandes de terrain cultivées sont séparées par des bandes sous végétation naturelle. Cette méthode qui permet de conserver la pente naturelle lorsqu’elle n’est pas trop forte, est beaucoup moins onéreuse que la précédente et est efficace contre l’érosion. Des mesures effectuées en Equateur ont montré que sur des bandes de 10m de large cultivées en maïs, séparées par des bandes enherbées de 1,5 m de large, avec une pente générale de 20%, l’érosion était de 1 t/ha/an alors qu’elle était de 19 t/ha/an sous maïs seul (Custode et al., 1992)

213 - Amélioration des propriétés chimiques.

2131 - Création d’un stock de matière organique. La désagrégment des particules de terre entraîne avec le temps une compaction et donc une diminution de la porosité et de la rétention en eau artificiellement créées par le sous-solage. Seule la création d’une structure par apport de matière organique permet d’éviter ces problèmes. L’apport de fortes doses de matière organique
sous forme de fumier est en général incompatible avec la réalité du monde paysan latino-américain. Le fumier, disponible en faible quantité, est cher et n’est apporté qu’à très faible dose. Au Mexique comme en Equateur, seuls les terrains situés près des lieux d’habitation en bénéficient. Par contre dans l’État de Tlaxcala (Mexique) quelques agriculteurs incorporent les pailles et en d’Equateur l’humus de lombrics est fréquemment utilisé dans certaines régions. La recherche d’un engrais vert à partir d’une culture dérobée, acceptée par le paysan, est en cours d’étude au Mexique.

2132 - Apport de fertilisants. Tous les auteurs (Avila, 1963; Tovar, 1987; Caujolle et Luzuriaga, 1986; Delgadillo, 1989) s’accordent à dire que les cultures sont possibles sur les sols volcaniques indurés et érodés après leur défonçage, avec des apports importants de phosphore et surtout d’azote. Les expérimentations récentes pratiquées au laboratoire (Etchevers et al., 1992 b) montrent que seuls l’azote et le phosphore sont limitants. Les essais réalisés sur le terrain au Mexique par Marquez et al. (1992) montrent que des doses de 60 U de phosphore et d’azote sont suffisantes pour que le blé, dès la première année de culture, atteigne des rendements équivalents à ceux obtenus sur sol normal. Par contre, même avec une fertilisation élevée, les rendements en maïs sont presque nuls en première année mais moyens à bons dès la deuxième année de culture (cf. chap. 3). Cette non réponse du maïs aux engrais serait dûe plus à un problème biologique qu’à un problème de nutrition (absence d’un micro-organisme végétal symbiote de ces plantes, Quantin, 1992).

Au Mexique tous les agriculteurs apportent de l’azote et du phosphore en quantités généralement suffisantes, parfois excessives, de telle sorte que les teneurs en ces éléments augmentent avec le temps (Fig. 2).
C'est essentiellement en Equateur et au Mexique que la mise en valeur des sols volcaniques induits érodés a été réalisée. Si les étapes chronologiques sont très semblables dans ces deux pays, les méthodes et les résultats y sont assez différents.

**221 - Historique.** L'utilisation des sols volcaniques induits en agriculture est une tradition ancienne. Au Mexique Garcia (1986) et Williams (1972) signalent que les indigènes cultivaient les tepetates, après les avoir rompus et aménagés en terrasses, dès 1600 ans AC. Hernandez (1987) affirme qu'il y a plus de 100 ans les habitants de l'Etat de Tlaxcala récupéraient les zones érodées à tepetate en 2 ans en cultivant fève (Vicia faba) et haricot "ayocote" (Phaseolus coccineus) la première année et mais la deuxième année. En Equateur des témoins de terrasses anciennes dans des zones où la cangahua est présente laissent également supposer que l'utilisation de celle-ci remonte à l'époque préhispanique, mais sa récupération par défoncement n'est certaine que depuis une centaine d'années.

L'intérêt des chercheurs quant à l'utilisation agricole de ces formations remonte à environ un quart de siècle tant en Equateur qu'au Mexique. C'est en 1967 qu'en Equateur l'ingénieur Marcial Nuñez fit les premiers essais de récupération agricole de cangahua en la défonçant à 90 cm de profondeur au moyen d'un tracteur D8. Au Mexique les premiers essais datent de 1961: le tepetate, défoncé au moyen d'explosifs, est façonné en terrasses au bulldozer (Garcia, 1961). L'intérêt des chercheurs, surtout au Mexique, n'a cessé de se manifester jusqu'à nos jours et les expériences tant au laboratoire qu'au champ montrent que les sols volcaniques induits peuvent être reforestés ou mis en culture après sous-solage et apport de phosphore et d'azote.

L'attention des responsables politiques a suivi d'assez près les premiers essais de récupération de ces formations.

En Equateur les premiers programmes de reforestation, essentiellement avec l'eucalyptus, réalisés par le Ministère de l'agriculture, remontent à une vingtaine d'années (De Noni et al., 1992). Les programmes concernant la mise en culture de la cangahua sont un peu plus tardifs. De 1976 à 1978 l'INERHI (Instituto Ecuatoriano de Recursos Hidraulicos) récupérait des zones érodées après les avoir défoncées mécaniquement et en implantant des cultures irriguées. En 1985 sont créés deux organismes, PROMUSTA (Proyecto de Manejo y Uso Sostenible de Tierras Andinas) et PROCOSA (Proyecto de Conservacion de suelos y Sistemas Agrosilvopastoriles), afin de diffuser des mesures de conservation des sols dans les communautés indigènes de la Sierra Equatorienne; bien que ces projets ne soient pas spécifiques à la récupération agricole de la cangahua, ils concernaient des zones où celle-ci était présente. Les cultures sont réalisées après l'élaboration manuelle de terrasses et avec irrigation.

Au Mexique, les premiers essais de reforestation datent de 1968 avec la création d'un programme de récupération de zones érodées par la direction de la "ordenacion forestal". Mais ce n'est qu'aux environs des années 72 et 73 que se sont multipliées, pendant près de 10 ans les programmes pour la réhabilitation des zones érodées, essentiellement dans les Etats de Puebla, Tlaxcala et Mexico, réalisés par des institutions officielles para-publiques telles que CODAGEM (Coordinación para el Desarrollo de la Agricultura y del Ganado en el Estado de México), C.L.T. (Comisión del Lago de Texcoco, maintenant Plan del Lago de Texcoco), D.G.C.S.A. (Dirección General de Conservación de Suelos y Agua), etc. Les énormes travaux de terrassement et de sous-solage entrepris au sein de ces programmes, grâce à la relative opulence économique du pays, étaient essentiellement orientés vers la reforestation afin de limiter l'érosion et l'apport de sédiments.
source de pollution, en particulier dans des zones à forte densité de population telle la ville de Mexico.

La réalisation de terrasses par les institutions officielles para-publiques pour la mise en culture des tepetates est plus tardive. Elle s'est faite dans les années 80 sous la pression des paysans désireux de profiter de ces puissants moyens pour mettre en valeur leurs terres érodées. C'est ainsi qu'en 1983, alors que par suite de la récession économique certaines institutions officielles disparaissaient, fut créé, dans l'Etat de Tlaxcala, MATET (Maquinaria para las Tierras del Estado de Tlaxcala), institution toujours très active de nos jours.

Les travaux de défonçage et de terrassement étaient effectués, au début de la décade 80, avec une participation minimum de la part des paysans. Cette participation financière a peu à peu augmenté et représente actuellement plus de 50%, parfois 90%, des coûts de revient des travaux.

222 - Bilan

Il est difficile à établir, en particulier en ce qui concerne les surfaces récupérées, faute d'inventaire général et détaillé, mais certaines conclusions peuvent néanmoins être dégagées.

Reforestation. Elle est généralement réalisée par des institutions officielles, mais:

- En Equateur, aucun chiffre concernant les surfaces reboisées n'est disponible, néanmoins De Noni et al. (1992) avancent un total de 15000 ha reboisés en eucalyptus. La plupart des techniciens récemment interrogés, affirment que ces reboisements ne sont pas efficaces contre l'érosion, faute d'un couvert végétal suffisant, et que la croissance de l'eucalyptus est très lente. Un essai de reboisement avec Pinus radiata a été réalisé, avec succès, chez un particulier.

- Au Mexique, il n'existe pas non plus de synthèse complète concernant les surfaces de tepetates reboisées. Mais les espèces plantées ont été très variées: pins, eucalyptus, cyprès, frênes, etc. D'après Llerena et Sanchez (1992) les Pinus montezumae et Eucalyptus sp. seraient particulièrement recommandables pour la reforestation des tepetates.

La reforestation a été particulièrement efficace dans certaines zones critiques telle la Cuenca de Mexico dans laquelle les 5000 ha reboisés par le "Proyecto lago de Texcoco" ont permis de stopper de façon presque totale l'érosion (Llerena et Sanchez, 1992)

Mise en culture. Le maïs, culture traditionnelle de l'Amérique latine, associé ou non avec le haricot, la courge et la fève, le blé et l'orge sont les cultures les plus fréquemment pratiquées sur les sols volcaniques indurés. Les cultures maraîchères sont surtout réalisées en Equateur où l'irrigation est fréquente.

En Equateur, l'intervention des institutions gouvernementale a donné des résultats différents. Le projet Montufar, réalisé par l'INERHI, est un échec. Malgré un fort investissement pour le défonçage des sols et la création d'un réseau d'irrigation, seuls 165 ha de cangahua (sur les 900 ha initialement prévus) ont été mis à la disposition des paysans. L'érosion des terres, faute de mesures de conservation, ainsi qu'une action non concertée avec les paysans semblent être responsables de cet échec. Par contre les projets PROCOSA et PROMUSTA dans lesquels des moyens de vulgarisation ont été mis en oeuvre, sont mieux acceptés par les paysans. La réalisation manuelle de terrasses, leur mise en culture, toujours sous irrigation, se répandent peu à peu. Les surfaces de cangahua ainsi cultivées restent néanmoins encore peu nombreuses (environ 400 ha en 8 ans dans le cadre du projet PROMUSTA). En fait la récupération des zones érodées à cangahua est surtout le fait d'initiatives personnelles de la part de paysans à très faibles ressources économiques, sans appui technologique de la part d'organisme officiel. On peut estimer à près de
1000 ha les surfaces récupérées, essentiellement par défonçage manuel, sans, ou avec très peu, de mesures de conservation.

Au Mexique l’adoption par le paysan de moyens mécanisés importants pour la récupération agricole des tepetates est actuellement générale. Le paysan loue le tracteur auprès de personnes privées ou fait appel à des organismes officiels tel MATET. Depuis sa création en 1983 MATET a récupéré en 8 ans 12800 ha dans l’Etat de Tlaxcala. La demande des paysans auprès de cet organisme pour une intervention sur leurs terres ne cesse de croître.

223 - Coûts des travaux. Les coûts sont extrêmement variables suivant qu’ils sont effectués mécaniquement ou manuellement, la profondeur à laquelle le sol est défoncé et la dureté du matériau (Tableau 3).

Défonçage. Au Mexique nous avons mesuré le temps nécessaire au défonçage d’un tepetate assez résistant réalisé au moyen d’un D5, à une profondeur théorique de 80 cm. Il a fallu 39 heures par hectare. Ce temps n’est plus que de 25 heures dans le cas d’un tepetate peu résistant ce qui donne des prix de 800 à 1200 US $/ha. Ces valeurs sont très proches de celles citées par De Noni et al. (1992) en Equateur.

Les prix du défonçage à la dynamite sont, avec 3700 $/ha, plus élevés, ce qui explique que cette méthode, par ailleurs plus délicate d’emploi, est peu utilisée.

Le défonçage manuel, réalisé au pic en Equateur entre 20 et 30 cm de profondeur, est évalué entre 5 et 6000 $/ha. Il faut en effet compter près de 5 m2/jour et par homme payé à 3 $/jour. Si la profondeur du défonçage est de 40 à 50 cm, un homme ne travaille plus que 3 m2/jour, ce qui fait monter le prix du défonçage à 10000 $/ha.

Terrasses. Le prix des terrasses réalisées, conjointement au défonçage, avec un D5, sur une pente moyenne de 15 %, est de 1500 à 1900 $/ha. Celui des terrasses réalisées manuellement est évalué de 2 à 3000 $/ha par PROMUSTA mais est dix fois plus élevé d’après PROCOSA. Ce dernier n’évalue pourtant le prix de la main d’oeuvre qu’à 3500 sucres (1.75 $) par jour, mais estime qu’un homme ne peut faire qu’un seul m2/jour de terrasse, alors que PROCOSA affirme qu’il en fait plus de 10. Tout dépend de la dureté de la cangahua.

Les coûts de réalisation des travaux sont donc élevés. Le problème de la rentabilité de telles actions se pose chaque jour, celle-ci dépend avant tout de la productivité des matériaux indurés.

3 - Productivité et rentabilité : exemple de l’expérience mexicaine

31 - Cadre de l’étude. La productivité des tepetates a été mesurée durant les années 90 à 92 sur des parcelles cultivées de façon traditionnelle par les paysans ainsi qu’au cours d’essais expérimentaux au champ durant les années 91 et 92.
Figure 3. Localisation de la zone d'étude.

Les lieux d'étude furent les Ejidos de Hueyotlipan et Tlalpan tous deux appartenant au Municipio de Hueyotlipan, lui même dépendant du District de Calpulalpan, localisé dans l'État de Tlaxcala (Fig. 3). Ce dernier, d'une superficie de 3914 Km², possède une densité de population, avec 128,4 hab/Km², parmi les plus élevées du Mexique. Les paysans sont regroupés en Ejidos. Dans le Municipio de Hueyotlipan, sur un total de 1532 producteurs disposant de 13230 ha de terres agricoles, 1095 sont ejidatarios et possèdent une moyenne de 6,15 ha/Ejidatario, alors que les 437 restants sont propriétaires de leurs terres et possèdent en moyenne 14,8 ha/personne.

L'État de Tlaxcala, situé à une altitude moyenne de 2500 m, présente un climat tropical subhumide tempéré. avec, pour la ville de Tlaxcala, des moyennes annuelles de précipitations totales de 772 mm et une température de 15,4°. La présence de gelées, fréquentes en hiver, limite la période de cultures à 150 jours, au nord de la zone d'étude, et à 210 jours au sud de cette même zone. Durant cette période, libre de gelées, les précipitations utiles aux cultures sont comprises entre 400 et 500 mm dans la zone d'étude (Figure 4).
Les sols volcaniques indurés, présents dans la zone d’étude, représentent 54% de la superficie de l’État de Tlaxcala, dont 27% de cette surface, soit près de 60 000 ha sont des zones érodées, avec mise en surface des tepetates. La nécessité de la réhabilitation agricole de ces zones est évidente pour les paysans tlaxcatecas. Ces derniers les mettent en valeur après sous-solage du tepetate et réalisation de levées de terres, plus économiques que les terrasses, pour limiter l’érosion. Ces travaux, toujours effectués au bulldozer, sont généralement réalisés sous forme de contrat et payés par le paysan.

Les principales cultures (Figure 5) sont le maïs, culture traditionnelle réalisée par tous, l’orge et plus récemment le blé, cultivés par les paysans possédant généralement plus de 5 ha de terres. Les agriculteurs ont coutume de semer le blé et l’orge en première année de culture du tepetate, réservant le maïs pour les années suivantes (Tableau 4).

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<th>Tableau 4. Cultures pratiquées sur tepetate après son défonçage</th>
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Figure 4. Journées libres de gelées et probabilité (à 70%) de pluies durant cette période.
Figure 5. Evolution de la superficie des cultures dans le District de Calpulalpan, de 1940 à 1992.

32 - Productivité en parcelles paysannes

321 - Méthodologie

La sélection des parcelles chez l'agriculteur a été faite en fonction de la nature du substrat, afin de comparer la productivité sur tepetate et sur sol agricole non induré, et du nombre d'année de mise en culture du tepetate, dénommé âge du tepetate. Les cultures suivies ont été le maïs, le blé et l'orge. Pour chacune d'entre elles et pour chaque parcelle on a déterminé les pratiques culturales ainsi que leur coût et les rendements finaux. L'analyse des rendements après la première année permet d'élaborer le protocole expérimental mis en place pour mesurer la production potentielle du tepetate (chap. 33).

322 - Pratiques culturales. Elles sont très semblables sur sol agricole et sur tepetate. La préparation du sol, généralement mécanisée, est réalisée au moyen d'un labour suivi d'un passage de disques. L'apport de matières organiques est peu fréquent, par contre la fertilisation, réalisée au moment du semis est générale, mais les doses apportées sont sans commune mesure avec les nécessités. Souvent trop faibles, parfois trop fortes, elles ne tiennent en particulier pas compte de la nature du sol, qu'il soit agricole, relativement riche, ou tepetate. Une deuxième fertilisation est parfois apportée trente à quarante jours après la levée. Deux pratiques culturales supplémentaires sont pratiquées sur le maïs, l'une pour détruire les mauvaises herbes, l'autre pour le butter. La récolte est mécanisée dans le cas du blé et de l'orge, manuelle pour le maïs qui est coupé puis mis en gerbes pour séchage avant la cueillette des épis.

323 - Rendements. L'analyse des rendements obtenus sur trois ans montre tout d'abord que ceux-ci présentent une forte variabilité interannuelle que ce soit pour le maïs (Figure 6) ou le blé et l'orge, cultivés sur tepetate ou sur sol agricole.
Figure 6. Rendements de maïs sur sol agricole et sur tepetates d’âges différents (3 ans de mesures)

Pour une année donnée les rendements obtenus sur sol agricole, tout comme ceux obtenus sur tepetate de même âge de culture, présentent également une variabilité importante, du fait que les parcelles, appartenant à divers agriculteurs, sont conduites de façons différentes (époques de semis, soins, apports d’engrais), spécifiques à chaque agriculteur. Malgré ces variations il est remarquable de constater que les rendements du maïs sont bien corrélés au nombre d’années de mise en culture du tepetate. Ceux-ci sont très faibles en première année de culture, moyens au bout de trois ans et bons dès la cinquième année de culture pour laquelle ils sont très semblables à ceux obtenus sur sol agricole.


Le protocole expérimental se proposait de mesurer:
- la réponse de différentes cultures avec ou sans apport de matière organique (40 t/ha de fumier), avec différentes fertilisations comportant, compte tenu des caractéristiques du tepetate, une dose constante de phosphore (60 U) et trois niveaux d’azote (0, 60 et 120 U.)
- le résultat des rotations qui sont le plus souvent pratiquées par le paysan, à savoir: blé en première année, maïs en deuxième année ainsi que blé sur blé.
Les rendements indiqués dans la Figure 7 ne concernent que ceux obtenus avec la dose de 60 U. d'azote, laquelle s'est avérée être la plus rentable. Les rendements en maïs furent très faibles (< 1 t/ha) en première année, mais acceptables en deuxième année (2 à 2,5 t/ha), ce qui confirme les résultats obtenus en parcelles paysannes. Ceux en blé furent bons dès la première année de culture (1,8 à 2,8 t/ha), d'où l'intérêt de commencer la rotation sur le tepetate récemment défoncé par cette culture. L'effet de l'apport de fumier est sensible sur le maïs mais surtout sur le blé.

En ce qui concerne les rotations pratiquées, on constate qu'il est plus intéressant de commencer la première année par une culture de blé avec apport de matière organique (fumier), puis de faire en deuxième année un maïs.

34 - Rentabilité. La rentabilité actuelle des cultures de maïs et de blé, fonction des rendements en grain de ces deux cultures sur les parcelles paysannes, a été calculée en incluant comme coûts indirects la rente de la terre ainsi que les intérêts du capital anticipé de la production, mais sans inclure le coût de récupération du tepetate. Les résultats (Figures 8 et 9) montrent que:

- Pour que la culture du maïs soit rentable il faut un minimum de rendement de 1,5 t/ha qui a été rarement atteint sauf pour quelques parcelles situées en sols agricoles sur lesquels les rendements en maïs sont généralement plus élevés que ceux obtenus sur tepetate.
- Pour que la culture du blé soit rentable il faut un rendement minimum de 1,8 t/ha, qui a été atteint dans la plupart des parcelles, qu'elles soient situées sur tepetate ou sur sol agricole.

En fait la rentabilité dépend du rendement, qui peut être amélioré par de meilleures pratiques culturales, et du prix de vente des produits agricoles, indépendant du paysan. Dans l'état actuel, il n'est pas possible d'amortir, avec la seule culture de maïs, le coût de récupération du tepetate.
Figure 8. Rentabilité et rendement de la culture du maïs en parcelles paysannes. Ce dernier ne peut être amorti qu'avec la culture de blé, d'autant plus vite que les rendements, supérieurs à 1,8 t/ha, sont plus élevés.

Figure 9. Rentabilité et rendement de la culture du blé en parcelles paysannes.

Conclusion. Malgré les contraintes physico-chimiques des sols volcaniques indurés, les zones érodées dans lesquelles ces formations affleurent sont mises en valeur. C'est un fait passé et présent en Equateur tout comme au Mexique. Ces formations sont situées dans des régions où la forte densité de population a conduit le paysan à étendre la zone de culture à ces zones qualifiées de marginales. Ce devra être également un fait d'avenir dans ces régions où l'érosion très active, source de désertification, est un réel danger. La productivité de ces sols correctement aménagés est démontrée; elle est sensiblement égale à...
celle des autres sols dits agricoles.
Le coût des aménagements, défoncement et protection contre l'érosion, peut paraître élevé, mais les paysans de chaque région ou pays surmontent cette difficulté en choisissant des méthodes adaptées à leur contexte socio-économique. Dans les milieux les plus pauvres, notamment en Equateur, les paysans disposant de peu de ressources effectuent les travaux manuellement; dans les milieux relativement plus aisés, les méthodes mécanisées, avec investissement financier parfois important de la part du paysan, ont été adoptées.
C'est avant tout la rentabilité de l'agriculture dans ces régions qui est l'obstacle majeur à la mise en culture de ces sols. La productivité en général doit être améliorée par la recherche de pratiques culturelles plus performantes, en particulier par l'emploi et la divulgation de méthodes de fertilisation plus adaptées aux besoins réels des plantes, tout comme l'adoption de systèmes de rotation, spécifiques aux formations indurées réhabilitées. Le recours à l'irrigation, fréquent en Equateur, pourrait être également généralisé. Une bonne caractérisation agro-physiologique des espèces employées localement ainsi que la recherche d'espèces nouvelles, adaptées à ce milieu particulier, devraient également être entreprises.
Les méthodes de conservation des sols qui devraient être toujours appliquées dans ces milieux fragiles doivent être améliorées et diffusées encore plus largement dans le milieu paysan. Il existe encore trop de cas où ces sols, récupérés sans mesures de conservation, sont rapidement érodés. Pour ce faire la participation d'instances gouvernementales est fondamentale. Le rôle de celles-ci a été décisive au Mexique où les paysans ont peu à peu adopté des méthodes mécanisées efficaces pour récupérer les sols indurés. En Equateur, en dépit de quelques échecs survenus en début d'intervention de l'État, les actions pour la diffusion des méthodes de conservation sont positives, bien que trop ponctuelles.
Mais la généralisation des actions visant à la mise en valeur de ces sols doit être plus ample. Pour cela il apparaît nécessaire de quantifier les zones qui restent à récupérer, d'établir un bilan précis des différentes expériences entreprises et de définir une politique d'intervention notamment en ce qui concerne le choix entre les zones à reforester et celles à mettre en culture.

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Soil Data Needs for Expressing Land Qualities at Different Scales

Convener: J. Bouma (The Netherlands)
Co-convener: Lenom Cajuste B. (Mexico)

Introduction to the symposium ID-15: soil data needs for expressing land qualities at different scales. J. Bouma and R. J. Wagenet. (The Netherlands)……………………………………………………………………………………………………… 612

Innovative soil sampling and analysis procedures for the local resource management of agricultural soils. D. P. Murphy, S. Haneklaus and E. Schnug. (Germany)………………………………………………………………………………………… 613

Data needs for sustainable land use scenarios for humid tropical Costa Rica. J J. Stoorvogel. (Costa Rica)……………………………………………………………………………………………………… 631

Modeling variations of land qualities at regional and global scales using geographic information systems. Norman B. Bliss and Sharon W. Waltman. (USA)………………………………………………………………………………………… 644

Advances and pitfalls in expressing land qualities at different scales. Peter M. Groffman and R. J. Wagenet. (USA)……………………………………………………………………………………………………… 662
Introduction to the Symposium ID-15: Soil Data Needs for Expressing Land Qualities At Different Scales.

This symposium was organized by the working group MV of the International Society of Soil Science, which covers soil and moisture variability in space and time. The working group MV, established in 1986 at the ISSS Conference in Hamburg, has organized a number of activities leading up to Symposium ID-15. An international Conference was held in Wageningen in 1988 on: "Land qualities in space and time". The proceedings of that Conference was published by Pudoc publishers, Wageningen, the Netherlands. A Symposium of the Soil Science Society of America on: "Spatial variability and map units of the soil survey" was co-sponsored in 1989, while two Symposia were organised at the ISSS Conference in Kyoto in 1990. Titles were: "Areal estimation of soil hydrological processes and their application in land evaluation and environmental protection" and in: "Watershed hydrology and efficient use of irrigation and drainage structures". In 1992 a Conference was held at the Dept. of Soils, Crops and Atmospheric Sciences at Cornell University, with the title: "Operational methods to characterize soil behavior in space and time". The Proceedings of that Conference will appear as a special issue of the Journal Geoderma.

The objective of Symposium ID-15 is to emphasize soil data needs for expressing land qualities at the local, regional and global scale, with a separate contribution emphasizing methods to link the different levels. Speakers were asked to pay attention to operational methodologies and to an analysis of variability and error involved. Also, the interaction between researchers and practitioners in shaping research programs was to be covered. The following papers cover the field level (E. Schnug et al), the regional level (J. Stoorvogel) and the regional and global level (N.B. Bliss and S.W. Waltman). Methodologies at different scales are discussed by P.M. Groffman and R.J. Wagenet. These papers are a valuable contribution towards the development of innovative methodology to characterize soil behaviour in space and time.

J. Bouma
R.J. Wagenet.
Innovative Soil Sampling and Analysis Procedures for the Local Resource Management of Agricultural Soils

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Abstract. The investigations reported here address the development of low cost and locally calibrated methods for quantifying spatially variable soil and crop parameters. Techniques are presented whereby the cost of collecting the necessary data is reduced by exploiting local correlations between analytical techniques, and combining these with data from the automated sampling of key agronomic parameters in the course of normal agricultural operations. Most studies of spatial variability in soils indicate that a sampling interval of 50-100 m (1-4 samples per ha.) is adequate for the mapping of agronomically important parameters. It is shown that a soil’s rubidium concentration is highly correlated with clay content. The use of acid extractants for available trace element or phosphorus determination also provides opportunities for the locally calibrated determination of soil organic matter content and available potassium. The exploitation of the ‘equifertile’ (i.e. areas that within seasons give consistently similar yields) is described. It is proposed that the measurement of rapidly changing variables such as soil mineral nitrogen at fixed sampling points within each equifertile provides key data for inputing into the calculation of the spatially variable applications. Methods to derive equifertiles using modern yield mapping technology or soil survey are outlined.

Introduction. Between 1945 and 1980, European agriculture was driven by the demands for self sufficiency in the supply of temperate foodstuffs. The agricultural support system generated farm income by subsidising production and guaranteeing prices. At the same time, fertilisers were cheap in relation to product prices; high fertiliser application rates were adopted in the knowledge that the economic penalty for over-application at any point in the field was lower than for the application of sub-optimal amounts (4). Thus, the effects of spatial variation in soil parameters on crop yield were minimised by high fertiliser application rates applied uniformly across whole fields. In this way, the near level above optima surface of most fertiliser response curves has been fully exploited to stabilise economic
returns. Similarly, the low price of pesticides in relation to yield benefits has also negated the need for critical assessments of their flat rate application.

To improve crop production technique in relation to soil variability, Schnug et al. (13) presented a cyclical local resource management (LRM) system centred on the processing of spatially variable data in an ecological data base. Crop performance data are combined with data quantifying spatial variation in agronomic resources, incidences of weeds, diseases and pests. The processing of these data together results in digital maps of the application of crop inputs. This concept accepts that the determination of the spatial variability in crop performance serves as a biological indicator of factors affecting productivity and thus provides a valuable diagnostic tool (10). The full exploitation of the concept requires that the spatial distributed crop data are combined with data on soil characteristics or any other related factor. The investigations reported here are concerned with realising this concept in farm practice, and show that the adoption of the technology at farm level may circumvent the problems normally associated with the calibration of soil test results.

The data requirements for the effective Local Resource Management (LRM) of agricultural soils are summarised as follows:

1. Geocoded sampling.
2. Crop yield mapping.
3. Innovative data interpretation.
4. Cost effective locally calibrated techniques.

Geocoded sampling. Accurate position finding is a pre-requisite for management of spatial variation in agricultural soils; it is necessary to be able to locate position, digitally, in a precise and unambiguous way. Ideally, the same geocoding system would be used for manual or automated crop, soil or terrain sampling as
well as the application of crop inputs. The Global Positioning System (GPS) satisfies these requirements. The basic system, as it was operating in 1990 and 1991, enables real time positioning within 10 m for 95% of the time. The imposition of selective availability in late 1991 reduced accuracies to within 100 m. The use of land based differential signals has restored accuracy and facilitated dramatic improvements in performance. At present, advanced GPS receivers with differential assistance (DGPS) enables position on the earth's surface to be identified within 20 cm. Receivers that give accuracies in the 10 m range and suitable for use in agriculture are already in mass production. The GPS system has many advantages for agriculture. It is widely used according to established standards and operates independent of surface features. Flexibility in receiver design facilitates easy installation into existing equipment and integration with established electronic control systems. The system as it is presently operating has proved to be adequate for all agricultural purposes. The most basic receivers with differential assistance are adequate for geocoding the hand sampling of soils and for real-time positioning of combine harvesters which move at relatively low speeds.

The positioning and computing requirements for the exploitation of geocoded digital application maps are more demanding. Post-processing to screen out erroneous positioning values is not possible. The demands on the system are determined by machine speed, rate of change of applications and the quality of supporting software. It is proposed that a raster (grid), rather than a vector, based information system should be used. Even though a vector based system is cartographically superior than a raster format, the raster system is likely to predominate with these applications because of advantages in computing within the data base. Ideally, the raster size would be determined by spatial variability in soil and crop parameters. However, with practical agricultural applications, the resolution of the application machinery used imposes a minimum grid intensity; most agricultural chemical application machines have an operating width of 12-24 m giving a minimum grid size of 144-576 m². In addition to raster size, the positioning requirements for real time control of applications depends also on the speed of machine operation. If the GPS antenna is mounted on the front of a 4 m long tractor unit operating at 15 km h⁻¹, positioning, output calculation and mechanical control of the application taking place at the back of the unit must be complete within 1 second if this operation is to
completed on a real time basis on exactly the boundary between raster cells. The presently available processing units provide the required processing speed; the main cause of delays are mechanical. If a further delay of 1 second takes place, as is realistic with present technology, changes in applications will take place 4 m away from the raster boundary. With a raster size of 12 x 12 m, this might be regarded as unacceptable. However, the adoption of a raster size of 50 x 50 m renders a 4 m delay in response insignificant especially as changes in output between rasters and over a series of rasters is most likely to be gradual. With current progress, determining position to within a few centimeters will be very easy in the future with the possibility of the required differential signals being provided as a public utility (16). With accuracies of 5 - 10 m required for soil management purposes, it is concluded that GPS satisfies the requirement for agriculture.

Conventionally, the accuracy of a GPS receiver is quoted as within a given distance for at least 95% of the time. No information on the performance of the system for the remaining 5%, during which time large errors in excess of 100 m may take place, is normally quoted. In addition, contact with satellites may be momentarily obscured giving poor or no positioning. For the use of GPS in controlling chemical applications, it is essential these short term positioning failures are detected immediately and that the associated software gives a default application rate that is used until the the accuracy of the system is restored.

Crop yield mapping. The cyclical LRM programme (13) uses yield mapping as both the starting point for determining a variable application system, and the point where the effect of the variable strategy can be monitored. Yield mapping is easy in concept but may be technically difficult in practice. Details of some of the technology used have been published (2,11). The methods employed to map crop yield in these studies have been reported (14). A map of the relative crop yield of wheat and oilseed rape is presented in Fig. 1. These trials have demonstrated clearly that GPS and flow meter technology can be integrated to provide the data for successful yield mapping. Direct observation of some of these operations showed that lag time between the start of a harvest run (when the threshing mechanism is nearly empty) and a stable grain flow may be as long as 60 seconds while the lag time between position and the appropriate yield reading is 15-20 seconds within the harvest run when the machine is working normally. These are
characteristics of the individual harvester and/or crop. Attention to this requires that the software controlling data logging is designed according to the harvester’s grain flow characteristics.

Innovations in data interpretation. Traditionally, the results of the analysis of available nutrients have been interpreted using univariate techniques. Development of a soil test and fertilizer recommendations for a given nutrient involves research into the selection of suitable extraction procedures, the correlation of these results with data from field or greenhouse grown crops, and the interpretation of results to give fertiliser recommendations. In some situations, agronomists remain skeptical about the ability of this process to deliver the best recommendations; this skepticism can be traced to awareness of spatial variation in the field and to the suspicion that the established procedures are not the most appropriate for the individual situation in question. The development of soil and yield mapping technology facilitates the calibration of a wide range of analytical procedures on the location in which they are used through exploiting the boundary line approach (17). The principle behind this can be traced back to the ‘Law of the minimum’ as proposed by Liebig. The yield data on which the map in Fig. 1 are based were synchronised with measurements of the pH (water) of soil samples taken on a 40 x 20 m grid. The resultant data for soil pH and relative seed yield were graphed and a boundary line was fitted using BOLIDES (Border Line Development System (12)). BOLIDES is a computer programme for fitting border lines according to statistical criteria (Fig. 2). This showed that yields in excess of 120% of the mean yield were confined to points where pH was greater than 5.55 and less than 6.05. Where crop yield and nutrient availability are mapped, the boundary line approach can be exploited to examine the response to increasing nutrient availability on those parts of the field where all other conditions are optimal. This approach has three advantages: a much wider range of analytical procedures can be used and calibrated locally, the technique presents critical values that are related to the crop grown with little or no other nutrient limitations on yield, and the results relate directly to the site on which the fertilizer applications are to be made.

Cost effective locally calibrated analytical techniques. The cost of establishing spatially variable soil treatments in practice is most likely to be determined by the cost of data as affected by analytical costs and sampling intensity. Our laboratory studies
highlight some possibilities for reducing the cost of analysis through the exploitation of correlations between analysed parameters. Field experience gained in formulating the LRM concept indicated that soil organic matter and clay content are essential data in determining spatially variable soil management strategies. Two new methods were developed to enable variation in these parameters to be evaluated quickly and reliably. The determination of soil organic matter relies on the extraction of coloured substances from the soil organic fraction on treatment with an acid. Humic substances account for 85% - 90% of the soil humus and are responsible for the cation and anion exchange properties of soil organic matter. Acids and alkalis extract a proportion of the humic matter in soils. Samples from brown earth and podzolic soils in northern Germany were subjected to extraction for micronutrients using 0.43 M HNO\textsubscript{3} (20). The intensity of the colour in the filtrate was quantified by the absorbance of light at 540 nm. Soil organic matter was determined on the same soils by loss on ignition and the correlation between the absorbance of light in the extract and soil organic matter was determined.

The relationship between absorbtion of 540 nm light in the 0.43 m HNO\textsubscript{3} extractant and total soil carbon (%) for soils taken from one field (Birkenmoor) with a brown earth soil, and from two agricultural areas dominated by podzolic and brown earth soils are given in Figs. 3 and 4. High correlations were observed in all three situations for soil samples with a common genetic and agronomic history (i.e. samples within one field or from one farm. A comparison between soils differing in genesis or previous management reveals the same general relationship between extractant colour and soil carbon; soil type or history has little effect on the slope of the line, it changes the Y intercept.

The basis of the method for the determination of the clay content relies on the close relationship between the clay content and the rubidium (Rb) content in soils. The rubidium content of soils is largely inherited from parent materials; high concentrations are found in acid igneous rocks and sedimentary aluminosilicates (7). Rubidium is a better indicator of clay content than potassium because it is more strongly bound to silicates than potassium; during weathering the K/Rb ratio decreases, and can be modified by K fertilisation. Surface soil samples taken from a test field in Denmark were subjected to X-ray fluorescence spectroscopy to determine total concentrations of all elements from sodium to
uranium on the periodic table. Particle size distribution was determined on each soil sample using the pipette method (5).

The relationship between clay concentration as determined by conventional particle size distribution analysis and rubidium concentration is given in Fig. 5. The highly significant (P<0.001) correlation of 0.97 on seven samples was observed despite considerable variation in the organic matter content. This shows that, for a soil with a common origin, the rubidium concentration is closely related to the clay content.

**Monitoring temporal changes in fertility parameters - the concept of 'equifertiles'**. For the most effective exploitation of spatially variable applications, the system must address the control of the short term variable parameters such as nitrogen and sulphur. Not only is the nitrogen requirement the most difficult to calculate, it is the variable that would give the greatest environmental response to spatially variable management. The cost of collecting the required data using standard soil mapping techniques annually prohibits the use of this technology for the application of nitrogen. More precise management of nitrogen applications requires the use of models simulating the simultaneous processes affecting the mineral nitrogen content of the soil (1). With a modelling approach, crop uptake as determined by crop growth is a key determinant of the fertiliser nitrogen requirement simulated. Thus, consistent variations in spatial distribution of crop yield is a key input into any model used to predict the spatial variation in nitrogen requirement. It is proposed that the spatially distributed data on key inputs to such models such as crop yield (to which nitrogen uptake is directly related) and soil mineral nitrogen content can be gathered efficiently through exploiting the 'equifertile concept'. Equifertiles are areas that have identical or similar productive capacity within each season. The objective is to categorise land areas according to their likely production potential. Permanent monitoring points or monitoring pedocells are located within each of these categories ('equifertiles'). These pedocells are used to monitor temporal changes in short term variables such as soil mineral nitrogen. The data so obtained are valid for the entire equifertile and can be inputed into a model as such.

The mapping of crop yield over 3-4 seasons enables the evaluation of equifertiles empirically; areas giving consistently similar yields in each season are identified. Provided the appropriate yield mapping and data handling software is available, the
empirical evaluation of equifertiles will not be difficult. The data handling process is concerned with deviations from the mean yield so that areas that have given consistently similar yields within a number of seasons are identified.

In many situations where yield mapping technology is not available, productivity patterns may be deducted from the spatial patterns of soil fertility parameters such as soil pH, clay and organic matter content and terrain related parameters. New techniques may provide the means to measure these variables easily in a large number of samples with a common genetic and agronomic history. Mulla (9) used geostatistical methods to examine selected soil properties and wheat yield in an area with an average annual precipitation of 41 cm in Washington State. In this region, profile water content is the single most important soil property influencing potential yield of winter wheat. Soil organic matter content was correlated with available phosphorus, profile water content and crop yield. The soil organic matter data alone enabled the field to be divided into soil management zones which differed significantly in crop yield and closely associated parameters. Thus, in the agricultural landscape concerned, it was established that soil organic matter content was a very effective indicator of crop yield variation and land management units.

Here, the use of multivariate statistical techniques applied to the task of deducting equifertiles from soil data without the aid of grain yield is discussed. This relies on the facilities of factor analysis analysis (3, 8) to examine the relationships between a number of relevant growth parameters that may be involved in the complex term 'soil fertility or productivity'. Factors are independent linear combinations of the measured variables and can be understood as crossing axes within the scattered data. With soil data, clusters of variables in the factor space represent empirical fertility units. Thus, the variables within these units that are easily measured are used as indicators of major 'fertility' classes in the landscape. The result of the principal component analysis of soil fertility parameters a brown earth in northern Germany is given in Fig. 6. In this example, the complex information observed in 8 of 10 soil fertility parameters are clustered close to the first factor extracted. The factor diagram shows that the soil organic matter content as the highest loading variable in the cluster related to the first factor. By the use of a cost efficient and quick
method for the determination of soil organic matter, the spatial distribution of the equifertiles can also be evaluated. It is proposed that these relationships are characteristic of each landscape or agricultural region, and that the results of a factor analysis data from an intensively sampled site can be applied to deduct equifertiles over a wide area.

The application of deducted equifertiles requires validation if they are to be used confidently in plant production. This can be achieved by combining data from yield mapping with data on the key parameters identified by factor analysis. The equifertiles deducted from soil parameters are compared with those obtained empirically from yield mapping. Fig. 7 shows equifertiles deducted from soil data compared with pea seed yield derived from a trial field managed by the Danish Agricultural Advisory Service near Aarhus. To evaluate the validity of the equifertiles for crop productivity both information layers were synchronised and correlated (Fig. 8).

Discussion The aim of the studies reported here is to establish a soil resource management system guided by spatial variation in key parameters. The feasibility of establishing this is determined by the cost of capturing the necessary data. Data relating to permanent features or parameters which vary only in the long term are distinguished from medium term variables such as soil pH, phosphorous and potassium content which require renewal every 3-4 years, and short term data such as plant available nitrogen which needs to be renewed every year.

The hardware required to operate a local resource management programme has developed very rapidly since 1990. A fully automated GPS aided yield mapping facility is now available with Massey Ferguson combine harvesters sold in Europe. Fertiliser spreaders equipped with GPS and variable rate technology are commercially available in Denmark and USA. The GPS satellite constellation was completed in 1993 giving 100% coverage of the globe 24 hours per day. At this stage, it is essential that the scope for this technology is clearly demonstrated at the commercial level so that the development towards universal availability continues. It is proposed that the application of the technology to long and medium term variables such as soil texture, pH, and P and K availability provides the most rapid means whereby the technology may be initially adopted. The scope for the technology to be used to manage just one parameter has
been clearly demonstrated in the case of soil pH (15). A simple soil mapping approach measuring soil pH, clay, available P and K in samples taken at a 50 - 100 m intervals will provide the data base for the calculation of optimised spatially distributed application strategies. This may be most commercially attractive if adopted by agricultural contractors specialised in base fertiliser applications to entire rotations (every 4-6 years). These operations have the advantage that the cost of the machinery used and the high rates of lime and fertiliser applied is relatively high compared with the cost of soil analysis, mapping and GPS/GIS aided applications. In this way, accepted critical soil nutrient and pH values are employed to produce application maps. These large applications once in a rotation are used to address spatial variation in long and medium term variables while conventional machinery continue to be used on an annual basis to apply lower rates of base nutrients on a crop specific basis. Thus, the technology is introduced into farm practice a simple level.

Exploiting the technology for short term variables such as nitrogen requires the complete adoption and the full exploitation of the yield mapping technology and the equifertile concept. Nutrient availability is monitored within each equifertile and incorporated into a model predicting nitrogen requirement based on parameters such as expected yield, soil clay and organic matter content. The prediction of yield for a given equifertile requires investigation. Equifertiles are only areas of similar productivity within a season; the yield of an equifertile relative to the mean yield may fluctuate between seasons in response to weather. Weather parameters such as winter rainfall may interact with soil type affecting the relative yield of equifertiles. These effects on relative yield of a given equifertile can only be predicted from field studies conducted in each agro-climatic area.

The use of yield maps in implementing a variable rate application programme is still an area that requires full field investigation; there are few examples where comprehensive soil analysis is combined with yield mapping conducted over more than two years. Thus, it is proposed that the adoption of a local resource management strategy would commence with three-four years automated yield mapping to determine equifertiles combined with a comprehensive survey of soil parameters. These foundation data would be updated by reference to permanent sampling points established within equifertiles. The establishment of the
foundation data set is the principle cost in setting up this system. The parameters relevant to a foundation soil resource information system include terrain (altitude), soil organic matter, soil texture, phosphorus, potassium and micronutrients. The cost of capturing such a data set is determined by the sampling interval in space and the cost of analyses. The variogram resulting from the sampling of experimental fields for the mapping of soil fertility parameters provides us with some guidelines regarding sample intervals. The variogram range (i.e. the distance within which data are spatially dependent and beyond which no increase in variance between samples is expected) from a number of studies is given in Table 1.

It is emphasised that the variogram is partly a function of the scale of the investigation and especially of the manner in which individual samples are taken. However, it is shown that variance ranges always exceed 50 m and are rarely less than 100 m for agronomically important parameters. These investigations point to an optimum sampling interval of 50-100 m for many agronomically important parameters. From a practical point of view, sampling at closer intervals is of little relevance since many machines have a spreading width of 20-24 m. A sampling interval of 50 m gives 4 samples per ha. A sampling interval of 100 m greatly reduces the sampling intensity and may be particularly appropriate where very gradual changes in topography or soil texture are the principal determinants of variation in crop productivity through effects on water supply.

Even with a sampling interval of 100 m, the cost of conventional soil analysis may prohibit the adoption of mapping technology in commercial farm practice. The laboratory studies reported here highlight some possibilities for reducing the cost of soil analysis through the exploitation of correlations between analysed parameters and through the local calibration of these techniques. Results reported here show that, within a given with a site with a common geological and agronomic history, some variables that are difficult or time consuming to measure are highly correlated with more easily assessed parameters. It is proposed that in many situations the treatment of a soil sample with a single acidic extractant for the measurement of available P and K, and soil organic matter content (derived from the extractant colour) combined with the determination of total elemental concentrations using X-ray fluorescence spectroscopy will yield the data required to assess many top-soil factors affecting crop productivity.
Correlations between soil test procedures are frequently referred to in the literature (6). In these studies, a correlation of 0.98 between K extracted by 0.1 M H₂SO₄ and ammonium acetate was observed for the Danish site (data not presented). Such extractants have potential for reducing the cost of soil analysis; available P is determined, the extracted K correlates well with standard extractants, and the colour of the extractant correlates well with the soil organic matter content. Thus, where a large number of samples from a site are analysed, all may be analysed by reduced cost techniques with a small number are subjected to the standard techniques established in the region.

Table 1.

Variogram range values for agronomically important soil properties reported in the literature.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range (m)</th>
<th>Location</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop yield</td>
<td>143</td>
<td>UK</td>
<td>(15)</td>
</tr>
<tr>
<td>Crop yield</td>
<td>70</td>
<td>US</td>
<td>(9)</td>
</tr>
<tr>
<td>Available P</td>
<td>145</td>
<td>US</td>
<td>(9)</td>
</tr>
<tr>
<td>Organic matter</td>
<td>114</td>
<td>US</td>
<td>(9)</td>
</tr>
<tr>
<td>Available K</td>
<td>428</td>
<td>UK</td>
<td>(19)</td>
</tr>
<tr>
<td>Clay content</td>
<td>200</td>
<td>UK</td>
<td>(18)</td>
</tr>
</tbody>
</table>

The success of a soil analysis procedure relies on its calibration with responses in conventional nutrient response trials. The combination of yield and available nutrient mapping provides opportunities for the local calibration of the soil analysis using the boundary line technique (Fig. 2.). In this way, the nutrient values determined at the highest yielding points on the site are treated as the target values in relation to the analytical procedure used. In this way, the calibration problems normally associated with the introduction of a new or unconventional analytical technique are circumvented and critical values relating directly to the site are determined.
Literature cited

Fig. 1. Contour map of relative crop yield.

Fig. 2. The boundary line analysis of soil pH and crop yield.
Fig. 3. Relation between total carbon and extract colour (relative absorption at 540 nm) for one field.

Fig. 4. Relation between total carbon and extract colour (relative absorbance at 540 nm) for two soil types (brown earth and podsol).
Fig. 5. Relation between rubidium and clay content in a brown earth soil (Vindum, Denmark).

Fig. 6. Factor diagram (varimax rotated) of the principal component analysis of soil fertility parameters in the topsoil of the Birkenmoor brown earth soil.
Fig. 7. Spatial distribution of equifertiles deducted by factor analysis and pea yield for a predominately brown earth soil (Vindum, Denmark).

Fig. 8. Relationship between equifertile values deducted by factor analysis and observed pea yield.
Data Needs for Sustainable Land Use Scenarios for Humid Tropical Costa Rica


Abstract. Many driving forces influence land use. Externally, land use can be affected by incentives and regulations. To determine the effect of these measures, scenarios can be defined and analyzed. For the analysis of scenarios data are vital. The amount of data which is necessary, depends on the complexity of the problem and the level of required detail. Three different scenarios for the northern part of the Atlantic Zone of Costa Rica are evaluated and their data needs studied: (i) the possible contamination of ground- and surface water with the commonly used nematicide Ethoprop, (ii) the possibilities for the cultivation of maize on the basis of a simple expert system and a quantitative model to estimate nutrient limited productivity of potential areas, and (iii) regional sustainability parameters of actual land use. The different cases vary in their complexity and the level of detail required for the results. Data requirements change correspondingly. Studies with a low level of detail are useful to precede studies where the level of detail is high. General inventories may already indicate which type of data collection is useful. Complex studies where the level of detail is high could benefit from a change of scale, associated with a more generalized representation of data.

Introduction. Land use is usually determined by a long history of development in a region. Driving forces influencing land use may be internal, like the available natural resources, or external, like prices on the world market. Governmental and non-governmental organisations are often interested to direct the development of land-use by incentives and regulations. They can vary widely but most of them have the same goal, to influence farmers’ decisions. As planners are interested in the effects of measures on regional land use, they may define scenarios to study the possible effects of incentives and regulations. Although several techniques such as crop growth simulation models, geographical information systems (GIS) and linear programming models are available to define scenarios, it is still very often the amount and quality of available data that limits the value of prognoses of these scenarios. For the northeastern part of the Atlantic Zone of Costa Rica (Figure 1) the USTED (Uso Sostenible de Tierras En el Desarrollo) system has been developed. USTED, meant as a tool for the analysis and planning of sustainable land use, integrates the techniques mentioned above, and can be used to evaluate different land use scenarios in terms of sustainability, net income and production. The database of the USTED system is based on a GIS called SIESTA (Sistema de Información y Evaluación de Suelos y Tierras en el Atlántico), which originally only contained data on geology, geomorphology and soils but currently includes data on land use and demography as well. Decisions concerning agricultural land use are taken at farm level. Although the actual location of the farms is not represented in the SIESTA system, land use zones and soil and terrain information provide necessary data on regional level. The land use zones are defined as areas which exhibit a similar land use pattern. Land use patterns may comprise one specific land use or an association of several types of land use. General trends and effects of incentives on scenario’s can be demonstrated to occur leaving detailed feasibility studies to be carried out on farm level.
To deal with sustainability three criteria will be considered: (i) depletion of the soil nutrient stock; (ii) the risk for ground and surface water contamination with an often used nematicide and (iii) the negative effects of compaction on soil physical parameters.

Figure 1 The location of the study area.

Data needs for land use scenarios. The amount and type of data needed for the evaluation of land use scenarios depends on the complexity of the problem and the level of detail of the required results as shown in Figure 2. In studies where the complexity of the problem as well as the required level of detail of results are low, available soil survey data may fulfil the data-need for the analysis. With increasing complexity and/or level of detail, additional data are necessary. These additional data may be based on e.g. a simple batch experiment. Complex problems and/or problems where a high level of detail is required need quantitative simulation modelling, including field trials, such as fertilizer experiments for calibration purposes or as independent data sets. At a certain level of detail,
problems become too complex or the level of required detail is so high that one has to change to a higher aggregation level or change the level of detail to answer the problem appropriately. The complexity of the problem is often inherent to the scenario. The required level of detail is often determined by the user, who defines the problem.

Figure 2  The amount of data required for a study on the basis of the complexity of the problem and the level of required detail.

The study area. The northeastern part of Costa Rica comprises approximately 500,000 ha of humid tropical lowland with an average annual rainfall of 4000-6000 mm and an average annual temperature of 26°C. The area contains a large variety of soils, which can be described as imperfect to well drained loamy Andisols and Inceptisols developed in Holocene alluvial deposits and clayey, acid, Inceptisols developed in Pleistocene laharic deposits. Colonization of the Atlantic Zone started at the end of the 19th century in the south of the area and continues until now. In 1984 almost 80% of the zone was deforested and land use was dominated by extensive cattle breeding and banana plantations, besides smaller areas under annual and perennial crops (Figure 3). Almost one fifth of the zone is still covered by the natural vegetation and is protected as national park or forest reserve. Different groups are influencing land use in the area. The national government tries to stimulate diversification, intensification and commercialisation of the agricultural sector as well as the conservation of nature. Several conservation organisations are active in the region trying to protect natural ecosystems and to promote sustainable agriculture around the reserves. Coinciding with the commercialisation, several private companies and organisations are interested in the development of the agricultural sector.
Three case studies and their data needs. Three different scenarios are elaborated: (i) the risk of ground and surface water pollution with Ethoprop; (ii) the possibilities for sustainable maize cultivation to be evaluated by a crop growth simulation model and a nutrient depletion model, and (iii) the sustainability of actual agricultural land use in the area.

The three scenario's originated from three user groups mentioned earlier. The conservationist is worried about the contaminations of ground- and surface-waters with Ethoprop, causing the death of a large number of fish. The policy maker might be working on import and export regulations for maize, and is interested in the regional production possibilities, and local government officials are
interested in the sustainability of the agricultural sector. The different scenarios all need soil data to express different land qualities but differ in quantity and level of detail, which is the object of this study.

Case 1: Risk of groundwater contamination with Ethoprop. The behaviour of biocides in the soil is highly complex and depends on characteristics of the biocides, as well as on climate and a large number of soil properties. A procedure for a relatively easy and fast appraisal of groundwater contamination with a biocide is based on soil survey data and one additional soil property, the biocide fixation to the soil (Figure 4). It indicates the potential risk for contamination of ground- and surface water after a biocide application. For hazardous areas one might be interested in detailed simulation modelling in order to obtain an indication, whether and to what extent biocide leaching is likely to occur or not.

Figure 4 A procedure for a fast and rapid appraisal of ground- and surface water contamination
One of the commonly used nematicides in the Atlantic Zone of Costa Rica is Ethoprop. Ethoprop is used in banana, palm heart and ornamental plantations which together occupied in 1984 approximately 5% of the total surface of the area increasing to almost 10% in 1992. Following the Pesticide Environmental Fate One Liner Database (Environmental Fate & Effects Division of the US Environmental Protection Agency), Ethoprop has a potential to contaminate ground waters in areas with sandy soils and a high water table. It is highly toxic to birds, marine crustaceans and fish. On the basis of the soil information system and a few additional measurements the risk of contamination of ground- and surface water with Ethoprop was determined for the Atlantic Zone of Costa Rica.

The 72 soil types occurring in the 1:150.000 soil map are described by 19 major soil horizons or building blocks. These building blocks represent different degrees of aggregation of existing soil horizons on the basis of a functional analysis: horizons that "behave" identical are lumped into one "functional" horizon. Soil horizons that occur below the ground water table and C-horizons that do not allow water transport are excluded from the measurements leaving 12 soil horizons to be sampled. 10 ml of a 226 ppm Ethoprop solution was added to 30 g of a 1:2 soil-water suspension. The soil samples were not dried between sampling and analysis to avoid irreversible drying effects. The soil moisture content was determined on separate samples. The Ethoprop concentration in the solution was measured after 30 minutes shaking. The Ethoprop fixation varied between 2% for the sand C-horizon and 48% for a well developed anitic epipedon. On the basis of these fixation figures for the building blocks, the stoniness of the soils and the depth of the groundwater table, the total amount of Ethoprop that can be fixed in the soil above the ground water table (E_r) is calculated for the dominant soil type in each mapping unit.

If E_r exceeds twenty times a normal Ethoprop application (E_app) of 10 kg Ethoprop per ha, the soil is not considered to be prone to Ethoprop leaching. The factor twenty is chosen arbitrarily on the basis of two considerations. When Ethoprop is applied to the main crops in the Atlantic Zone, the application normally takes place close to banana and palm heart plants and is thus not equally spread over the soil. Secondly it is known that water transport in most soils does not take place uniformly but along preferential patterns of water flow. This indicates that fixation of Ethoprop may occur around these preferential patterns of water flow and not in the complete soil matrix. For this exploratory study the factor is set at twenty to be sure that only soils with no Ethoprop leaching are selected. For soils where E_app ≥ E_r, Ethoprop leaching is almost certain to occur and the soils are classified to be extremely susceptible. In soils where E_r > E_app > 20 E_r, the present study considers the risk of Ethoprop leaching to be intermediate.

Additionally, it can be concluded for strongly sloping areas that surface run off is likely to occur, leading to a contamination of surface waters when Ethoprop is applied on the surface.

Figure 5 indicates the relative hazard of Ethoprop leaching in the Atlantic Zone of Costa Rica as based on the above procedure.

This case study is in position 1 in Figure 6. The contamination problem is a complex one, especially in a humid tropical environment where few data on biocide behaviour are available. In the present case study only a general overview of problem areas is required. The amount of necessary data is limited to data available from existing soil survey and some additional data i.e. Ethoprop fixation estimates for the major soil horizons or building blocks.

If the level of required detail is higher and, for example, accurate assessments of critical Ethoprop applications are required, quantitative simulation and further measurements are inevitable. The problem then moves to position 2 in Figure 6, where field trials are necessary to calibrate quantitative simulation on Ethoprop behaviour in the soil.

The integration of qualitative and quantitative procedures are increasingly propagated. If in the case
of Ethoprop leaching a high level of detail is required, the problem may be similarly structured. First, on the basis of existing data and few additional measurements an inventory of problem areas is made. Secondly, in problem areas where the qualitative procedure does not yield a clear answer on the extent of Ethoprop leaching, additional data collection and quantitative modelling can take place.

Figure 5  Risk of ground- and surface water contamination with Ethoprop in the Atlantic Zone of Costa Rica, based on soil and terrain data.

Case 2:  Possibilities for maize cultivation. A rapid assessment of soil suitability can be obtained by a qualitative land evaluation. The accuracy of such a procedure is in most cases unsatisfactory to advise a farmer, but may be sufficient to decide whether and where detailed studies are worthwhile. This first step can be taken on the basis of a soil survey. With additional data, like specific fertility analysis, a more quantitative approach can be followed, which may include assessment of production on the basis of expert knowledge. Reliable quantitative assessments of
production and its sustainability can only be reached after field experiments and model calibration. First a qualitative selection of maize-growing areas was made on the basis of soil fertility, drainage and land use (i.e. national parks and commercial banana plantations were excluded). To assess possibilities for maize cultivation in the potential areas which remain, QUEFTS' ('Quantitative Evaluation of the Fertility of Tropical Soils') was used. QUEFTS can estimate the nutrient limited production of maize for different cropping systems. Twenty one relatively fertile, well drained soil types are found in the potential areas. These soils comprise five different major A-horizons with comparable soil fertility. From the soil database the input parameters for QUEFTS (pH-H₂O, C-Kurnies, Exchangeable K and P-Olsen) for the major A-horizons were determined. Production possibilities for three levels of fertilization were analyzed. Figure 7 illustrates the results for non-fertilized maize. However, QUEFTS evaluates the soils on their present nutritional status and does not include an analysis of the sustainability of the production. Models like NUTDEP enable an additional evaluation of the nutrient balance of land use systems. Table 1 shows the estimated average nutrient balance for two possible levels of fertilization. Not only does the fertilizer reduce to a certain extent the loss of nutrients, it also increases the production. However, for an equilibrium of the nutrient balance an integrated management of the soil nutrient stock is necessary.

1 Ethoprop leaching estimate
2 Ethoprop leaching simulation
3 Soil suitability maize
4 Estimation nutrient limited maize production
5 Sustainability actual land use

Figure 6  The data requirement for five case studies.
Like in the first case the problem can be analyzed at two levels of detail, a general inventory and a quantitative assessment of productivity, including a possible evaluation of the sustainability of that production on the basis of the nutrient balance. The data requirement for both levels of detail can be seen in Figure 4. The qualitative study (position 3) is based on the soil survey with accompanying data and the quantitative study (position 4) on the basis of field trials, which were used for the calibration of QUEFTS. The complexity of the problem as treated by QUEFTS is relatively low.

Figure 7  The productivity of non-fertilized maize in the Atlantic Zone of Costa Rica (average per mapping unit)
Table 1  The average nutrient balance for non-fertilized and fertilized maize production in the Atlantic Zone of Costa Rica (in kg/ha.yr).

<table>
<thead>
<tr>
<th>Nutrient inputs:</th>
<th>Non-fertilized maize</th>
<th>Fertilized maize</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>fertilizer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>organic material</td>
<td>9</td>
<td>1.2</td>
</tr>
<tr>
<td>deposition</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>N-fixation</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nutrient exports:</th>
<th>Non-fertilized maize</th>
<th>Fertilized maize</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>product</td>
<td>36</td>
<td>7.2</td>
</tr>
<tr>
<td>crop residues</td>
<td>11</td>
<td>1.4</td>
</tr>
<tr>
<td>leaching</td>
<td>9</td>
<td>1.0</td>
</tr>
<tr>
<td>gaseous losses</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>erosion</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>nutrient balance</td>
<td>-51</td>
<td>-9.2</td>
</tr>
</tbody>
</table>

Case 3  Some sustainability considerations of actual land use. The sustainability of the agricultural sector of the Atlantic Zone may be assessed on the basis of three factors which can be evaluated in sequence to obtain a general impression of sustainability problems at regional level: (i) nutrient depletion, (ii) degradation of soil physical characteristics due to compaction and, finally, (iii) contamination of groundwater and surface waters with biocides. The basis for the analysis is the inventory of land use in land use zones. Studying sustainability on a regional level will be restricted to a general evaluation of the different land use zones in terms of Ethoprop leaching, the nutrient balance and a degradation of soil physical properties. The six generalized land use zones for the study area (Figure 3) will be discussed in terms of their sustainability.

- Natural vegetation is normally considered to be the most sustainable land cover. Nevertheless, it may be influenced by land use around it. A clear example would be the contamination of ground- and surface water which drain in the direction of the ecosystem. The sustainability of a natural vegetation may then be threatened.

- A colonization area is defined as an area where both natural vegetation and agricultural land are found and where the latter is gaining in importance. Agricultural land use in these areas is normally extensive. However, some nutrient depletion, biocide leaching and compaction may occur.

- Although in general grazing pressure in pastures of the Atlantic Zone is low, compaction, resulting in a decrease of the infiltration capacity, is found in almost all pastures (1989).

- Mixed agricultural use is found in the settlement for which the nutrient balance was calculated. The net annual loss per ha was estimated at 22 kg N, 5 kg P and 13 kg K. It is likely that other areas with comparable land use have similar depletion rates. Additionally, compaction will occur.

640
in the areas under pasture.
- **Annual crops** had, in general, a higher loss of nutrients than pastures. Although nutrient inputs and the technology level is higher in this land use zone, it is likely that mining of the soil nutrient stock takes place.
- **Plantations** in the area have very high levels of fertilization, compensating completely for nutrient losses. However, they also use large quantities of biocides, associated with a high risk of contamination.

Figure 8 illustrates the results. The complexity of this problem is moderately high due to the wide variety of aspects which are included. To come to relatively accurate assessments for nutrient depletion, compaction and pesticide leaching field trials and case studies will be necessary (Figure 6).

![Map of Atlantic Zone](image)

**Figure 8** Three sustainability parameters for 1984 land use in the Atlantic Zone of Costa Rica.
Discussion and conclusions. Data needs for land use scenarios vary as a consequence of the complexity of the problem and the level of detail required for the results. The latter mainly depends on the objectives of the users as shown by the different examples. General inventory studies for government planning may require a relatively low level of detail. On the other hand, agricultural extensionists require a high level of detail to allow accurate advise to farmers. Tools like GIS may facilitate general inventory studies so that they become more valuable to studies where a high level of detail is required. Their main value is that they may indicate the best strategy for additional data collection or field trials. The level of detail requested by users influences the scale on which the study takes place. A combination of a high level of detail and a complex problem may require a larger scale and, on the contrary, a very low level of detail with a relatively simple problem can be evaluated on a smaller scale with less data requirements. Next to the user, it is often the available data that determines the scale of studies. In the case of the Atlantic Zone of Costa Rica most data are available at a scale of 1:100.000 and 1:150.000, leading almost automatically to the generation of land use scenarios at the same scales.

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Bibliography


Modeling Variations of Land Qualities at Regional and Global Scales Using Geographic Information Systems

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1. Introduction. Global change researchers and agricultural policy makers need soil data that are understandable at global scales, yet rigorously linked to more detailed soil maps and data bases of soil properties. Theories of ecological hierarchy provide a framework for understanding differences in soil behavior at various scales in space and time. The hierarchical view provides a perspective for understanding the representations of multi-scale soil data in geographic information systems. In particular, continental and global soil maps can be generalized from detailed and regional maps using generalization rules that preserve information on the diversity of the original data. A data model that views soil units as inherently heterogeneous, and allows the distributions of soil properties to be aggregated toward the global scale is illustrated using the State Soil Geographic (STATSGO) data base developed by the United States Department of Agriculture, Soil Conservation Service (SCS). The STATSGO data base incorporates some limited examples of spatially and temporally integrated variables. The variability of the STATSGO map units is illustrated with sets of maps that create spatial histograms. Recommendations for improved data include recording primary measurements rather than ratios or other derived measures, using distributions of values rather than averages or dominant characteristics, and including in the data base codes for measurement units, methods, missing data, and source of observations. Recommendations for techniques to improve the analysis of data include applying a mathematical symbology to represent complex aggregation sequences over space and time, developing quantitative measures of the information loss upon simplification, and providing explicit mechanisms for substituting modeled surrogates for hard-to-measure data items.

2. Users of regional and global soil data. Traditionally, soil surveys have been conducted to improve management of agricultural lands. The information is used by local farmers and agribusiness as input to microeconomic decisions. At regional and global scales, information on the soil resource is important for making macroeconomic decisions and designing government programs for agriculture. In the last few decades, detailed soil surveys have taken on additional purposes, such as protection of the soil resource and site evaluation for urban development. Similar applications of regional and global soil information include identifying unique ecological resources, and understanding the global scope of soil degradation (United Nations Environment Program, 1992).

Recent developments in modelling global systems include interactions between the atmosphere, oceans, and land surface processes. Interdisciplinary scientific studies link processes in the soil to processes in the atmosphere. In biogeochemical studies, the linkages may be through trace gases such as carbon dioxide, methane, and nitrous oxides (Bouman, 1990). Studies of global warming using general circulation models of the atmosphere use soil information to account for the fluxes

1. Hughes STX Corporation work performed under U.S. Geological Survey contract 1434-92-C-40004
of water and energy from the soil (Dickenson and others, 1986).

A global soil data base for the FAO Soil Map of the World is available (FAO, 1991), but the data are not explicitly linked to more detailed soil maps, field data, remotely sensed data, and topographic models. A set of procedures for developing a more detailed global soil and terrain (SOTER) data set has been developed with international cooperation (ISR1C, 1993).

An efficient approach to improving global soil information should include making use of existing data sets, incorporating them in a flexible structure that can accommodate information collected in various ways and at various scales, and formatting the data in a variety of ways to meet the needs of specialized users. Ecological hierarchy theory provides a starting point for the conceptual framework for such a system, and new developments in sample design and statistics will help soil mapping agencies and researchers collect information to fit within the framework.

3. A conceptual framework for a hierarchy of scale. This paper reviews some conceptual ideas that are important in representing the variability of soils in space and time. Ideas of ecological hierarchy can be applied to issues ranging from the interdependence of the global economy and ecological processes to providing organizing principles for the development of soil data sets.

3.1 Scaling issues for society and the global environment. Di Castri and Hadley (1988) explore some aspects of scaling as having important repercussions on ecology's relationship with other scientific disciplines and with societal concerns. They present diagrams showing some of the physical and societal dimensions of scale in environmental processes and phenomena, they present examples of how switching scales reveal processes, patterns, and constraints, and they examine the importance of scale in scientific cooperation. Citing Clark (1986), they postulate that the current "wave of human development can be thought of as an era of chronic, large-scale, and extremely complex syndromes of interdependence between the global economy and the world environment." Citing Allen and Starr (1982) and others, they note "an increasing interest in what can be called a hierarchical view of life--the notion that the natural world can be profitably viewed as a multi-layered system, hierarchical in space and time, and that one needs to look up a step in the hierarchy (e.g. in terms of space and time) to understand the constraints under which a phenomenon occurs and descend a step to determine causality."

3.2 Scaling issues for ecology. Di Castri and Hadley (1988) cite Urban and others (1987) to give examples of phenomena that need to be taken into account for understanding the mosaic of heterogeneous land forms, vegetation types and land uses that make up landscape patterns. These factors also influence soil landscape patterns.

Four main groups of agents of pattern formation can be recognized, and each of these can be considered across a gamut of spatial and temporal scales. Thus, disturbances that affect terrestrial landscapes vary in spatial extent, frequency and intensity, and range from the localized effects of an individual death (e.g. through treefall) to the large-scale effects of extensive fires, drought, epidemic diseases, floods, etc. Biotic or regenerative processes also vary in scale from the development of an individual to the reorganization of species assemblages. Environmental constraints range from microclimatic and fine-scale soil conditions that control seed germination and seedling establishment, up to sub-continental climatic regimes that determine broad biogeographical patterns and the delimitation of biomes.

Di Castri and Hadley (1988) consider the importance of episodic extreme events (such as fire, flood, and drought) and large scale phenomena (such as El Niño). They also consider the role of
cumulative impacts (such as changes in the composition of radiatively active gases in the atmosphere) and the coupling of 'fast-slow' processes.

The climate system has a number of 'memory reservoirs', each with its characteristic time and space scales. Thus the time scale for soil moisture memory runs from a few weeks to about a year. The snow and sea ice memory has a time scale of a few years, while the time scale may be much longer for ocean memory, referred to by Dickinson (1986) as the 'fly-wheel' for storing thermal energy in the climate system.

Allen and Starr (1982) describe a hierarchical approach as useful for human understanding of complex ecological systems, rather than as an intrinsic property of the systems:

We see most important complexity as related to the interaction of different levels of organization; in order to give complexity proper account in our scientific models, those models are almost required to be hierarchical. We suggest that there is something about either our facility for observation or that which generates our observations which gives patterns that generally remain opaque unless we model using hierarchies. By hierarchy is understood a system of behavioral interconnections wherein the higher levels constrain and control the lower levels to various degrees depending on the time constants of the behavior. ... Since bulkier structures in biology generally behave more slowly, not only do slow entities constrain fast, but also large entities usually constrain small.

Usually an increase in the length of time over which individual observations are made will increase heterogeneity, as will an increase in the area or time span of the universe from which data are collected. Nevertheless, an increase in time and space sometimes only means more of the same, with only small increases in heterogeneity accompanying increased size.

We feel that the major problems and imponderables that today face community and ecosystem studies are to be answered by treating these entities as complex systems. More and better differential equations with more carefully specified initial conditions will not substantially improve our understanding unless we take complexity at face value.

3.3 Scaling issues for soil. Burrough (1993) notes that there are two related strands in the studies of soil variability:

The first is a pragmatic, a post hoc understanding of the way soil varies so that data from what are effectively point observations can be extrapolated to larger areas of land. The second is scientific inquisitiveness in the way in which soil forming processes can lead to the observed diversity of natural and anthropogenic soil patterns. ... The degree of spatial variation in a soil depends on the kind of soil forming processes and their balance in space and time [citations omitted]. Considerable short range differences in parent material, drainage and biological (including human) activity can cause large differences in soil cover over short distances.

In evaluating a multi-scale linear formulation for soil variation, Burrough (1993) concludes:

In practice, ... soil formation is rarely a truly linear process being more episodic than continuous, and in the short term, at least, may undergo considerable changes of direction at different rates and with different degrees of feedback and reinforcement.

In principle, if the processes controlling the spatial and temporal properties of the soil-forming factors can be modelled physically, then one should be able to predict the patterns of soil variation that result.

As we develop hierarchical representations of the soil variability for use in models, we will need to evaluate the quality of the source data. If there is good information on the soil forming factors, then it may be possible to use this information to increase the precision or lower the cost of predictions of soil properties. Conversely, we may have better information about the result of the soil forming processes than about the processes themselves. We can observe a soil as it presently exists, and often must try to infer from these observations something about the detailed variations...
Table 1. Scale and modeling approaches relevant to description of the effects of water and chemical fluxes upon pedogenesis.

<table>
<thead>
<tr>
<th>Scale</th>
<th>System</th>
<th>Examples of appropriate modeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>i+6</td>
<td>World</td>
<td>Conceptual</td>
</tr>
<tr>
<td>i+5</td>
<td>Continental</td>
<td>Conceptual</td>
</tr>
<tr>
<td>i+4</td>
<td>Counties, States, Provinces</td>
<td>Statistical models</td>
</tr>
<tr>
<td>i+3</td>
<td>Soil region (interacting watersheds)</td>
<td>Hydrological models</td>
</tr>
<tr>
<td></td>
<td>Catena or watershed</td>
<td>Catchment models</td>
</tr>
<tr>
<td>i+2</td>
<td>Polypedon (field)</td>
<td>Distributed or statistical hydrologic models</td>
</tr>
<tr>
<td>i+1</td>
<td>Pedon</td>
<td>Two or three dimensional, lateral flows</td>
</tr>
<tr>
<td>i-1</td>
<td>Profile horizon</td>
<td>Mass flow modeling</td>
</tr>
<tr>
<td>i-2</td>
<td>Secondary structures (peds, aggregates)</td>
<td>Pattern recognition</td>
</tr>
<tr>
<td>i-3</td>
<td>Basic structures (grain interactions)</td>
<td>Bypass flow, preferential flow</td>
</tr>
<tr>
<td>i-4</td>
<td>Molecular (pore, particle)</td>
<td>Electrochemical modeling</td>
</tr>
</tbody>
</table>

Source: Simplified from Wagenet, Bouma, and Hutson (1993)

in topography, climate, biota, and parent material that have interacted in complex ways over centuries or millennia to form the observed soil. To develop data bases for scientific and land management purposes, it is appropriate to follow a pragmatic approach and describe the soils as they are observable. The representation of the variations of soil properties will likely be more efficient and understandable if it is guided by an understanding of the soil forming processes.

Wagenet and others (in press) apply a hierarchical approach to organize the modeling and measurement methods relevant to describing the effects of water and chemical fluxes upon soil formation (pedogenesis). The predominant feature for modeling pedogenesis is the soil pedon (typically 1-10 m$^3$ of soil), and Wagenet and others (in press) assign this to the i-level in a spatial hierarchy. They describe 11 levels for the hierarchy from i-4 (molecular) to i+6 (global). Selected aspects of their schema are shown in table 1. The approach considers the hydrologic aspects of soil at many scales from the molecular to the global. Some of the modeling approaches are applicable to any scale. For example, the principles of the conservation of mass and energy are among the most fundamental scientific principles because they apply at all scales of observation (Morrison, 1992). We could thus include mass balance models as being appropriate at all levels. Some differences are appropriate based on the type of calibration or verification that
is used. For example, hydrologic models are listed at level i+3 (interacting watersheds), presumably because there is a capability to measure a set of calibrating variables for the area being modeled, such as precipitation inputs and the streamflow through time at a gaging station.

Wagenet and others (in press) use three criteria to differentiate models of water and chemical fluxes that influence pedogenesis (soil formation). First, they align models on a continuum according to the degree of computation, with conceptual models (qualitative, mental, spoken, written, descriptive) toward one end and quantitative (deterministic, stochastic, computer codes) at the other end. Many of the models needed to evaluate the effect of water as a driving force for pedogenesis are intermediate between the end points of the continuum. Second, they define a continuum based on the complexity of model structure. At one end of the continuum are functional models with simple functional form, often from empirical or statistical relationships such as a regression equation. At the other end of the second continuum are complex mechanistic model forms that explicitly model the dynamics of a system and include rate processes, such as a rate of water flow or the kinetics of mineral dissolution. Third, they define a continuum based on an organizational hierarchy on scales of space and time. At the micro end of the scale, molecular processes are modeled, and at the macro end global processes are modeled. The micro-scale models tend to be more quantitative and mechanistic, and the macro scale models tend to be conceptual and functional. A wide variety of modeling approaches are used at the intermediate scales.

Wagenet and others (in press) consider a variety of modeling strategies from the microscopic (i-4) to the global (i+6). At the microscopic level (i-4), the particle to particle interactions are dominant. Very local variations in chemical potential energy provide the main driving force for the dynamics of water and chemicals. At the i-3 level, the flow in soil pores is modeled, with surface tension dominating the forces. The flow in macropores (between peds) is modeled at the i-2 level and gravitational potential energy is the dominant force. Flow in the soil matrix may be modeled as a separate but hydraulically linked domain. The antecedent water content and subsequent boundary conditions influence the model behavior. At the level of the soil horizon (i-1), a representative elementary volume may be defined over which aggregated values of hydraulic conductivity, water content, and matric potential may be calculated that include the movement of water in both the macropores and the soil matrix. Spatially and temporally variable boundary conditions involve vegetation, climate, and groundwater. At the pedon level (i), comprehensive models of water and chemical fluxes may be developed that include both water and chemical transport and solution chemistry. The boundary conditions include rainfall, temperature, and wetting/drying cycles. At the field or polypedon level (i+1) and the catena or watershed level (i+2), the models of water and chemical flow may include lateral flow, leaching, runoff, and erosion. As the spatial scope of the models increase, the heterogeneity of the volume or area being modeled increases, and the models tend to become less deterministic and more statistical. The water retentivity and hydraulic conductivity may be estimated from particle size distribution data, and water fluxes are driven by daily potential evapotranspiration and infiltration that are estimated from rainfall and irrigation rate values. Chemical fluxes can be linked to water fluxes using diffusion and convection equations. Interpolation may be needed to extend point measurements to areas using spatial statistics (such as geostatistics) and temporal statistics (such as time series). At the level of interacting watersheds (i+3), process level physical and chemical relationships may become embedded in lumped parameters for models that represent features at the scale of square kilometers. Landscape ecologists have described soil forming processes at this scale in terms of soil creep, movement of sand dunes, and fluvial transport and deposition. At the state (i+4), continental (i+5), and global (i+6) levels, data bases of soil, climate, geohydrology, and vegetation can be manipulated using geographic information systems and spatial statistics to infer, but not quantify, the effects of water and chemical fluxes upon pedogenesis. Aerial
photography and remote sensing are used to map topographic features, including fluvial depositions, and human alterations of the landscape, such as erosion or desertification.

The capability to quantify a process at a given scale depends on being able to make some type of calibrating measurement at that scale. For example, in watershed modeling the output flow pattern of a stream as a function of time (the hydrograph) provides a calibrating measurement for models of water flow through soil at the landscape scale. Although pedogenesis may not be directly observable at the global scale, it may be possible to appropriately summarize what is learned at more detailed scales.

At the continental and global scales, there may be relationships, such as the flux of water from the soil to the atmosphere via evapotranspiration, that cannot be directly observed, but that if carefully modeled, will improve the calibration of general circulation models of the atmosphere. Soil data bases can provide information on the water holding capacity of soils, climate data can be interpolated from stations to continuous data fields, and vegetation dynamics can be observed using remote sensing. These measured and modeled inputs can provide a basis for calibration experiments with GCMs, in which various land surface parameterizations are tested with historical climate data.

An adaptation of the framework provided by Wagenet and others (in press) is given in Table 2. This adaptation uses map scale and approximate linear distance rather than an arbitrary i-level coding. The STATSGO data base has been developed at 1:250,000-scale, and the FAO Soil Map of the World was published at 1:5,000,000-scale. A soil-related feature that may be measured with a base (linear, areal, or volumetric) at that scale is indicated. Once the linear dimension exceeds the usual depth to which soil is described (about 2 meters), the volume of soil is proportional to the square of the linear distance rather than the cube of the linear distance.

Wagenet and others (in press) warn that “in many cases models developed for use at smaller scales are used without regard for their limitations.” Several issues may contribute to this concern. One is that as the scope is broadened, additional landscape components are included for which the model is not appropriate. Thus a model for evapotranspiration from soils is not likely to be appropriate for evaporation from lakes, yet lakes may form a significant portion of the landscape. A second concern is that the wrong type of quantity is being aggregated. It is legitimate to aggregate quantities for which the conservation laws hold (such as conservation of mass). It is not legitimate to aggregate rate variables (such as flux rates or coefficients). If a research strategy accounts for both of these concerns, then it may be possible to perform aggregations over a large range of scales. In the case of evapotranspiration from a vegetation-soil surface, the primary processes occur in the plant leaf (on the order of several centimeters), and in the soil profile (on the order of several meters). Attempts may be made to aggregate the results of these processes to the scale of GCM grid cells on the order of ten thousand square kilometers. Aggregations of the quantity of water evaporated that are modeled at the scale of a pedon will probably be appropriate until there are significant magnitudes of spatial interaction or feedback. A landscape model may be needed to account for spatial interactions, such as when a wetland is recharged by groundwater from precipitation upslope, because a pedon-scale model does not account for lateral flow of water. A mesoscale climate model may be needed to account for feedbacks in the evaporation-precipitation cycle if a GCM grid cell is large enough that the transpired water could be re-precipitated in the same cell.

3.4 Implications of ecological hierarchy theory for soil mapping. Burrough (1993) provides a review of conceptual and mathematical approaches to representing spatial variability of soils. He notes that modern sampling and analysis techniques may be used to better understand how soil properties vary, improve maps, optimize sampling programs, improve the results of modelling,
Table 2. Scale relationships related to map scale and linear distance.

<table>
<thead>
<tr>
<th>Map scale</th>
<th>Linear distance for 1 mm on the map</th>
<th>Area for 1 m² of map surface</th>
<th>Example of mappable feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:200M</td>
<td>200 km</td>
<td>not relevant**</td>
<td>World on page-sized map</td>
</tr>
<tr>
<td>1:25M</td>
<td>25 km</td>
<td>625,000,000,000 km²</td>
<td>World on wall-sized map</td>
</tr>
<tr>
<td>1:10M</td>
<td>10 km</td>
<td>100,000,000 km²</td>
<td>Continent on wall-sized map</td>
</tr>
<tr>
<td>1:5M</td>
<td>5 km</td>
<td>25,000,000 km²</td>
<td>Continent on wall-sized map</td>
</tr>
<tr>
<td>1:1M</td>
<td>1 km</td>
<td>1,000,000 km²</td>
<td>Large state on wall-sized map</td>
</tr>
<tr>
<td>1:250K</td>
<td>250 m</td>
<td>62,500 km²</td>
<td>Major river basin on several sheets</td>
</tr>
<tr>
<td>1:100K</td>
<td>100 m</td>
<td>10,000 km²</td>
<td>Subbasin of a major river</td>
</tr>
<tr>
<td>1:25K</td>
<td>25 m</td>
<td>625 km²</td>
<td>Catena or watershed; County soil survey</td>
</tr>
<tr>
<td>1:10K</td>
<td>10 m</td>
<td>100 km²</td>
<td>Detailed agricultural soil survey</td>
</tr>
<tr>
<td>1:2,500</td>
<td>2.5 m</td>
<td>6 km²</td>
<td>Research station soil survey</td>
</tr>
<tr>
<td>1:1,000</td>
<td>1 m</td>
<td>1,000,000 m² = 1 km²</td>
<td>A polypedon</td>
</tr>
<tr>
<td>1:250</td>
<td>25 cm</td>
<td>62,500 m²</td>
<td>Influence of a large tree</td>
</tr>
<tr>
<td>1:100</td>
<td>10 cm 1 hectare = 10,000 m²</td>
<td></td>
<td>Observation of a large pedon</td>
</tr>
<tr>
<td>1:25</td>
<td>2.5 cm</td>
<td>625 m²</td>
<td>Direct observation of a soil pedon</td>
</tr>
<tr>
<td>1:10</td>
<td>1 cm</td>
<td>100 m²</td>
<td>Profile horizon</td>
</tr>
<tr>
<td>1:2.5</td>
<td>2.5 mm</td>
<td>6 m²</td>
<td>Secondary structures (peds, aggregates)</td>
</tr>
<tr>
<td>1:1</td>
<td>1 mm 1,000,000 mm² = 1 m²</td>
<td></td>
<td>Basic structures (grain interactions)</td>
</tr>
<tr>
<td>2.5:1</td>
<td>0.4 mm</td>
<td>62,500 mm²</td>
<td>Clay particles</td>
</tr>
<tr>
<td>10:1</td>
<td>0.1 mm</td>
<td>10,000 mm²</td>
<td></td>
</tr>
<tr>
<td>100:1</td>
<td>0.01 mm</td>
<td>100 mm²</td>
<td></td>
</tr>
<tr>
<td>1,000:1</td>
<td>0.001 mm</td>
<td>1 mm²</td>
<td></td>
</tr>
</tbody>
</table>

* M = 1,000,000; K = 1,000.

** The surface area of the earth is on the order of 500,000,000 km²; the land area of the earth is on the order of 150,000,000 km².

and reduce uncertainties on cost estimates so that people can manage the environment in a more sensitive way.

Both conventional choropleth and geostatistical methods tend to treat soil variability in terms of a limited set of patterns at the scale of the landscape and the variation within it, although geostatistics permits the use of nested variograms to describe several linked spatial scales of variation. A priori there is no reason why any particular scale should dominate, and when attempting to link soil forming processes to the resulting spatial patterns the next step is to look for general procedures for describing soil variation over the complete range of scales from the sub-microscopic to the continental.
Our knowledge of the geological, geomorphological, soil-forming and land-use processes in a landscape gives us good reason to think that certain processes do operate only at certain discrete scales (e.g. glaciation, the formation of volcanoes) while others (e.g. wind and water erosion) operate at a wide range of scales. Because many landscapes are the result of many processes operating both simultaneously and in historical sequence, it is no wonder that the patterns of variation on the earth's surface are so complex.

The causes behind the different scales lie in the chemical, biological, geomorphological and geological processes that shape the earth's surface. Processes such as the movement of clay in a soil profile work over distances of a few hundredths of a millimetre to a few centimetres, the biological actions of plants and small animals such as ants may affect areas from a few centimetres to a few metres, river erosion and sedimentation occurs over distances from a few metres to several tens of kilometres, and the mountain-building processes of plate tectonics act at continental scales. The value of a chemical property of the soil at any given point is the sum of all these different effects acting in concert.

In spite of a huge research literature, knowledge about soil variability is still dispersed and not well organized. There is a need to organize and systematize our knowledge on soil variability in such a way that users of soil information unskilled in geostatistics or chaos theory can make the best possible decisions under conditions of uncertainty. Once the knowledge has been gathered and organized, then it may be sensible to use expert systems to help the user choose how best to deal with uncertainty.

3.5 Representations of soil variability. Burrough (1993) describes a paradigm shift that has begun in the representation of the variability of soils in soil data bases:

Given the variety and complexity of soil, and the lack of tools for dealing with continuous variation (computers, interpolation methods) it is no wonder that until twenty years ago or less, soil scientists attempted to reduce the plethora of variants to manageable proportions by defining taxonomic classes and uniform, homogeneous mapping units. As long as the soil was only sampled at subjectively chosen “representative” locations there were no grounds for challenging the conceptual model that was used to make most soil maps, namely that the soil landscape consisted of homogeneous (or nearly homogeneous) patches of similar soil, with all important change occurring at boundaries. Also, as long as observations of soil properties were classified directly into nominal classes (e.g. texture, structure) then it was difficult to consider gradual, within-unit variation. Besides field soil scientists [citations omitted], soil physicists were among the first to question the conventional model of soil variation used in systematic mapping and classification [citations omitted]. They realized that the physical properties of the soil, such as infiltration capacity and porosity, not only varied from place to place, but that these properties varied with the size of the sample used to make the observation (Bouma and others, 1971). Very short range variation or temporal variation can also cause unexpected variation in measurements of soil properties [citations omitted].

A choropleth map has delineations of polygons, with the assumption that the attribute values are uniform over the area of each polygon. In a fuzzy classification, the requirement of uniformity is relaxed, and more than one attribute value is allowable, with explicit representation of the probability of occurrence for each value. The probabilities may be determined by statistical analysis of sample points within the delineation. In areas of intensive surveys, techniques of spatial interpolation such as geostatistics or spining may be used to extrapolate from the sample points to areas between the points. This is typically done with a raster (grid cell) representation, rather than a polygon representation. The geostatistical techniques do not work well if the observation points are sparse compared to the variability of the observations (Burrough, 1993). For county soil survey mapping in the United States, the frequency of sample points is small compared to the area to be mapped. In such cases, choropleth maps may be at least as accurate as maps based on geostatistical methods, because they can use features observable at the surface and
in aerial photography that are between the limited number of field sampling locations. A soil scientist may correlate limited field observations with more complete laboratory analyses of soil profiles (even from outside the study area) and describe the soils in terms of a soil series or other formal soil classification or soil taxonomy. This step of the process has often been problematic, because the local conditions often do not fit exactly to the defined characteristics of the soil series based on experience in other areas. It then becomes necessary to define taxadjuncts—descriptions that are closely but not exactly related to the defined series. A fuzzy logic approach to this process would allow specification of a set of soil descriptions, and then the soils at a given location could be described as a combination or a distribution of the characteristics of the soils in the set.

Burrough (1993) suggests:

Combined methods involving some combination of choropleth mapping and continuous interpolation can yield significant improvements if data are sufficient. More work on the theory of combined methods is necessary.

One approach to a combined method would use a hierarchical perspective, where the variation at a particular level is described using a polygon map. The statistical characterization of the variation within the polygons could be based on small areas of intensively sampled soils. The data representation would indicate the probability of each of the intensive representations within each polygon. The intensive representations could be of a simple form (such as a single soil profile or the average of a set of representative soil profiles), an intermediate form (such as all the data for a set of representative soil profiles), or a complex form (such as a complete three dimensional hydrologic model of a toposequence). The simplest forms represent a traditional choropleth map. Geostatistical methods may be appropriate for developing the more complex descriptions. A comprehensive data structure could simultaneously handle representations of several degrees of complexity.

If boundaries are drawn around similar soils, we will need to describe them according to the probabilistic distribution of properties that occur within the delineation. Because soil properties covary from one locale to another, it will be preferable give the proportions of complete profile (pedon) descriptions rather than to give the distributions of the properties independently. In fact, we would be providing proportions of a multi-level hierarchical representation that is an extension of the traditional profile description. In national-level soil mapping programs, it is not feasible to sample with enough intensity to characterize the entire soil surface with geostatistical techniques, so there is still room for the mapper’s judgement. The selection of the typical pedons, their proportions within the landscape unit, and if applicable, their relationship to each other (as a toposequence or other basis for systematic variation) would be explicitly tied to their authorship in the data base. Then other investigators would have a basis for revising the descriptions, and adding their interpretations to the data base.

4. STATSGO as a level in a hierarchical framework. The State Soil Geographic Data Base (STATSGO) has been developed by the U.S. Department of Agriculture, Soil Conservation Service (Soil Survey Staff, 1993). It is currently available for all States of the United States, except that additional work is needed for Alaska. It is an example of a recently developed operational data base at a regional scale that incorporates some aspects of a hierarchical framework. Although it was not explicitly designed as an implementation of ecological hierarchy theory, several soil attributes provide a limited representation of soil variability in space and time.

4.1 The STATSGO data structure. The STATSGO data are compiled on 1:250,000-scale base maps by generalizing soil maps at scales between 1:15,840 and 1:62,500. Map units from the
detailed maps are combined to form map units on the STATSGO maps with a minimum area of 6.25 square kilometers. STATSGO map units are comprised of phases of soil series. Up to 21 phases may be identified for each STATSGO map unit, and the area of each phase within the mapunit is recorded in the data base as a component percentage. Data for approximately 100 soil properties are recorded in a set of relational tables, that can be linked to the digital map using a geographic information system. The properties include the soil taxonomic classification, soil texture, bulk density, organic matter, depth to rock or restrictive layers, and other chemical and physical properties. The frequency and duration of flooding and soil moisture and temperature regimes are examples of temporal properties.

4.2 Representing variability in space and time in STATSGO. Burrough (1993) categorized conceptual models for soil variation based on whether they are discrete or continuous, deterministic or stochastic, and single scale or multiscale. Using this framework, traditional soil mapping in the United States may be considered to use a discrete model (choropleth or polygon map). Soil scientists recognize that soils are variable within polygons (a stochastic model), but the data base may not reflect this and may only report a single value for each polygon (a deterministic model). Traditionally, only a single scale has been represented in the data base, without formal discussion of the relationships between the scales at which various soil attributes are measured.

The STATSGO data base has two levels of a multi-scale representation. STATSGO polygons (mapped at 1:250,000-scale) are explicitly considered to be heterogeneous collections of phases of soil series and the percentage composition of the detailed units within the generalized units is encoded. The percentage composition information is based on the maps that are developed at the level of the county soil survey (typically mapped at scales between 1:15,840 and 1:62,500). Although a user does not know where within a STATSGO polygon a particular soil phase would occur, the proportion of the soils that occur at the more detailed level forms the basis for a more complete analysis than would be possible with a single-level representation. Attributes that are coded with nominal categories may be mapped by selecting a set of the categories, and showing what proportion of the polygon is included in the set. Attributes coded with values of quantities subject to the conservation laws can be aggregated over the component soil phases to give a single value for the map unit or polygon. For example, soil organic carbon is subject to the law of conservation of mass, so the number of kilograms of carbon for the map unit can be calculated. To display this on a map, the average for the polygon can be calculated by dividing by the area of the polygon (for example, kilograms per square meter). It is useful to have an inset map showing the average depth of soil used in the calculation.

One limitation of the current STATSGO data base is that the percentage composition of soil phases within map units is calculated on a statewide map unit basis, rather than an individual polygon basis. As soil data bases at the county level become available, it will be possible to recompute the percentage composition of soil phases for each polygon rather than on a map unit basis.

The STATSGO data base has a minimal representation of the stochastic model by including a range (minimum and maximum) for many of the soil properties encoded in the data base. For example, the organic matter percentage from which organic carbon is calculated is reported as “organic matter–low” and “organic matter–high”. A more complete description of the histogram (perhaps 10 quantiles) would be useful for some modeling purposes. A first step would be to include a “representative value”, because the mode is often not the midpoint of the range. The most complete example of a distributional representation in STATSGO is the particle size
distribution. The percentages of the soil by weight for rocks greater than 10 inches and rocks between 3 and 10 inches are given on a whole-soil basis. The percentages of soil passing through sieve sizes #4, #10, #40, and #200 are given on the basis of the fraction of soil less than 3 inches. All of these measures are given as a range (low, high). Soil texture is a classification based on percentages of sand, silt, and clay, and can be used to estimate the ranges of these proportions for the fraction of the soil less than 2 mm diameter (passing the #10 sieve). Texture information is given by layer, and up to three textures can be coded per sub-surface layer, although the likely proportions of these on the landscape are not given.

Variability in time is explicitly represented in STATSGO for flooding and ponding. Attributes in the data base include flooding frequency, month flooding starts, month flooding ends, and duration of flooding, for both annual flooding and growing season flooding. Similarly, the start, end, and duration of ponding are recorded, if applicable.

An implicit description of variation in time is encoded in the soil moisture regime and the soil temperature regime descriptions for each soil phase based on soil taxonomy (Soil Survey Staff, 1975). For some purposes, it might be useful to reconstruct relationships of soil moisture surpluses and deficits over the growing season. This STATSGO representation of temporal behavior is highly generalized, comparable to suborders or great groups of soil taxonomy. Another implicit representation of variability in time is the range site productivity attribute. Values are given for favorable, normal, and unfavorable conditions, but there is not an indication of the frequency with which each condition is likely to occur.

4.3 Displaying spatial variability of STATSGO data. When a State soil science staff characterized the STATSGO map units as a collection of phases of soil series, they had considerable latitude to match their description to more detailed soil surveys and field experience. The only limitation was that there must be between 1 and 21 soil phase or non-soil categories for every map unit. The resulting distribution of component percentages can be analyzed as an indicator of the structure of the inherent variability of the STATSGO data. An analysis of the attributes that are used to characterize the soil phases can decrease this variability when several components have the same characteristics for a given property, but it will not increase it.

Several methods have been devised to portray the variability within the STATGO data with graphs and maps. Organic carbon is used as an example, although the methods may be adapted for any attribute.

1. Show the component number in relation to the cumulative area (sorted by decreasing proportion of area).
2. Show the percentage area by the classes of organic carbon. This is a traditional histogram when considered for each individual map unit, or a set of maps when considered for all map units simultaneously.
3. Show the cumulative percentage area by the classes of organic carbon. This is a traditional cumulative histogram for individual map units, and can also be displayed as a set of maps.
4. Show the carbon class by the cumulative area. This is the same data as the previous method, with the perspective reversed.
5. Compute the mean and standard deviation of organic carbon for each map unit. The standard deviation may be useful as a rough index of variability, but should not be used for establishing confidence limits because the data typically do not follow a normal distribution.
6. Compute an information theory measure of uncertainty for the map units. This can be done for the distribution of component percentages in the data set, or for the distributions of percentages based on organic matter classes. This method is not sensitive to the quantities of...
Methods #1 and #4 are illustrated in figures 1 and 2, respectively. Figure 1 represents the structure of variability in the STATSGO data for the State of New Jersey. A sequence of 10 maps shows the component number class for each 10 percentile of area. The sequence was formed by sorting the components within a map unit according to descending area. The component with the largest area was labeled component 1. If a map unit was homogeneous it had only one component, representing 100 percent of the area, and the first class (lightest shading) was assigned to the map unit in all 10 maps. If a map unit had only 5 components, the map labeled “100th Percentile” will be coded with the second class (component 5 to 8). Thus, light shading in the “100th Percentile” map indicates a low number of total components. A large number of components indicates that the soil scientist observed considerable variability in the map unit. If the percentages of the components are evenly distributed in area, then there is a high degree of complexity. This is reflected by having high component numbers early in the sequence. If there are many components, but most are a very small proportion of the area, then the “100th Percentile” map will have dark shading, but the others will be light. Figure 1 is equivalent to a spatial cumulative histogram of component number.

Figure 2 provides a similar analysis for soil organic carbon. The components are sorted in order of increasing organic carbon content. Map units that have low carbon values in all components have light shading throughout the sequence of maps. Map units that have low carbon contents in the “90th percentile” map, but high carbon contents in the “100th percentile” map have high carbon values only in components that represent a small proportion of the total area.

4.4 Applications at continental and global scales. Techniques to quantify and display soil variability will be useful in generalizing from detailed to regional soil maps. The authors are involved in preliminary work to include the data and procedures developed for STATSGO to construct continental and global data sets.

A soil organic carbon map of the Eastern United States has been created by plotting the STATSGO data at 1:4,000,000-scale. This effort is being expanded to form a map of North America showing organic carbon in the soil at a mapping scale of 1:10,000,000, based on data compiled at 1:1,000,000 and 1:250,000 scales for Canada, the United States, and Mexico.

A National Soil Geographic Data Base (NATSGO) is being developed as a set of generalizations of the STATSGO data to the continental and global scales. A statistical approach to the generalization aims to aggregate STATSGO map units that have similar distributions of soil taxonomy or other soil properties to form a NATSGO map unit. A geographic approach to the generalization combines contiguous map units. The two approaches can be used in combination. The higher-level generalizations are stored in the data base as additional relational tables. In each case, a new distribution of component percentages is calculated. A consistent method of querying the data base to create maps, including variability maps, is applicable to any of the generalizations.

Methods to generalize soil maps have also been investigated at the global level. A data set of global texture (GLOBTEX) has been prepared by aggregating combinations of texture, slope, and FAO soil type from the FAO Soil Map of the World into one-degree cells.

A map of the Major Soil Regions of the World is being developed by modifying the FAO World Soil Resources map to include soil moisture and temperature regimes, and a translation to the suborder level in the USDA system of soil taxonomy.

The understanding gained from these efforts should be helpful in supporting the development of the Soil and Terrain (SOTER) digital data base of the world, being developed under the auspices
Figure 1. Components are sorted by area for each polygon in New Jersey, USA. Maps show the component number for each 10-percentile of area. Complex map units have high component numbers early in the sequence.
Figure 2. Components are sorted by organic carbon (kilograms per square meter). Maps show the soil organic carbon for each 10-percentile of area. High carbon contents occur in only a small percentage of the area.
of the International Soil Reference and Information Centre (ISRIC), the United Nations Environment Programme, the International Society of Soil Science, and the Food and Agricultural Organization of the United Nations. The SOTER data base is targeted at the 1:1,000,000 scale, and the current data structure includes some aspects of a spatially hierarchical structure (ISRIC, 1993).

5. Data Needs. Many applications of soil data at regional and global scales are possible. Each application will require a different combination of variables, and the ways in which the variables are combined will depend on the quality of the available data. The following recommendations are offered for structuring a data base so that it is useful for many applications.

• The volume of soil on which a measurement is made should be recorded, as well as the variability that occurs as similar volumes are sampled over space. Analogously, the time period within which a sample is observed should be recorded, and how the properties of interest change with time.

• A user should be able to estimate the spatial area and time period over which the observation can be reliably extrapolated.

• If possible, the observed soil variability should be partitioned into inherent soil variability, measurement errors, and the reduction in information introduced by generalization. It should be recognized that most measures of accuracy or error are made in terms of the observable data at the next lower level, and that error statistics are thus relative and not absolute.

• An understanding of soil forming processes at the global and landscape levels should be represented in the data base as constraints on the detailed soil pattern. This “top down” approach makes use of information on mountain building, glaciation, climate, and the transport of soil materials by wind and water to define regions with similar soil forming influences.

• Explicit procedures should be defined for generalizing soil maps from the most detailed scale to the scale of required application. One example of this “bottom up” approach would be to combine units from detailed maps that have similar statistical properties. First, define a population at a given level of the hierarchy by space, by time, or by classes of attributes. Second, summarize the variety in the population using statistics stored at the next higher level of the hierarchy, such as averages, ranges, wave forms (as a characteristic of a time series or spatial pattern), regression equations, or covariance matrices. It is important that information on the generalization procedures is recorded with the generalized data. Measures of the information losses that occur with generalization should be an explicit part of the data base.

• The “bottom up” approach should be viewed as complimentary to the “top down” approach. Both ways of viewing the soil landscape will contribute to the process fitting observations into the appropriate parts of the hierarchical data framework.

• Existing data bases should be reformatted into a structure that explicitly accounts for our hierarchical way of understanding processes over many scales. At the present time in the United States, the soil attributes for small-scale maps are derived from a national data base of soil properties. In the future, it will be desirable to link the map unit components directly to pedon descriptions, so that more rigorous statistical procedures can be used to evaluate and improve the data quality. The locations of the pedon samples should be labeled with latitude and longitude. Taxonomic unit classifications will be useful in linking the pedon descriptions to the maps. The resulting data base should have a set of pedon descriptions linked to each map unit, weighted to indicate the importance of each pedon for describing the variation within the map unit, and with explicit authorship noted for the people making the weighting judgements. More than one set of pedon descriptions, weights and authors can be attached to a map unit, allowing for improvements in the data as new samples are taken and new concepts are developed. Linking pedon descriptions
to map units is only one example of a linkage between soil maps of different scales. This process can be repeated between any two sets of scales.

- The data structure should allow for the data elements to be complex objects. For example, at a given level, the processes affecting the elements at the level below may be understood in terms of horizontal and vertical flows over time. To represent these spatial interactions, soil data bases should be able to represent soil properties in some type of three dimensional form, such as: (1) a two-dimensional surface to display a map unit, with a tabular data base giving variations of soil properties with depth, (2) a map with shaded relief, to give the impression of topography without using it analytically, (3) a surface with explicit elevation values (sometimes called a 2-1/2 dimensional surface), but with soil properties represented at an infinitely thin surface, (4) a surface with a finite thickness draped on the topography, (5) and a full volume representation in a three-dimensional grid. These various representations may each have advantages and disadvantages for data input, storage, analysis, and display. Better techniques for converting data between the representations should be developed.

- There is presently a limited characterization of temporal variability in soil data bases. For example, soil moisture regime information is generalized and classified before being recorded in soil taxonomy. Currently a soil map unit is classified in the Udic moisture regime if it meets the criteria for Udic in 6 years out of 10. An improvement to the representation would involve a hierarchical representation of time periods, with the complete weather station record being successively generalized into monthly averages, an annual classification of the moisture regime, a calculation of the proportions of the moisture regimes over a 10 or 30 year period, and finally the summary classification of the dominant moisture regime. These steps may have been followed in the calculation, but have not necessarily been incorporated as an integral part of the soil data bases. In the future, improved data on soil moisture changes may be expected based on improved techniques for measuring precipitation and soil moisture using weather radars and remote sensing.

6. **Analysis needs.** Developing hierarchical data bases is likely to be an iterative process involving successive approximations. A structure will be developed, researchers will find its shortcomings, and a new structure will be developed. Tools are needed to help in this process. One set of tools that would be useful would be automated techniques for defining regions based on similarities in multivariate data.

To aid in the evaluation of the quality of the hierarchical representations, measures to calculate the reduction in information content as detailed data are generalized should be developed and applied. The model results can be incorporated in the soil data bases as surrogates for data that are hard to measure, along with descriptions of how the results were obtained. It would be helpful to have a mathematical symbology to concisely convey complex sequences of modeling and aggregation operations.

To model the temporal variability of soil hydrology, interpolation techniques can be applied to climate data and digital elevation models, resulting in detailed surfaces such as temperature, precipitation, slope, aspect, solar insolation, potential erosion, and potential sedimentation. Hydrologic units can be defined, and statistics calculated on curvature of slope and other features. These measures can be used to complement traditional soil survey techniques, to gain a better understanding of the distribution of soils in terms of soil forming processes, and the potential response of vegetation (crops, rangelands, or forests). To model the temporal variability of soil-plant interactions, the soil maps may be overlayed with time series of satellite imagery. These techniques provide analysis tools at regional scales that complement the traditional soil mapping at local scales.
7. **Conclusions.** Soils are inherently variable, and our representation in data bases should assume they are heterogeneous at every scale. The representations will never capture all of the complexity of the real soils. We can gain maximum human understanding by taking a hierarchical approach, and attempting to represent the major processes at each scale, seeing these as a mix of the processes at the lower levels, and constrained by processes with a slower rate of change (that may be episodic) at higher levels.

Understanding the soil forming processes that operate at each scale can guide the development of a hierarchical representation, but the action of the soil forming processes is not always observable, so we must depend on the observable soil properties. New developments in instrumentation, sampling designs, interpolation methods, database software, and geographic information systems are making it possible to collect, organize, and visualize information at a variety of scales.

Soil data bases have traditionally been at a single level and used a choropleth representation with limited descriptions of variability. Information from higher and lower levels has been represented in the data base as generalized or averaged attributes. Soil classification has been seen as an essential element in representing and understanding the complexity of soils. A transition is possible to a new paradigm for representing soils. Soils can be mapped at many scales, with explicit linkages between the information portrayed at each scale. Mapped units may be considered as inherently heterogeneous rather than inherently homogeneous. A probabilistic representation that shows the distribution of possible properties for the next lower level can be maintained at each level. The data bases will be the primary representation of our understanding, and soil classification systems may evolve into expert systems that guide those unfamiliar with the details of the data bases access to the concepts and information that are important for particular applications.

**Literature Cited**


Advances and Pitfalls in Expressing Land Qualities at Different Scales

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Abstract.

Translating information about soil characteristics and qualities across different spatial and temporal scales has emerged as a major theme in Soil Science. The interest in scale has developed as our understanding of processes operating at scales larger (e.g. landscape, regional) or smaller (molecular, aggregate) than the field plot has increased. While we have made great progress in producing conceptual and practical tools for translating information across scales, many problems remain. In particular, our ability to predict soil processes at the small scale given large scale information ("down" scaling) is much worse than our ability to scale "up". Moreover, while there have been several successful efforts to scale up certain types of information, we have been unable to predict large-scale phenomena given small scale information in several important instances. Different approaches to scale translation, and the successes and failures of these different approaches, have important implications for soil characterization and identification of land qualities as we address contemporary environmental problems at different scales. We suggest that current scale translation efforts of all types fail for one of two main reasons; (1) either a key controlling process or characteristic has been overlooked, or (2) when multiple factors interact to create unique phenomena. In this paper, we review the progress that has been made in developing conceptual and practical tools for scale translation and then discuss areas where such translation has failed. We then go on to discuss approaches for predicting and then often adjusting our estimates of soil behavior based on contemporary scale translation approaches. We also discuss the implications of scale translation problems for soil data needs to address contemporary environmental problems.

Introduction.

Soil scientists are increasingly being called upon to translate the basic characteristics and properties of soils as determined at one spatial scale into assessments of land behavior that reflect the dynamic nature of natural processes at another, usually larger scale. Traditional soil survey activities have focused upon characterization and classification of static attributes of the soil system, particularly at the scale of the soil profile or horizon. This focus has produced highly detailed descriptions that focus more on morphological than on functional characterization. While providing a useful catalogue of soil properties, such exercises have generally been directed inward to a peer audience of other classifiers, rather than outward to a larger group of users, who often look at morphological characterizations and rightly ask
"How do I use this information to predict soil behavior and performance?" Such predictions focus on questions related to the dynamic behavior of soils, rather than their static attributes.

It is necessary to recognize several definitions before proceeding with further discussion of soil behavior at different spatial and temporal scales. Soil survey activities have traditionally focused on the measurement and classification of soil and land characteristics and properties. As defined by FAO (1976), land characteristics are attributes of land that can be measured or estimated, usually during soil surveys (e.g. soil texture, structure, organic matter content). Some characteristics are increasingly needed for addressing contemporary issues, but they are not routinely determined by soil survey (e.g. moisture retention, hydraulic conductivity). However, determination of characteristics alone is insufficient, since these static soil attributes tell us little about soil processes that are use-dependent, and therefore temporally variable. A necessary next step is to establish land qualities, which are defined by FAO (1976) as complex attributes of land which act in a distinct manner to influence the suitability of land for a specific kind of use. This definition implies that land qualities cannot directly be measured (e.g. water supply capacity, trafficability, erosion hazard, nonpoint source pollution attenuation potential, soil carbon storage potential, trace gas fluxes). Land qualities can be related to land characteristics through a variety of methods. This approach of using basic information to derive the suitability of land for a particular use is called land evaluation, which according to the original definition of FAO (1976) is concerned with estimating land performance when the land is used for specific purposes. The land evaluation process at different scales must be based upon land characteristics that are appropriate to scale-specific land qualities.

Interest in scale translation has developed as our understanding of processes operating at scales larger (e.g. landscape, regional) or smaller (molecular, aggregate) than the field plot has increased. Interest in scale has been driven by the emergence of new technologies and environmental problems that require information on soil processes and properties at large and small scales. These problems have created a need for the development of techniques to relate soil parameters to new land qualities such as soil-atmosphere trace gas fluxes, soil carbon storage, non-point source pollution attenuation, soil biodiversity, and biological control of pathogens and weeds using introduced organisms. New techniques in molecular biology have created a need for understanding how micro-scale factors that influence the survival of introduced organisms are expressed at the field scale (Tiedje et al. 1989, Gilbert et al. 1993). Landscape-, regional- and global-scale water quality and atmospheric chemistry questions have created a need for understanding how field-scale soil factors that influence these questions are expressed at large scales (Bouma et al. 1986, Kachanoski 1988, Duxbury et al. 1993). In the modeling arena, the necessity of aggregating data from different scales has greatly complicated the structure and input data needs for different models (Wagenet et al. 1993), but in fact, new technologies such as geographic information systems (GIS) and dynamic computer simulation modeling have proven useful aids. For example, Petach et al. (1991) used properties measured in soil profiles, integrated over a watershed by simulation modeling and GIS techniques, to translate soil characteristics from the scale of the profile to the scale of a watershed, in the process accomplishing an assessment of the
A major conceptual and practical problem in scale translation is determining the extent to which mechanistic understanding of processes at lower or higher scales is necessary for investigating a particular phenomenon at a particular scale. One line of reasoning suggests that quantitative, mechanistic understanding at any scale \( i \) is dependent on the extent of understanding at the next lower level \( i-1 \) (Wagenet et al. 1993, Figure 1). By this reasoning, the potential for producing mechanistic understanding and models declines with increasing scale (Table 1). Large-scale (landscape, watershed, regional) models then are based on functional, statistical or conceptual formulations based on "lumped" parameters that subsume much of the process-level complexity of lower scales. This view, that mechanistic understanding must be built from the "bottom up", calls for a different definition of scientific rigor when translation across landscape, regional and global scales is the issue. This conceptualization assumes that particularly at large scales, where internal complexity is high and forces external to the system are important driving forces, development and application of mechanistic approaches is not an orderly process. In such cases, it is often unacceptable to allow lack of mechanistic insight or understanding at an intermediate scale, which may well never be a possibility due to the influence of external forcing factors, to hinder the investigation and/or modeling of higher scale phenomena. In some cases, enlightened field studies at the higher scale might actually be used to indicate the most promising cases for further work at lower scales. For example, the use of remote sensing to identify the temporal and spatial patterning of plant response to soil water at landscape or field scales may lead to better identification of the causes of spatial variation in soil properties at the field or plot scale.

An alternative approach to scale translation is less concerned about the use of lumped parameters that subsume lower scale process-level complexity (Rosswall et al. 1988). This alternate approach views these parameters as appropriate "minimum essential element" variables at the scale in question. A determination of the minimum essential element is made in all fields. For example, in some fields of soil science, the minimum essential element resides at the organism, particle, or element scale, rather than at the enzyme, mineral, or molecule scale, even though dynamics at these smaller scales influence processes at the scales used by soil scientists. Soil scientists working at the soil profile, pedon, or field plot scale have recognized such effects through conceptual definition of a representative
Figure 1. Scales of soil processes and simulation modeling relationships. From Wagenet et al. (1993).
TABLE 1. Modeling approaches related to pesticide leaching at different spatial and temporal scales. Adapted from Wagenet (1993).

<table>
<thead>
<tr>
<th>Scale</th>
<th>System</th>
<th>Example process considered</th>
<th>Possible modeling approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>i+4</td>
<td>County, State, Province</td>
<td>Pesticide contamination of groundwater.</td>
<td>Mass balance functional models of fluxes combined with GIS [valid (i+1) to (i+4)].</td>
</tr>
<tr>
<td>i+3</td>
<td>Soil regions (interacting watersheds)</td>
<td>Ecosystem response to pesticide.</td>
<td>Statistical models, compartment flux and pool models (not leaching models).</td>
</tr>
<tr>
<td>i+2</td>
<td>Watershed</td>
<td>Delivery to surface water, groundwater recharge, erosion.</td>
<td>Distributed (functional) or statistical models, lumped parameter models, functional management models.</td>
</tr>
<tr>
<td>i+1</td>
<td>Polypedon (field/farm)</td>
<td>Runoff, erosion, lateral flow, atmospheric dispersal.</td>
<td>Two or three dimensional, lateral flow, Ad hoc stochastic use of deterministic models, functional management models</td>
</tr>
</tbody>
</table>
elementary volume (REV), as a soil volume, consistent across a soil type, that depends on soil structure and soil characteristics, within which all micro-scale variations are found and can be expressed as an average value (Bear 1979, Wagenet 1985). The physical size of a sample should be scaled to the REV (Bouma 1983) for any soil and characteristic measured. The REV can then be used as a sampling volume to estimate spatial variability at the scale of interest, usually up to the scale of watersheds. Researchers at landscape, watershed, and regional scales use much larger minimum essential elements such as catenas, geomorphic features and regional plant communities. These large scale elements may appear to many soil scientists to subsume too much process-level information, just as investigation of soil aggregates may appear to a physical chemist or molecular biologist to subsume too much process-level information. The danger in all efforts that integrate or generalize lower-scale complexity is that at some point, lower-scale processes will change, perhaps in response to an external forcing factor, such that the relationships between minimum essential elements are not stable. Instability changes the nature and pattern of soil variability, with a resulting change in land qualities related to soil behavior.

We suggest that current scale translation efforts of all types fail for one of two main reasons; either a key controlling factor has been overlooked, or when multiple factors interact to create unique phenomena. In this paper, we review the progress that has been made in developing conceptual and practical tools for scale translation and then discuss areas where scaling has failed. We then go on to discuss approaches for predicting and rectifying when current scale translation techniques will fail, and discuss the implications of scale translation problems for soil data needs to address contemporary environmental problems.

Approaches to scale translation "up".

One conceptual basis for moving from small to large scales involves focusing on the factors that control the variable in question at the next higher scale (Groffman 1991). For example, if we are interested in translating upward information on soil moisture from the field to the landscape scale, we focus on soil texture as a controller of variation in soil moisture across the landscape (Table 2). If we want to scale information on soil moisture from the landscape scale to the regional scale, we focus on geologic and geomorphic factors that control variation in soil texture at the regional scale. This conceptual approach provides practical guidance for the specific types of data needed to address questions at different scales. This approach should also be reflected in the modeling, as it allows us to "scale-up" process-level descriptions of physical, biological and chemical phenomena and eventually integrate them into more comprehensive models at successively larger scales. Data needs and modeling at each scale are linked by the degree of resolution with which the processes are represented and the consequent demand for specific data (Wagenet et al. 1993).

Derivation of land qualities at different scales has relied on the development of relationships between easily measured soil characteristics and more dynamic processes of the soil system at different scales. While land qualities cannot be directly measured (e.g. water supply capacity, trafficability, erosion hazard, leaching potential, nonpoint source
<table>
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<th>SCALE</th>
<th>CONTROLLING FACTORS</th>
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<td>Aggregate</td>
<td>Pore size, organic films</td>
</tr>
<tr>
<td>Field</td>
<td>Precipitation, soil texture, organic matter content</td>
</tr>
<tr>
<td>Landscape</td>
<td>Soil texture, plant community type</td>
</tr>
<tr>
<td>Regional</td>
<td>Geomorphology, land use</td>
</tr>
<tr>
<td>Global</td>
<td>Biome type, climate</td>
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pollution attenuation potential), they can be estimated from such land characteristics as soil texture, depth to water table, and organic matter content (Wagenet et al. 1991). Estimation methods include pedotransfer functions that essentially correlate easily measured soil characteristics (such as particle size distribution) with dynamic variables (such as hydraulic conductivity) (Bouma and van Lanen 1987) to extend the estimate of the latter with minimal and easy to obtain data. Land qualities are thereby obtained using the estimated characteristics, often through simulation modeling.

Translations can also be between scales, as demonstrated by Wösten et al. (1985) who characterized the physical soil properties of 12 different pedogenetic soil horizons, in an area of 800 ha, and found that only six of these were different when the criteria was difference in hydraulic properties. This work demonstrated that pedogenetic differences do not necessarily correspond with functional differences, and perhaps more importantly it demonstrated that by using pedogenetic soil horizons as carriers of information, the basic issue of extrapolation of point (pedon) to area (landscape) data can be solved. By this approach we can translate soil information from one scale to others, provided we recognize that each land quality at each scale encompasses a different range of spatial and temporal behavior, and therefore requires different measurement methods, pedotransfer functions, and approaches to modeling system behavior.

Much of the interest in scaling up has been driven by watershed-scale water quality and regional- and global-scale atmospheric chemistry questions. For example, Groffman et al. (1992a) scaled up field measurements of denitrification to landscape and regional scales by focusing on the land characteristics soil texture and drainage as landscape-scale controllers of soil moisture, which is a field-scale controller of denitrification. Landscape and regional-scale soil databases were then used to extrapolate field-scale denitrification rates to larger areas. Interestingly, predictive relationships between denitrification and environmental factors were easier to establish at the landscape scale than at the field scale. Groffman and Tiedje (1989) were able to explain more than 80% of the variation in annual denitrification N flux with soil texture and drainage, while previous studies had generally been able to explain less than 50% of the variance in hourly or daily rates of denitrification with fieldscale measurements of soil moisture or other variables. O'Neill (1988) developed the concept of "coherent levels" as the scale of investigation at which predictive power is maximized. For denitrification, and perhaps for other variables such as soil erosion, mechanistic process-level understanding may be best achieved at scales larger than the field or plot scales that are the focus of much soil science research.

Several studies have focused on ecosystems as the optimal unit of study for landscape and regional-scale investigations. Different ecosystems within a landscape or region exhibit distinctive patterns of vegetation, soils and biogeochemical processes in response to differences in resource (primarily water and nutrients) availability at a site. Matson et al. (1989) proposed applying the state factors of soil formation (parent material, time, topography, organisms, climate) developed by Jenny (1980) as a construct to analyze the variation in ecosystem types across the earth's surface. Focusing on ecosystem type as a minimum essential element variable in landscape-scale studies integrates much of the
process-level complexity of lower scales. From a data needs standpoint, ecosystems are very useful for extrapolating information from site-specific studies to larger areas. Moreover, there are large databases of ecosystem classification for most of the globe (Stewart et al. 1989), and remote sensing technologies for ecosystem classification are developing rapidly (Hall et al. 1991). If we can establish links between ecosystem properties and land qualities of interest, then we will be able to use these databases and remote sensing techniques as scale translation tools to produce large-area estimates of these processes.

Ecosystem-based approaches to scale translation have been vigorously applied in research on soil-atmosphere trace gas fluxes that influence regional and global atmospheric chemistry (Bouwman 1990). The simplest approaches have used large-area soils databases as input to "bookkeeping" models that assign single flux values to different soil types and sum the results to produce large-area estimates of flux (Matson et al. 1989, Van Breemen and Feijtel 1990). Burke et al. (1990) and Matson et al. (1991) used whole ecosystem classification approaches to produce large-area estimates of soil N gas flux for areas of shortgrass steppe and sagebrush steppe. Moore et al. (1990) found that different boreal ecosystem types exhibited distinctive patterns of soil-atmosphere methane fluxes. Such work summarizes a systems' behavior, but it remains to translate these observations into dynamic qualities.

In a more functional approach, Groffman and Turner (in preparation) analyzed relationships between net primary production (NPP) and soil N gas fluxes in tallgrass prairie, and used a satellite remote sensing-based index of plant productivity (normalized difference vegetation index, NDVI) to produce large-area estimates of fluxes for a tallgrass prairie landscape. This type of functional approach can guide the development of more mechanistic dynamic models that should be capable of depicting how trace gas fluxes change along with related ecosystem variables.

Ultimately, a functional approach allows for the development of complex mechanistic simulation models where some type of dynamic information (climate, soil moisture, plant variables) is used to drive models of ecosystem functions including trace gas fluxes, soil carbon storage, N mineralization rates and N leaching (Figure 2, Running 1990, Schimel et al. 1990, 1991a,b, Burke et al. 1991, Lauenroth et al. 1993, Brown et al. 1993). These models often integrate large amounts of mechanistic and process-level variability at the field and microsite scale. However, these models can still be considered to be mechanistic at the landscape and regional scale since they are based on mechanistic process-based relationships between landscape and regional-scale variables. Reliance on these variables is necessary from a basic science viewpoint that focuses on landscape and regional-scale science, and from a practical viewpoint where the capacity for computational complexity and input data is finite.

Ecosystem-based approaches to scaling, either classification or simulation model-based, fail when lower scale processes subsumed within the ecosystem affect landscape or regional-scale dynamics in unexpected ways. Juma (1993) compared two models that simulate soil organic matter dynamics, one that includes faunal dynamics and one that subsumes these dynamics. While both models produced roughly the same net results, internal dynamics
Compartment flow diagram for FOREST-BGC (Bio-Geo-Chemical cycles), a simulation of carbon, water and nitrogen cycling processes for forest ecosystems, designed to accept remotely sensed data. From Running (1990).
differed strongly. While this comparison might suggest that not explicitly including faunal
dynamics would be appropriate for landscape and regional-scale studies, the results might
also suggest that if changes in management, climate or other external or internal factors that
affect faunal dynamics changed, the simpler model might be inadequate.

Approaches to scale translation "down".

Scale translation "downward" has proven to be much more difficult than translation "up".
Deriving certain land qualities requires translation down from the field to the micro-scale.
For example, while we know that soil moisture, nitrate and available carbon level control
the rate of denitrification in field soils, we have been unable to predict the occurrence of
micro-scale "hotspots" within field plots where high levels of these factors converge. These
hotspots account for a very high percentage of the denitrification that occurs in field soils
but we have no conceptual or practical basis for predicting their occurrence. Parkin (1987)
and Christensen et al. (1990) found that nearly all the denitrification in a soil core occurred
in microsites created by decomposing plant residues. Predicting the occurrence of such sites
is difficult. Arah (1990) was able to model the occurrence of denitrification hotspots in soil
aggregate centers, which is a more promising approach given that there is a base of
information about aggregate formation and turnover. However, aggregate centers are not
the only denitrification microsites in soil (cf. Parkin 1987) and little is known about the
details of microbial dynamics in aggregates.

Lack of understanding of microscale dynamics has greatly limited our ability to predict if
introduced organisms or genetic material will become established in the soil community
(Tiedje et al. 1989, Gilbert et al. 1993). We need to be able to use field-scale information
on soils, plant type, management system and other factors to design management strategies
for beneficial organisms such as biocontrol or biodegradation agents, and perhaps to contain
introduced genetic material. While we know that factors such as soil aggregation, fauna,
rhizosphere effects, cracks and other phenomena influence population interactions among
the soil microflora, we lack an understanding of how these factors are linked to field-scale
soil physical, chemical, biological or management variables (Smiles 1988, Focht 1992).

In soil physics, we know that macropores transport a high percentage of water through soil,
but we are unable to predict their occurrence with our current understanding of field-scale
soil physical properties. While we can distinguish different soil structural components by
observation as being blocky, angular or prismatic, we cannot yet quantitatively relate
macroporosity to these comparatively qualitative soil descriptions. Identifying a "hotspot"
of macroporosity is therefore a very tenuous proposition. However, lack of understanding
of the nature and extent of macroporosity may not be an impediment to the derivation of
land qualities related to water and nutrient movement. In many cases of field
management, macropores are not continuous either from the soil surface downward (due
to tillage and residue management) or to deep depths due to soil structure, rooting depth,
or limited depths of faunal activity. It is important to identify where our inability to
translate across scales inhibits our ability to derive land qualities (as in denitrification
hotspots or introduced organisms), and where is does not (as in macroporosity).
Scale translation failures #1 - factor interactions that produce unique phenomena.

Denitrification hotspots and macropores represent unique phenomena that are produced by the interaction of multiple factors in the soil environment. In biological hotspots, some forcing factor such as root turnover, tillage, or soil frost causes high levels of soil moisture, nitrate and available carbon to converge at one micro location (van Nooordwijk et al. 1993). Macropores represent physical hotspots, and are created by a similar interaction of converging factors of soil formation processes, landscape position, and in some cases management. The interaction of multiple factors to produce unique phenomena, and the external factors that drive these interactions, are difficult to predict and model and act as a major constraint on our ability to translate information from larger to smaller scales.

The interaction of multiple factors to produce unique phenomena can also constrain our ability to translate information from smaller to larger scales. A good example of this constraint has been our inability to predict nutrient outputs from agricultural watersheds with riparian ecosystems. While we have a strong conceptual basis and models to predict which types of watersheds should have high nutrient outputs given particular soils, land use and geologic information (Ritter 1986, Huang and Ferng 1990, Frink 1991, Correll et al. 1992a), it has always been difficult to use these models to accurately predict the importance of riparian ecosystems as modulators of watershed outputs (Dillaha 1989, Smith 1992, Correll et al. 1992b, Muscutt et al. 1993, Osborne and Kovacic 1993). Predicting the importance of these ecosystems is difficult because they are the unique product of interacting factors at the watershed scale.

Riparian ecosystems have unique structure and function due to the interaction of hydrologic, geologic, soil, and biological factors (Lowrance et al. 1984, Peterjohn and Correll 1984, Jacobs and Gilliam 1985, Pinay and Decamps 1988, Simmons et al. 1992, Groffman et al. 1992b, Figure 3). To be able to scale information on nutrient transport to the watershed scale, we will need to be able to understand which factors control the nature and extent of process interactions within riparian ecosystems. These interactions are strongly influenced by whether contaminated surface or ground water interacts with biologically active portions of riparian forests. This interaction is controlled by multiple factors and may produce a very narrow band of riparian ecosystem with a large functional significance. Predicting the occurrence of these narrow bands is difficult given our current understanding of factor interactions at the watershed scale. From a data needs viewpoint, the scale of readily available data bases such as soil survey maps and USGS topographic, surficial geology and ground-water maps, which are typically coarser than 1:24,000, is not fine enough to detect narrow bands of different soil types that vary greatly in their ability to attenuate pollutants. Standard soil survey maps, and geographic information systems based on these maps, lump all these soils into one soil series that is either much wetter or drier than the actual soils in the field. Such lack of resolution in measurement or tabulation of basic soil characteristics limits the sophisticated use of this information as ecosystem processes are studied and modeled. As concluded by Wagenet et al. (1993), "modeling results are sensitive to the nature and quality of input variables at a given scale . . . . interpretation of model output is limited to the resolution and quality of environmental
Figure 3. Cross section of a stream-riparian interface. From Triska et al. (1993).
data”.

Scale translation failures #2 - unknown or overlooked controlling factors.

In addition to failures due to the interaction of factors that create unique phenomena, translating information across scales can also fail when key controlling factors are unknown or overlooked. A good example of this is our inability to predict if introduced organisms will become established in the soil community. It would be very useful to be able to use field-scale information to predict if certain types of organisms or traits will or will not become stable in the soil biological community. Unfortunately, our lack of knowledge of where soil organisms live, what they eat and how they interact limits our ability to make these predictions, or to develop these predictions from basic soil properties or characteristics.

Prospects for rectifying scaling failures.

Failures of scale translation due to either factor interactions that create unique phenomena or unknown and/or overlooking controlling factors limit our ability to model and manage the structure and function of soils and ecosystems. We suggest that failures of scaling can be identified and rectified by iterative interaction between simulation modeling, field experimentation and functional modeling.

All scale translation and modeling involves generalization; making assumptions about what processes are important and what processes and factors can be subsumed. We can only tell if our generalizations are correct by constant validation of our models and extrapolations. Only by iterative testing and reformulation of predictions and extrapolations can we determine where we have overlooked controlling factors, subsumed too much lower-scale complexity, or have multiple factors interacting to create unique phenomena. The work by Juma (1993) on the role of fauna in controlling soil organic matter levels described above, is an excellent example of how models and extrapolations can be developed, tested and refined.

In many cases, especially at large scales, validation is difficult or impossible. In these cases, functional models based on statistical relationships, or conceptual simplifications of more mechanistic models, that test basic assumptions of the models or extrapolations, can be quite useful. For example, we can produce landscape- or regional-scale estimates of denitrification N gas flux, but we have no way of directly validating these estimates. As described above, Groffman et al. (1992a) produced regional-scale estimates of denitrification by extrapolating data from field-scale measurements to larger areas based on relationships between annual denitrification N flux and soil texture and drainage. To validate this extrapolation, they measured denitrification enzyme activity as a proxy for annual denitrification N flux at a large number of sites across the region to determine if the relationship between denitrification and the land characteristics soil texture and drainage was robust at the regional scale. While this was certainly not a direct validation of the region-wide extrapolation, at least the basic assumption behind the extrapolation was tested...
Another example of how functional models and field measurements can be used to rectify problems of scale translation is the use of capacity-type, one-dimensional soil water and chemical transport models to describe the leaching fluxes of field soils (Hutson and Wagenet 1993). In this case, a simplified version of a much more comprehensive mechanistic water and solute transport model was developed to assess leaching over large areas in which soil survey measurements at the 1:24,000 scale were the only available data on soil characteristics. Estimates of potential pesticide leaching over seven states at the scale of 1:250,000 were then produced. This exercise showed that translation from the local to regional scale was technologically possible, but scientifically tenuous given the uncertainties inherent in extrapolating point data to areal estimates of a rate-dependent process such as leaching. The work suggested that only annual, cumulative mass of pesticide exiting the root zone could be estimated at the large scales. Even so the approach and results of this project have been eagerly seized by regulators and planners, perhaps even being used beyond the limits that scientific judgement would consider wise.

Implications for soil data needs.

Soil science has a critical role to play in the solution of many contemporary problems. In many cases, these problems occur at scales above or below those where our knowledge is most detailed and our models are well defined. Addressing these problems stretches the limits of our science and requires making predictions that are difficult or impossible to validate. The iterative interactions between modeling and field studies that are required to maintain a high level of science in these endeavors require a variety of soil data sets (Wagenet et al. 1991). We must be able to provide soil data that ranges from oxygen and nutrient availability at the scale of soil aggregates to remote sensing-derived images of plant-soil interactions across landscapes and regions. We may need to modify basic soil mapping and survey techniques to provide useful data for certain types of investigations (cf riparian zone discussion above, environmental assessments of pollutant transport, degradation rates of xenobiotics, sustainability of soil quality with new tillage and management, etc). Providers of soil data will need to work closely with modelers and field experimenters so that the processes of knowledge generation, modeling and scale translation can go forward in an orderly fashion.
Literature cited.


### Representing Soil Spatial Variability in Geographical Information Systems for Resource Assessment and Environmental Monitoring

**Convener:** Raúl Ponce Hernández. **(Canada)**
**Co-convener:** Gustavo Arévalo Galarza. **(Mexico)**

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GIS Error Models and Visualization Techniques
for Spatial Variability of Soils

Michael F. Goodchild. National Center for Geographic Information and Analysis, and Department of Geography, University of California, Santa Barbara, CA 93106-4060, USA.

Abstract. The paper begins by describing the major data sources, applications, and software characteristics of GIS, and then compares them within a consistent terminological framework that emphasizes the digital representation of continuously varying spatial data. Because the spatial continuum can be discretized in many different ways, and because each necessarily approximates the truth, GIS data are subject to error and uncertainty. The paper reviews the models of error that have been developed in recent years for spatial data and examines their use in GIS. Choice of representation is also driven to some extent by the needs of analysis and modeling, although these have emerged relatively recently. The paper looks at the functional requirements of modeling, and includes discussion of error propagation. The results of GIS are often presented in visual form, and the paper concludes with a review of recent research in visualization of spatial data.

Introduction. A variety of technologies for collecting, handling, and analyzing spatial data have emerged in the past three decades. Of these, GIS in particular is increasingly used in mapping the spatial variability of soils. A geographic information system (GIS) is a somewhat broad and nebulous concept - a system for the input, storage, manipulation, and output of geographically referenced data (for general overviews see Star and Estes, 1991; Maguire, Goodchild, and Rhind, 1991; Burrough, 1986). Although there is wide acceptance of this general definition, the actual specification of a GIS can vary widely depending on the assumptions that its designers are willing to make about its uses. For example, a GIS designed to process only data derived by remote sensing would be very different from one designed to process only data derived from maps.

The purpose of this paper is to develop a general conceptual framework for geographical data, and soil mapping in particular, and to embed GIS within it. Because the technology creates approximate representations of geographical distributions, issues of error and uncertainty are critical to its successful use. The GIS field has developed several apparently incompatible approaches to error description, and the paper presents a general framework for overcoming this significant impediment. Finally, spatial data technologies are inherently visual, and the paper concludes with some observations on the role of visualization in understanding error and uncertainty and their implications.

The Nature of Geographical Data. At the most fundamental level, geographical data can be defined as a collection of facts about places. The atom of spatial data is the tuple \( <x,y,z> \), where \( x \) and \( y \) define a place, and \( z \) some fact about the place, such as soil class. A convenient way to define the difference between spatial and geographical data is to insist that for geographical data, the coordinates \( (x,y) \) be defined by some system of measurement on the Earth, such as latitude/longitude, or the UTM (Universal Transverse Mercator) coordinate system.
Current measurement technologies place fairly coarse limits on one's ability to determine geographical position accurately. A hand-held GPS receiver, for example, can determine absolute position on the Earth to perhaps 1000 sq m, or approximately the area of one arc-second of latitude and longitude, outside the polar regions. The problems of approximating the complex shape of the Earth with simple mathematical functions also place limits on absolute positioning. On the other hand, it is possible to establish relative positions with millimeter accuracy, even over distances of hundreds of kilometers, using modern surveying techniques.

For many types of geographical facts, it is appropriate to conceive of a measurement z being made at a point, or infinitely small area, even though the accuracy of that point's location may be limited. For example, ground elevation can be measured at a point, as can air temperature, rainfall, or atmospheric pressure. Although a rain gauge will average rainfall over a discrete radius, that radius will be much less than the positional error in the location of the rain gauge, and irrelevant in any likely analysis.

For other types of geographical facts, the definition of the value at a point requires an observation over some significant radius around the point. Soil classes, for example, can only be defined over discrete areas that substantially exceed the area covered by any one soil sample, and depend on the specific level in the taxonomic hierarchy. This spatial resolution of the fact should not be confused with the positional accuracy of the point, or with measures of the size of the study area. In a typical example, the positional accuracy of the observation might be 1000 sq m using GPS, while the spatial resolution of soil class might be 1 hectare, implying that it is necessary to observe an area of 1 hectare to determine the soil class recorded at its central point. Unfortunately, neither measure is explicitly defined in much soil mapping practice.

In any discussion of positional accuracy it is common to mix units - some parameters may be expressed as areas, some as radii, and some as diameters. To avoid confusion, area measures will be used consistently throughout the paper. Thus the size of a pixel or raster cell, minimum area of a polygon, and positional accuracy of a point will all be expressed in area measure. In the case of positional accuracy of a point, the measure will express the area of a circle centered on the point within which the true location is assumed to lie with some determined probability.

In this conceptual framework, it is possible to determine the value of any fact z at any location (x,y). For some types of geographical data, such as ground elevation, the value at any location is potentially unique, and thus an infinite number of tuples would be required to capture geographical variation over a finite area completely. In practice, measurement systems determine values only at a discrete number of locations, or adopt other strategies to limit the volume of data that must be handled.

Fields and Entities. Two distinct mental models underlie the various strategies that have been devised for the representation of geographical variation (Goodchild, 1992). In the field view, geographical variation can be conceived as a set of distinct variables \( \{z_1, z_2, \ldots, z_n\} \), each with a precise definition that allows the variable to be measured at any point (x,y).
Mathematically, geography is a multivariate or vector field. Some variables may be measured on continuous (interval or ratio) scales, while others, such as soil class, may be discrete (nominal or ordinal). Because all variables show some degree of spatial dependence or autocorrelation, continuous variables may be differentiable, although ridge lines, cliffs, and faults are obvious sources of exceptions. Similarly, the values of discrete variables may be constant over substantial contiguous areas.

While the field view may be appropriate for rigorous definition and precise measurement, it is generally inadequate for interpretation and many forms of modeling, where it is replaced by the entity view (the terms field and entity have many precise and imprecise synonyms in the geographical data handling field). In this mental model, geography is conceived as an empty space littered with various kinds of objects, with associated characteristics. For example, interpretation of a raw field of ground elevations would yield such topographic objects as mountain, valley, watershed, ridge, pass, or saddle. Interpretation of a raw field of atmospheric pressure might yield high, low, trough, or front. Many models address the behavior of these discrete entities, rather than the continuous fields from which they may have been derived.

In some cases, the derivation of entities may be well-defined. However, not all maxima in a continuous field of ground elevation are significant enough to be called summits - the rule of interpretation is likely to be complex. Definitions of entities often fail to give them precise footprints (the summit of a mountain is often better defined than its geographic limits; there are no precisely defined limits to the Atlantic Ocean) and entities of the same class may overlap (the Gulf of Mexico may be considered part of the Atlantic Ocean) or have hierarchical relationships with each other.

The field and entity views are mental models of geographical variation that allow the mind to comprehend what is potentially an infinitely complex world. In everyday life the entity view is dominant, and reflected in the construction of topographic maps, or the giving of navigational directions. The State of Minnesota is described as having 10,000 lakes, not a continuous field of "lakeness" that can be evaluated objectively at any point on the surface of the state. In science, on the other hand, both views are in common use; atmospheric pressure is captured and recorded by sampling a field, and the field view is reflected in the finite difference simulation models used to predict future conditions; but weather forecasts provide the public with predictions of the behavior of highs, lows, and fronts as discrete entities moving in an otherwise empty space.

Digital Representation. Although fields and entities are useful mental models of real geography, they both contain a potentially infinite amount of information. The digital representation of entities is relatively straightforward. A finite set of point entities can be represented with no information loss as a series of tuples \( <x,y,z> \), and the numerical precision of a digital representation normally exceeds both the positional accuracy of the coordinates and the measurement accuracy of \( z \). A line is conventionally represented as a polyline, an ordered set of points assumed to be connected by straight line segments. Although accuracy can be improved by increasing the density of points, the polyline convention has two significant disadvantages: the length of a polyline is normally less than
the curve it approximates; and it is difficult to estimate tangents or perpendiculars from a polyline representation. Area entities are conventionally represented as polygons, with similar problems regarding the measurement of perimeters, perpendiculars, and tangents.

The representation of fields offers more alternatives, and at the same time raises more problems. Six methods are in common use (Goodchild, 1992):

- randomly located sample points;
- sample points in a regular rectangular array;
- a regular rectangular array of cells, with some aggregate value of the field recorded for each cell;
- a polyline representation of selected isolines (contours);
- an irregular array of triangles, with the value of the field recorded at every vertex, and the field assumed to vary linearly within each triangle (the TIN, or triangulated irregular network model);
- an irregular array of polygons, with the value of the field assumed constant within each polygon.

Although many other representations are possible, such as arrays of hexagonal cells, they have not been exploited to any great extent in geographical data modeling to date.

Each of the six field models creates sets of points, polylines, or polygons, and thus at this superficial level the distinction between field and entity becomes moot within a digital representation. The term "vector" is used to refer ambiguously to all three types of entity models, and all but two of the field models, while the term "raster" refers to the second and third field models. Moreover, any set of non-overlapping entities can be represented as a field whose value is the entity identifier at locations inside an entity, and zero elsewhere.

However, the distinction between entities and fields is critical when the behavior or processing of points, polylines, or polygons is considered. The polygons of a field representation must collectively exhaust the space, and cannot overlap; one polygon cannot be dragged over another during editing, and common boundaries can be moved only as long as they do not intersect other common boundaries. The polylines of a contour representation cannot cross, and adjacent contours must have adjacent values. At a more sophisticated level, the common process of interpolation between a sample of points representing a field, exemplified by the contouring operation, makes no sense whatever if the points are conceived as entities littering an empty space.

Each of the six field models has its own characteristics, and some of these are important in soil mapping. First, only two of the field models are appropriate for discrete (categorical, multinomial) fields: the regular array of cells, termed the "raster" model for the purposes
of this paper, and the polygon model. In both cases the value assigned to each object in the representation, respectively cell and polygon, is assumed to be the most common or modal value of the field within the limits of the object.

Second, only three of the field models include a representation of the value of the field at every point in the plane: the regular array of cells, the polygon model, and the TIN. In the remaining cases (irregular points, regular array of points, and digitized contours) the model must be coupled with some set of rules about interpolation if values are to be determinable at any point in the plane. From an object oriented perspective, it would be desirable to encapsulate the method of interpolation with the data model, but in practice this is rarely done; instead, selection of an appropriate rule or rules is left to the user.

The next section of the paper discusses the traditions of GIS within this conceptual framework.

**Geographic Information Systems.** GIS uses a broad range of data models, and some currently available GIS support all of the entity and field models. In this paper the focus is on soil mapping, conceptualized as a discrete or multinomial field. In GIS, such data may have been obtained by remote sensing or aerial photography, or alternatively by digitizing or scanning an existing map. Thus the field's digital representation may use either the raster or polygon model. The choice may depend on the original source of data (raster is more likely if the data came from a classified photograph, or by scanning a map, and polygon is more likely if the data were created by digitizing a map); the processing software used (some GIS require the raster model for analysis and modeling, and some require the polygon model); the analysis and modeling to be performed; or the preferences of the user.

Thus several options for the representation of a soil map can be found in GIS practice. A raster model may have been obtained by classifying a photograph, or by scanning a map; a polygon model may have been obtained by digitizing a map, or by vectorizing a raster representation. In the raster case the error inherent in the model is attributable to the replacement of the true value at a point by the dominant value in one or a small array (e.g., 3 by 3) of pixels; in the polygon case, the model imposes an error through the replacement of the true value at a point by the dominant value within a polygon of arbitrary size and shape.

Thus both approaches involve information loss. In the raster case, this is imposed by the pixel size, which is likely a characteristic beyond the user's control, and by the perceived need to remove "salt and pepper". In the polygon case, the reasons behind the lumping of space into polygons are more complex, and are reviewed here at some length. In each case, the discussion includes an interpretation of the minimum mapping unit, the area of the smallest polygon in the model.

**Cartographic:** The traditions of map making have evolved under the constraints imposed by available technology. It is comparatively easy to draw a map of homogeneous areas separated by sharp boundaries - the boundaries can be drawn by pen, and the areas can be filled using a variety of forms of shading or by applying prepared textures. It is much more
difficult to portray fuzzy boundaries, or small inclusions within larger areas, or spatially continuous change of any kind. The minimum mapping unit may be the smallest area that can be conveniently drawn and labeled at the planned scale of the map. In addition, area boundaries may be smoothed to create a cleaner appearance.

**Management:** Maps of soils are often made for well-defined purposes, such as agriculture, and the areas shown on them may be managed as agricultural fields. While soils may change continuously, management practice must work within well-defined boundaries, and must be applied uniformly over each well-defined area. The minimum mapping unit may be the smallest area that can be conveniently managed.

**Cognitive:** Much mapping tradition is concerned not so much with the accurate measurement of conditions on the ground as with the communication of an impression of geographic variation; in this interpretation, the cartographer plays a distinct role. It was observed earlier that the entity models have more in common with everyday human spatial cognition than the field models; the polygon model, which blocks space into entities of uniform character, can be seen as a response to human patterns of thinking about geographic variation. The minimum mapping unit may reflect a human need to impose a certain level of uniformity on the landscape.

For some mix of the above reasons, it is common for soil data obtained in the field or by interpretation of aerial photographs to be aggregated into polygons with area greater than some minimum mapping unit. Note that when this strategy is used there is an implicit assumption that the spatial resolution is much less than the minimum mapping unit; if it is not, it is in principle impossible to define the class to which a polygon belongs. Aggregation produces polygons whose value becomes the commonest class observed within the polygon. Other classes which may be present as inclusions contribute to the error inherent in the model, unless they are part of the definition of the class.

**Error models.** For the reasons discussed in the preceding section, it is impossible to create an exact representation of the spatial distribution of a phenomenon as complex as soil within a digital database. At the same time, a digital representation is precise, and capable of giving unambiguous answers to simple queries. This discussion will focus on two particular generic queries, on the assumption that more complex queries can be reduced to them. The two queries of interest are:

- the value of the soil class field at some specified point \((x,y)\); and

- the area of a specified soil class.

In order not to be misled by the precision of answers to these queries, it is desirable that the database respond with some appropriate measure of uncertainty in both cases. In the case of a point query, the response should include not only the class of the containing pixel or polygon, but also some measure of the variation known to exist within the spatial object, whatever its source. In the case of an area estimate, the response should include some expression of confidence limits around the value of the estimate.
Databases containing soil maps are being widely used at this time for purposes such as land use control, and environmental management. If uncertainty is known to exist in the responses to these two generic queries, it is crucial that that information be conveyed as succinctly as possible to the user or decision-maker. It would also be helpful if map displays could also convey some impression of uncertainty, as discussed later in the paper.

For these reasons, there has been increasing interest in accuracy issues in recent years, particularly in the research community. This research follows three distinct threads, which will be discussed here under the headings of classification, cartographic, and spatial statistical. Each offers its own answers to questions of how accuracy should be described and measured, and propagated into estimates of the uncertainty associated with responses to queries. In a much quoted paper, Anderson et al. (1976) proposed that 85% be an appropriate accuracy standard for land cover mapping. The following sections review the various meanings that have been ascribed to that statement, and associated methods of measurement.

**Classification.** In this context, accuracy is viewed as a problem of misclassification. A pixel or polygon is said to be misclassified if its true class, as determined by ground check or from a source of higher accuracy, is $j$, but its assignment by the database is $i$ (in this discussion the terms true or truth should always be taken to imply ground check or a source of higher accuracy; the general term reference data is often used). Pixels or polygons assigned to a class other than their true class are termed errors of omission, or false negatives; pixels or polygons assigned to class $i$ that are not truly of that class are termed errors of commission, or false positives. Note that any one misclassified object can be regarded as either an error of omission or an error of commission, depending on the perspective taken. Story and Congalton (1986) refer to omission errors as producer’s accuracy because the producer’s concern is presumably to avoid them; commission errors define user’s accuracy because a user is interested in knowing how many objects that appear to be of class $i$ are actually of class $j$.

Consider the idealized case discussed earlier, an image of an agricultural area, divided into fields growing different crops. Because of the inherent limitations of data gathering and spatial databases, it is inevitable that some misclassification or confusion of classes will occur, where pixels or polygons falling in fields growing crop $j$ are mistakenly assigned to class $i$. If the data have been obtained by remote sensing, the likelihood that this will happen for a given pixel depends largely on the difference in spectral response of the two crops, and also on the technical efficiency of the classification method used. It is helpful to think of misclassification in the form of a matrix, in which the cell in row $i$, column $j$ gives the number of pixels that are truly class $j$ but have been assigned to class $i$. This matrix has also been called the error matrix or confusion matrix. The term error matrix will be used in this paper.

If the pixels that have been subject to accuracy assessment can be regarded as a random sample of the entire population of pixels, then the entries in row $i$ can be divided by the row total to give an estimate of the probability that a pixel of class $i$ is actually of class $j$, $p(j|i)$. Alternatively, the entries in column $j$ can be divided by the column total to given an
estimate of the probability that a pixel that is actually in class \( j \) has been assigned to class \( i \), \( p(i|j) \). Here, as elsewhere in this approach, it is assumed that the probability of misclassification is constant for a given class over the entire image. In practice, some fields may be more likely to be misclassified than others, because of differences in the growing stage of the crop, and numerous other factors. Several studies (e.g., Campbell, 1981; Congalton, 1988a) have looked at the extent to which errors tend to cluster in space, indicating that the probabilities of errors are not constant.

In order to estimate the error matrix, it is common to conduct a random sample stratified by class. A random sample of pixels classified as \( j \) is selected and checked against the truth. The proportion that are found to be of true class \( i \) is then used to estimate the probability \( p(i|j) \). Stratification is used because some classes tend to be more abundant than others; in order to obtain a reasonably sound estimate of the accuracy in each class, it is necessary to assign a greater number of samples to the rarer classes than would occur if sample points were located randomly. There have been several studies comparing the effectiveness of alternative sampling designs, particularly concerning the number of samples to be allocated to each class in the stratified approach, and the location of samples within areas of each class (e.g., Rosenfield, Fitzpatrick-Lins, and Ling, 1982; Hay, 1979; Fitzpatrick-Lins, 1981; Congalton, 1988b).

Much research effort has gone into devising suitable overall measures to summarize the contents of an error matrix. Let \( x_{ij} \) denote the number of cases recorded in row \( i \), column \( j \) of the matrix, that is, the number of cases where the true class was \( j \) and the assigned class was \( i \). The percent correctly classified compares the number of correctly classified pixels (those appearing on the diagonal of the matrix) to the total number of pixels. In order for this statistic to be meaningful, as an estimate of the probability that a randomly chosen pixel will have been assigned the correct class, it is necessary that the proportion of test pixels in each column (the ratio of the column total to the grand total) be the same as the proportion of total area that is truly of that class. Since this is generally unknown, the proportion of total area assigned to that class is used instead. Thus the row totals, rather than the column totals, are in the same proportions as the observed areas. When a stratified sampling scheme has been used, the totals must be adjusted by weighting each case by the inverse of that class's sampling density.

Unfortunately, and although it is the most obvious interpretation of Anderson et al.'s (1976) recommended 85% accuracy threshold, the percent correctly classified can be a misleading statistic, because a certain number of correctly classified cases are expected to occur by chance, even in the most confused classification. Thus it is often replaced by a statistic which allows for chance, and ranges from 0 in the case of the most confused classification to 1 in the case of the most accurate. Variously known as Cohen's Kappa and KHAT, it is defined as follows:

\[
\text{Kappa} = \frac{\sum_{i=1}^{k} \text{diag}_i - \text{MP}_{ij}}{\left( \sum_{i=1}^{k} \text{corr}_{ij} - \text{MP}_{ij} \right) \left( \sum_{i=1}^{k} \text{obs}_{ij} - \text{MP}_{ij} \right)}/(1 - \text{MP}_{ij})
\]

where a subscript replaced by a dot indicates summation over that subscript, and \( N \) is the total sample size (Congalton, Oderwald, and Mead, 1983; Hudson and Ramm, 1987). Rosenfield and Fitzpatrick-Lins (1986) describe a variant on the Kappa statistic that can be calculated separately for each class; this is especially useful when it is desirable to know the
classification accuracy of each class.

In some applications it may be useful to compare error matrices. For example, a study may compare the effectiveness of two image classifiers applied to the same scene; it is then important to know whether one classifier has outperformed the other. It may also be interesting to compare the effectiveness of a classification to a random assignment of classes, to see if the classifier has done better than chance. For many purposes, a simple comparison of Kappa values is sufficient. But since any error matrix or Kappa statistic is based on a limited sample, one might want to know whether the apparent difference between two Kappa statistics could have occurred by chance, implying that if other samples had been taken, the answer might have been different.

Congalton, Oderwald, and Mead (1983; see Hudson and Ramm, 1987, for corrected equations) describe methods for conducting inferential tests of Kappa, using the methods for testing discrete contingency tables described by Bishop, Fienberg, and Holland (1975). In their simplest form, such tests assume that the entries in the error matrices are strictly the number of times a condition was observed. Weighting, or other numerical manipulation of the table, will invalidate this assumption, and must be dealt with using special variants of the test.

The approach just described relies for its success on the validity of its underlying conceptual model, of areas of homogeneous class divided by sharp discontinuities. This model may apply well to agricultural fields, but in soil mapping it may be confused by continuous variation within more or less homogeneous areas, and slow transitions across boundaries. Both of these lead to a condition described statistically as non-stationarity, in which the error matrix captures only an average over the entire study area; locally, and for a variety of reasons, the probabilities of misclassification may vary markedly. To deal effectively with non-stationarity, it is necessary to partition the study area into regions of more or less constant error probabilities, and to sample them with as many samples as would have been used to characterize the entire study area under stationarity. Moreover, the basis of regionalization is unlikely to be known in advance, although Congalton, Oderwald, and Mead (1983) describe discrete multivariate methods that can potentially be used to identify the factors that cause spatial variation in rates of error.

In addition to the problems of misclassification of spectral response, some pixels will fall on the boundaries between homogeneous patches, and will therefore contain more than one class. Such mixed pixels are not misclassifications in the same sense, and it is common to avoid pixels that straddle boundaries in accuracy assessment and the development of error matrices. Recently, there has been much interest in improved image classification methods that deal explicitly with the mixed pixel problem.
Cartographic. To a cartographer, the problem of map accuracy assessment is perceived very differently. Whether its source was aerial photography or ground mapping, a map of soils shows a set of non-overlapping, space-exhausting areas with homogeneous characteristics, bounded by lines of constant width. In one of the final stages of the map-making process, the boundaries will likely have been smoothed, or splined, to create a pleasing, orderly appearance.

The accuracy of such maps is often seen in terms of two questions:

- are the boundaries in the correct locations; and
- have the areas been assigned to the correct classes?

Hord and Brooner (1976) use this approach in their analysis of land-use map accuracy. The new spatial data transfer standard, now known as Federal Information Processing Standard (FIPS) 173 (see Morrison, 1992, and other papers in that journal issue), refers to these as positional accuracy and attribute accuracy respectively. Positional accuracy can be measured by the Perkal epsilon band, a band of width epsilon centered on the observed location of the boundary, within which the true position of the boundary is assumed to lie (Blakemore, 1984), and Mark and Csillag (1989) have described an alternative probabilistic approach. Attribute accuracy can be described by a form of error matrix, but note that the matrix now refers to the classification of each area, rather than to each pixel. In this approach, the percent of areas correctly classified is compared to Anderson et al.’s (1976) threshold of 85%.

This form of accuracy assessment asks only whether each area or polygon has been assigned to the correct class, and thus ignores the almost inevitable heterogeneity that results from the approximation of continuously varying land characteristics. If an area is known to be heterogeneous, the "correct" class is normally assumed to be the commonest class, but no assessment is made of the occurrence of other classes within the polygon. This approach to accuracy assessment is often referred to as per polygon accuracy assessment, to distinguish it from the per pixel or per point approach of the classification school. Unfortunately, this means that an accuracy assessment based on the cartographic approach cannot be transformed into one based on the classification approach, or vice versa.

The cartographic approach has clear advantages if it is reasonable to assume that areas are homogeneous, and that boundaries are sharp and distinct (crisp). On the other hand the classification approach is clearly more appropriate if areas are heterogeneous, with substantial inclusions of unmapped classes, or if boundaries are indistinct (fuzzy). Chrisman (1989) shows how it is possible using the cartographic approach to distinguish between different sources of error, by observing whether they result in small shifts in boundaries, or in reclassification of entire areas. In reality, some boundaries on soil maps are more distinct than others, and some areas are more homogeneous than others; the distinction is rarely clearcut.

Spatial statistical. From a statistical perspective, error is variation that cannot be explained.
Most forms of measurement are subject to error, and statistics has developed methods for describing the amount of error present, and for analyzing data despite the presence of error.

In the measurement of a simple quantity like temperature, it is conventional to conceive of a true value, which has been distorted to an unknown degree by error. Repeated measurements using different observers, or different measuring instruments, would produce a range of values characterized by a mean and a standard deviation, and often with a histogram that follows the normal or Gaussian distribution closely. A range of well-developed methods allow such data to be analyzed.

The spatial equivalent of the Gaussian distribution is a range of maps, each showing the same general characteristics but with individual patterns of distortion, and each being equally likely to have been observed. The range might represent the work of different interpreters, or the use of different training sites for image classification. An error model is defined as a statistical process capable of generating such a range of maps given appropriate parameters (the Gaussian distribution is the most commonly used error model for simple measurements). Any one such map is termed a realization of the model. Simple measures of error, such as the percent correctly classified, are termed error descriptors, and may be related to the parameters of an error model. For example, the standard deviation, a commonly used measure of measurement uncertainty, is a parameter of the Gaussian distribution.

The use of an error model has numerous advantages. The effects of uncertainty can be visualized by using the error model to simulate a sample of possible maps. Errors can be propagated by performing analysis on several realizations of the error model, and computing the variation in results across them. The parameters of an error model can be calibrated by adjusting them so that the range of outcomes under the error model matches the range observed in reality.

One of the more straightforward applications of soil mapping is in the estimation of areas having particular characteristics. For example, one might want to know the total area of sandy loam in Mendocino County. Knowing that the database includes misclassifications and errors, it would be useful to know the standard error associated with the estimate of area. Unfortunately, neither the classification approach, with its error matrix and Kappa statistics, nor the cartographic approach with its epsilon bands and polygon error matrix, are capable of providing such an estimate. However, given an error model, an estimate of standard error can be made by generating a sample of realizations, calculating area on each, and computing the variation between them.

Several recent papers have described error models for maps, and their use in predicting the effects of uncertainty. Of most relevance to this paper are those that deal with maps of classified land, generally known as area class maps. Goodchild, Sun, and Yang (1992) propose a general error model, and show how it can be used to obtain estimates of uncertainty in such GIS products as area estimates. In their model, the uncertainty associated with the class at any point is represented by a probability vector in a raster representation. Each pixel ij is associated with a vector of probabilities \( \{p_{ij1}, p_{ij2}, \ldots, p_{ijn}\} \).
giving the probability that the pixel truly belongs to each class 1 through n. These probabilities can be interpreted as the consequence of mixed pixels, of uncertainty of class definition, or in remote sensing as the effect of confusion of spectral signatures - in this spatial statistical approach, the origins of error are not of immediate concern. The classification approach described earlier assumes that the contents of the vector are determined by the class to which the pixel appears to belong.

In this model, the classes allocated to the pixels in the database represent one realization of a stochastic process defined by these vectors of probabilities. For example, if there are two classes and the probabilities for a given pixel are \{0.5,0.5\}, then one interpretation might be that in the maps made by two independent observers, one map would assign the pixel to class 1 and the other to class 2. Over a large number of realizations, the proportion of times the pixel is assigned to each class will converge on each class's probability.

In addition, Goodchild, Sun, and Yang (1992) propose that within any one realization, the outcomes in neighboring pixels be correlated, and the model also includes parameters describing the level of spatial dependence. For example, if a large area of many pixels is suspected of being sandy loam, but with a small probability of being clay, a low level of spatial dependence would imply that clay occurs in small inclusions; a high level of spatial dependence corresponds to large inclusions, or to the possibility that the entire patch is clay rather than sandy loam.

The relationship between this model and the error matrix discussed earlier is straightforward: the error matrix assumes that probability vectors are a function only of the class assigned to each pixel in an observed realization, and leaves spatial dependence undefined. The relationship to the cartographic approach requires more detailed explanation.

Consider a fuzzy boundary line between two soil classes A and B. In probabilistic terms, the fuzziness can be represented as a rate of change of probability as the boundary is traversed. Well to one side of the boundary, the probability that a pixel belongs to class A is 1, and the probability of class B is 0. As the boundary is approached, the probability of class A falls, at a rate depending on the degree of fuzziness. Each realization of the stochastic process will assign each pixel to one class, allowing the boundary to be inferred in a position that will vary from one realization to another within the general area of the fuzzy boundary. Crisp boundaries are represented by sharp changes in pixel probabilities as the boundary is crossed; every realization will place the inferred boundary in the same position.

A less general model that omits spatial autocorrelation between outcomes in neighboring cells has been described by Fisher (1991) for soil maps. A general model for raster data has been developed by Haining and Arbia (1993), and Fisher (1992) has used a model of spatially autocorrelated errors in digital elevation models.

In summary, while the classification and cartographic approaches are useful to monitor errors in image classification and map making respectively, they are mutually incompatible,
and only the spatial statistical approach offers sufficient generality to deal comprehensively with the problem of error propagation into the products of GIS analysis, and to provide a bridge between the distinct traditions of remote sensing and GIS.

**Visualization.** The first section of this paper discussed the issues of data modeling, as they affect the representation of fields in general, and soil maps in particular. GIS was seen as making use of two specific representations of multinomial fields: the raster and polygon models. Various forms of approximation and generalization are involved in each of these methods. In the second section, the concept of error modeling was introduced as an approach to allow representation of the uncertainty inherent in each data model, and its incorporation into the reported responses to two basic forms of query.

GIS is a visual technology, and derives much of its value from its ability to present a visual representation of geographical variation. In turn, the human eye and brain are extraordinarily effective processors of visual information, and able to detect patterns, particularly lineations, with great speed and efficiency.

In the classification approach described above, it is conventional to present spatial variation in the form of a display of each pixel’s most likely class. Knowledge of error and uncertainty is captured in aspatial (or spatially stationary) form in the misclassification matrix.

The cartographic approach offers somewhat greater opportunity to communicate knowledge of uncertainty visually. If an area of a given class is known to contain a mixture of some other class, cartographers will sometimes cross-hatch the area with alternating stripes of colors, with widths appropriate to the proportions of each class in the mixture. The regularity of the stripes should be sufficient to discourage any notion in the mind of the map reader that they are real features of the landscape. Other techniques, such as blurring or widening, can be used to express uncertainty about boundary positions.

In general, however, few techniques are available for communicating knowledge of uncertainty. In 1991, the U.S. National Center for Geographic Information and Analysis instituted a research initiative in the Visualization of Spatial Data Quality (Beard, Buttenfield, and Clapham, 1991) to try to respond to a perceived need for improved techniques.

Leung, Goodchild, and Lin (1992) identify three approaches that can be taken to visualization within the spatial statistical approach discussed earlier. First, uncertainty can be hidden by displaying only the most likely class at any point in the plane. Second, a series of displays can be used to show the probabilities of each class at each point. While this approach conveys some information on uncertainty, it fails to deal with spatial dependence, and Leung, Goodchild, and Lin (1992) show that it can confuse the reader by showing a pattern of spatial variation that cannot exist in reality (see also Englund, 1993). Finally, uncertainty can be communicated through the display of a sample of realizations of the error model. Each realization is a possible map, and the reader gains an impression of uncertainty through the variation observed between realizations.
Conclusions. Mapping of soils has a long and largely effective history. However, the issue of error and uncertainty in soil maps has led to two contrasting and potentially conflicting approaches, termed here the classification and cartographic. The two approaches are particularly distinct in the communication of information on map uncertainty to the user.

This paper has proposed a reconciliation of these two distinct traditions, through what has been termed the spatial statistical approach. A soil map is viewed as a multinomial field, a single realization of a multinomial error model. Uncertainty is described through the parameters of the model, and expresses itself in the variation between realizations of the model. The representation of the infinite information present in a field in the discrete space of a digital computer is one significant source of error, together with a variety of other forms introduced at various stages in the data collection and interpretation processes. Uncertainty can be visualized through the parameters of the model, but the most direct and unambiguous way to visualize it is by generating a series of realizations of the model.

Recent interest in conservation, and in environmental change, has led to a renewal of efforts to devise better methods of land surface characterization, of which soil mapping is a significant element. Such mapping will necessarily always fall short of being a precise exercise in scientific measurement, despite the availability of remote sensing. However, the unification of classification and cartographic approaches under a single framework may help to remove some of the problems that have plagued the field in the past.

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Regionalized Variable Theory and Geostatistics for Modelling and Representing Soil Spatial Variability in GIS.

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Introduction  In studies on soil spatial variability an increasing demand is observed to model spatial variability and to use it for a broad range of practical applications (1). Examples include the use of threshold values to be maintained for environmental protection of soil properties (2, 3) and the determination of the effects of land use scenarios for fertilizer and pesticide application (4) Soil properties may be available as maps and as point observations. Several procedures have been proposed in the past to combine prior information with point observations.

Procedures for soil sanitation, however, are still hampered by financial and methodological problems. The potential economical gain of using a well-defined scientific approach can be recognized in the fact that in nearly all sanitation activities, actual costs exceed estimated costs by at least 100%. Part of this problem is caused by the high spatial variability of soil contaminants and can be solved by estimating the volumes of polluted soil, including the associated confidence bounds, in particular using geostatistics (5, 6). In addition, Geographical Information Systems (GIS) offer facilities to allow optimal use of available information, such as of collected field data, advanced pedogenetic information, digitized maps and satellite images, simulation models and furthermore geostatistics. The aim of this study is to analyze the contribution of regionalized variable theory to model spatial variability of point observations, e.g. to calculate exceedance probabilities, and of new developments for using of GIS to combine different sources of information. When analyzing the contribution of GIS, the interactive aspects will be stressed. Special attention is given to spatial variability and the associated consequences for risk evaluation. Following a review of current methodological and practical issues, the benefits of using interactive GIS will be discussed in terms of new scientific contributions as well as improved use of existing methodologies.

Materials and Methods  Two ways to represent soil properties are distinguished (6). Continuous soil properties, such as clay content and depth to soil horizons, are modelled by means of regionalized variable \( Z(x) \), where \( x \) denotes the place dependent of the soil property \( Z \). Discrete soil properties, such as land suitability and drainage classes, are modelled as deterministic information, available on a soil map, which displays a stratification of the area according to major pedological units: \( A = U A_c \). Within a GIS the different sources of information can be combined, and exceedance probabilities can be calculated.

Geographical information systems. A Geographical Information System is a computer system for collecting, storing, retrieving at will, transforming and displaying spatial data (7). The general structure for processing data in a GIS from data collection towards decision making for soil contaminant regulation is presented in fig. 1. This diagram is well in line with intelligent GIS as
Fig. 1. Description of a Geographical Information System for environmental risk assessment
defined by Burrough (8). The main process is indicated by the thick line that runs through the different activities (indicated with sharp brackets) when arriving from the contaminated area towards environmental decision making. In addition four major fields of science, indicated in the text with capitals, can be distinguished, which focus attention on subjects related to soil contamination activities, that are indicated with double brackets.

As concerns activities we distinguished <contaminated area>, <soil stress analysis>, <sampling> and <interpolation>, <risk assessment> and <decision making>. For the latter, four decisions are distinguished: <sanitation>, <isolation>, <leaving as it is> and <norm adjustment>, being the most commonly encountered ones, whereas modifications are possible and alternative decisions may be added. As the major fields of science, marked by shaded boxes are distinguished: i) [GEOSTATISTICS], which provides the basis for <sampling> (sometimes using expert-systems) and for <interpolation>, ii) and iii) [SOIL SCIENCE] and [HYDROLOGY] which on the one hand provide <models> such as «pedotransfer functions» and on the other hand information for <interpolation> and iv) [HEALTH SCIENCES] which provides the basis of the «norms». One may add other disciplines, such as [ECONOMICS], and [INFORMATION SCIENCE], but these fields are not included in this study. The «models» can be either deterministic or stochastic, dynamic or static, and are applied to set, justify and validate the «norms». Model results are interpolated, e.g. using geostatistical procedures. Necessary «model validation» and «sensitivity analysis» is beyond the scope of this paper. Geostatistics may contribute to a sensitivity analysis by means of Monte Carlo procedures like conditional simulations. It is further assumed that <decision making> is based on «risk assessment» and on evaluation of «financial consequences». Several other activities that are known to influence decision making may be distinguished as well.

In recent years much emphasis has been given to building state of the art geographical information systems, including facilities to use models, geostatistics and many forms of digitized areal information (9, 10). Techniques and models have been developed to estimate the risks caused by soil contamination, to model pollution at a micro scale and to develop a knowledge based system for risk identification of soil pollution. Recent geostatistical advances include the development of sampling strategies (11) of methods to calculate probability distributions of exceeding threshold values (12) and of cokriging to better use available soil data (13). Decision support systems have been developed for spatial inventarization of environmental soil properties and of aquatic soils (14, 15). Recent advances include methods to analyze the propagation of error (16) chaos theories (17) and fuzzy classification (18).

Emphasis will be given to interactive elements of Geographical Information Systems, requiring regular feed-back and decision making by skilled experts. Especially if the scientist or the skilled practitioner wishes to make environmental decisions using these systems application at the wrong level of detail, with incomparable scales of measurement or when using geostatistics in an undefined setting, totally incorrect conclusion may be arrived at (19). For a GIS to function in an optimal way it is essential to distinguish the appropriate moments at which interaction is required. These moments are associated with spatial variability, e.g. <sampling> and <interpolation>, with <model selection> and with <risk evaluation>. Interactivity, most often present in a GIS, is especially useful if some knowledge is included in the system as well. If the quality of a decision supporting map is well-defined, for example, a script may be generated to produce the maps. Such a script may contain several parameters to display the effects of different scenarios and to zoom in on sub-areas. An i-GIS may become very complex, even if the aims for application are relatively straightforward. For example, the A-levels applied in soil sanitation studies are based upon the clay and organic matter contents, and hence require calculations at each node where a map is to be displayed.

A statistically sound GIS may focus on aspects of updating existing data, e.g. to display if and if so how many and where additional data should be sampled. Further, data should be
screened on basic statistical properties, as well as on the existence of outlying and spatially deviating data, e.g. data that differ from closely located data points more than some pre-specified value.

Regionalized variable theory When studying soil contamination, one is always confronted with spatial variability of the pollutant. Spatially highly fluctuating patterns are caused by the way the pollutant is spread and the way it reacts with the soil. Spatial variability influences assessment of the risks, as well as the use of spatial analysis procedures to be followed. In order to analyze spatially varying data, one may assume that the observations were subject to unknown influences. These influences can either have a local support, such as the measurement error, but may as well have a spatial support, such as soil genesis, activity of soil biota, soil processes, etc. One approach to analyze spatial variability is to consider the observations as realizations of some random function. This assumption is quite strong, because one will seldom, if ever, be able to take replicate samples: visiting the same location twice may often not be possible, because either the measurement was destructive, or the property to be measured is subject to temporal influences. Measuring at a very short distance from the original location will be subject to spatial variability, that is well known to exist for very short distances as well. Taking replicate samples in the laboratory only yields information about the non-spatial error. So there is not much more left to be done than analyzing spatial variability and making some assumption concerning stationarity.

In this section, therefore, the main concepts of regionalized variable theory will be given. First, the univariate and multivariate random functions will be considered, next increments of a certain order and the stationarity thereof will be defined. Finally the covariance structure between increments will be defined.

Data collected in space may be considered as realizations of a regionalized variable, generated by a random function (20). A regionalized variable in a d-dimensional region S will be denoted by Y(s) where the location in S is given by s. For example, Y(s) may be the moisture deficit for grassland and S an area in the eastern Netherlands. Or Y(s) is the amount of a heavy metal within a volume S of polluted soil. In the first example, attention focuses on the quality of land related to crop yield, d being equal to 2. In the second example, d is obviously equal to 3. A regionalized variable can never be observed everywhere, only at a finite number, say n, of locations. Hence, on the basis of the regionalized variable Y(s), n individual variables are defined in each of the observation locations \( s_i \) for \( i=1,...,n \). The vector of n values \( Y(s_i) \) is denoted by \( Y \).

To be clear: \( Y \) is a vector of random variables, similar to the regionalized variable.

To be able to model the spatial variability, assumptions have to be made about the expectation of the regionalized variable at each observation location. Also, the variability as a function of the distance between two observation points needs to be modelled: observations close to each other are more similar to each other than observations at a larger distance. The most simple form of stationarity is to assume for the individual locations that the regionalized variable has a constant spatial expectation, i.e. each variable at each observation point has the same expectation, and that it does not follow a (say, polynomial) trend. For modelling the spatial variability it is then assumed that the spatial variability can be described with the covariance function \( C(h) \) as a function of the distance vector \( h \).

\[
E[Y(s)]=\text{Constant}=\mu
\]

\[
C(h) = \text{Cov}(Y(s+h), Y(s)) - \mu^2
\]

The main problem with this approach becomes evident upon estimation of the mean and the
covariance function. This is illustrated by assuming that \( n \) observations are collected on the variables at the observation locations. These are denoted with \( y(s_i), i = 1, \ldots, n \). When we assume that the covariance function is given, an unbiased estimate for the mean is given by

\[
\hat{\mu} = (1_n C^{-1} 1_n)^{-1} (1_n C^{-1} y)
\]

where the vector \( 1_n \) is a vector of \( n \) elements, all equal to 1. However, the covariance function is never given, so it has to be estimated from the available data. But we notice from the above equations that for that purpose \( \mu \) has to be given. Therefore, we need \( \mu \) to estimate \( C(h) \) and we need \( C(h) \) to estimate \( \mu \). This problem can never really be overcome. For example, simply estimating \( \mu \) by taking the average value of the observations causes considerable bias.

For this reason, regionalized variable theory has focused attention on the semivariogram and its generalizations. In the absence of a trend in a regionalized (i.e. \( E[Y(s)] \) is constant) the semivariogram \( \gamma(h) \) is defined as half the variance of the differences of the regionalized variable as a function of the distance vector \( h \) between (observation) points:

\[
\gamma(h) = \frac{1}{2} E[(Y(s) - Y(s + h))^2]
\]

Here \( Y(s) \) and \( Y(s+h) \) forms a pair of variables at locations separated by a the distance vector \( h \) and \( E \) denotes the mathematical expectation, taken over the study area. One may notice that only differences between variables are involved, and not the actual locations. When no serious objections can be raise, the semivariogram is assumed to depend solely on the length of \( h \), in which case the stochastic field is assumed to be isotropic.

Observations of a regionalized variable are used to estimate the spatial relationship of that variable. Let observations \( y_1, \ldots, y_n \) be made at the locations \( s_1, \ldots, s_n \), being the realizations of \( Y(s_1), \ldots, Y(s_n) \). To estimate the semivariogram, attention is focused on differences between observations, \( y_i - y_j \) as related to the distance between the measurement points \( h_{ij} = |s_i - s_j| \). In order to estimate the semivariogram for distance \( h \), all pairs of points with intermediate distance approximately equal to \( h \) are formed, of which there are \( N(h) \), say. The \( i^{th} \) pair is denoted with \((y_i, y_{i+h})\), \( i = 1, \ldots, N(h) \). The mean of the squared differences of their observations is calculated as an estimate of the semivariogram for that distance

\[
\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (y_i - y_{i+h})^2
\]

The number of pairs of points in every distance class \( N(h) \) should not be smaller than 30 (6).

Through the pairs \((h_{ij}, \hat{\gamma}_i)\), being the mean of the distances within the \( i^{th} \) distance class and the estimated semivariogram value in this class, a semivariogram model is fitted. Examples include a Gaussian, an exponential or a spherical model. In general, such models are characterized by three basic properties, being the nugget, the sill and the range. The nugget effect is the variation between observations which is not of a spatial nature. It therefore models the variance of the measurement error, the operator bias and the spatial variation at a very detailed scale. The sill, being the limiting value of \( \gamma(h) \) for \( h \to \infty \) (and hence of \( C(h) \) for \( h \to 0 \)) is equal to the variance of the variable. Since many semivariograms increase for increasing \( h \) one may notice that the variance as estimated by the semivariogram takes a higher value than the variance obtained with the traditional estimator, which neglects the spatial character of the variance. The sill is usually
reached for a specific distance, the so-called range of dependence between the observations: if observations are separated by a distance exceeding the range they may be considered to be (spatially) independent.

Mapping the probabilities

Several procedures are described in the literature, that all serve the purpose of mapping probabilities. The two most widely used procedures are disjunctive kriging (4) and multiple indicator kriging (12).

Disjunctive Kriging (DK) aims at obtaining an estimator of the conditional probability at an unvisited location. In DK the probability is conditioned on both the spatial distribution of the variable and on the set of n observations. It is assumed that the observations are obtained from second order stationary random fields. Let n observations \( y(s_i), i = 1, \ldots, n \), be available. The observations are transformed into standard-normal distributed values on the basis of the observed distribution and a sequence of Hermite polynomials \( \sum C_i H_i(Y) \) with coefficients \( C_i \) is determined that represents with sufficient precision the observed distributions. Values of the Hermite polynomials are determined in the observation locations. Next, predictors at the prediction location \( x_0 \), each associated with one Hermite polynomial, are determined by making a linear combinations of the values of the Hermite polynomial at the n observation points. The DK predictor is obtained by adding the predictions of the K individual Hermite polynomials at \( s_0 \) multiplied by the coefficients \( C_i \) obtained previously. The prediction error variances for DK are obtained as well. Finally, the conditional probability that the predicted leaching concentration at location \( s_0 \) exceeds a critical threshold (the cutoff value \( y_c \)) is estimated.

Indicator kriging is somewhat different from disjunctive kriging. On the basis of the observations, a limited number of indicator variables are defined, each associated with one cut-off value. The indicator variables are equal to 1 if the observation exceeds the associated cut-off value and are otherwise equal to 0. Each of the indicator variables is predicted towards the prediction location. The predicted indicator value is an estimate for the conditional probability that the cut-off value is exceeded in this point.

The conceptually most simple form of soil contamination is caused by a single source, the so-called point contamination. An example of a point contamination is waste dump material at a single spot. Spatial variability usually is high with this type of pollution, and it is of a typical non-stationary nature: high concentrations around the source, and gradually decreasing concentrations with increasing distance from the source. If the pollutant is modelled by means of a regionalized variable, \( Y(s) \), \( Y \) being the contaminant and \( s \) the location in the contaminated area, this implies that the variance of the difference of \( Y(s) \), measured at two locations \( s \) and \( s+h \), \( \text{Var}[Y(s)-Y(s+h)] \) is high for locations \( s \) close to the source and is larger at larger distances. For point contamination, therefore, the semivariogram depends on both \( s \) and \( h \). A second form is line contamination, caused by river flooding, spread of contaminated basement materials of roads, etc. The spatial variability typically shows an anisotropic structure, with low changes in variability parallel to the line, and high variability perpendicular to the line, i.e. \( \text{Var}[Y(s)-Y(s+h)] \) is independent of \( s \), being large for \( h \) perpendicular to the line and small for \( h \) parallel to the line. Finally, diffuse soil contamination is distinguished, caused by different sources or by wind deposition. An example is the pollution of a field with nitrate and copper used as fertilizers. Spatial variability of diffuse pollution is likely to be more gradual than spatial variability of point or line contamination, because the pollutant is spread more evenly over the area. For diffuse pollution, \( \text{Var}[Y(s)-Y(s+h)] \) depends on the length of \( h \) only.

Risk evaluation. Risk assessment is defined in terms of critical levels related to the risks for human health. For many substances the so-called A-, B- and C-levels have been defined, based
on multifunctionality: now and in the future the soil quality must be such that the natural functions of the soil remain possible. These levels include a differentiation according to organic matter content and clay content for heavy metals (21). If measurements are below the A-level, the soil is uncontaminated. If measurements are between the A- and the B-level, the soil is lightly polluted. If measurements are between the B- and the C-level, the soil is moderately polluted, and further detailed research is required. Values above the C-level indicate an unacceptable risk for man and the environment, when all potential exposure routes would be operational (22). If observations are above the C-level, the soil is heavily polluted and special treatment is required, for example immediate sanitation. After determination of risks in terms of threshold values, an evaluation of the size of the population at risk is carried out. The effects of a worst case scenario are modelled (e.g. to analyze what happens if a member of the most vulnerable demographic group ingests the maximum possible amount of soil), or an empirical distribution of ingestion and pollution is calculated and Monte Carlo type techniques are applied to obtain a probability distribution of the risks.

Measurements are usually made by means of point observations. Judgements for areas of land are required, stressing the need for interpolation procedures. If several variables are involved, different scales of mapping can be appropriate for different variables. For example, a detailed sampling pattern may have been followed to measure the concentrations of the pollutant (say at scale 1:5,000), whereas soil survey information is available only at a 1:50,000 scale. The latter information may be unusable particularly since point observations are typically representative for small areas of land, whereas soil units are based on what are assumed to be representative profiles for larger areas of land.

Three practical studies on soil pollution were carried out at different scales. At the scale (1:5,000) a detailed analysis of polluted factory premises was carried out. The regionalized variables were the concentration of cadmium and of poly-aromatic organic compounds, and the position of the polluted volume in the total volume of soil, characterized by its starting and its ending depth. A GIS was used to combine the point observations with the organoleptic observations and to visualize the volume of polluted soil, including its uncertainty bounds. The uncertainty of the total cost was determined. At the scale (1:50,000) an inventarization was carried out in an urban area. Pure and mixed samples on lead, copper and zinc were taken at three different depths, which served as regionalized variables in this study. A GIS was used to combine topographical information and information on the sampled areas with maps displaying the spatial variability. A fuzzy clustering to homogeneous strata was applied. At the scale (1:500,000) an inventarization was carried out to the natural constituents of heavy metals in the groundwater. The concentrations served as regionalized variables. The most important explanatory factors were determined, concerning variation in the regionalized variables. A GIS was used to combine geological and soil maps with maps displaying the spatial variability.

Applications to three practical case studies. Three practical cases that were analyzed in the course of this study. The first case involves soil pollution at a fairly large scale, i.e. at an area of 1 to 10 ha. This case is exemplary for small areas of land that are polluted by waste materials. Attention has been given to: (i) the analysis of current practice of soil sanitation, emphasizing determination of the total volume of polluted soil; (ii) the scheme applied for collecting samples and (iii) the use of geostatistical procedures for making probability statements for environmental decisions. The second case concerns a larger area, affected by diffuse air pollution from a single source. Risks for human health are typically associated with consumption of legumes from allotment gardens. These risks are associated with pollution that occurs around industrial estates and large farms where pollution may spread unto surrounding areas. The third case covers an
analysis of the effects of soil stress. Leaching of nitrate and pesticides towards the ground water is described by means of models and land use scenarios. Furthermore, the relation between GIS employing models at a regional scale using the soil map, digital satellite information and modelling of nitrate leaching towards the ground water has been analyzed. The role of GIS for the three cases ranges from a closed, geostatistically advanced raster GIS to an interactive, geostatistically quite simple, vector-based GIS.

**Spatial variability of cyanide pollution at former galvanic factory premises in Vlijmen.** Former galvanic factory premises in Vlijmen in the southern Netherlands were heavily polluted with cyanide. The primary cause of this pollution was leaching of cyanide containing fluids during the galvanization process, but dumping of waste materials at several spots and depths has also been recorded. Within this area of 100 x 80 m² the soil was colored blue at many spots, due to the reaction of cyanide with iron. In 1988 the area was cleaned-up by excavating the polluted soil, guided by organoleptic and laboratory measurements. Laboratory measurements were used in this study to model the spread of the polluted volume. Attention was focused on the unsaturated zone, that extends approximately 3m below the soil surface, although pollution was reported at a depth of more than 70m below the soil surface. A total of 344 observations were made at depths up to 4m below the soil surface. In this area the basic unit consists of layers with thickness of 0.5m, a volume determined by the excavating machines which could handle volumes of soil with size 0.5 x 0.5 x 0.5 m³. Samples were taken using a sand pump with a diameter of 7 cm and a length of 0.5 m. The 2-dimensional sampling scheme was mainly determined by a grid with a 5m mesh, samples were collected at different depths if and when this was necessary to establish the boundary between the polluted and the unpolluted part of the soil volume, the distinction being determined by the B-level (50 g cyanide per kg dry matter).

The main purpose of this research was determining the total volume (V) of polluted soil and the volume (V') of the polluted soil including its 95% uncertainty boundary, which is of importance, a.o. to correctly determine the sanitation costs. During this research, a geostatistical analyses of the available data was carried out. Universal kriging was applied. Data were stored in a raster GIS and spatial interpolation procedures were applied. Effects of spatial variability on soil sanitation processes at a field level were analyzed, including evaluation of the applied sampling scheme.

**Table 1. Summary statistics of cyanide concentrations and effects of spatial uncertainties a the Vlijmen site.**

<table>
<thead>
<tr>
<th>depth</th>
<th>#obs</th>
<th>mean</th>
<th>sd</th>
<th>min</th>
<th>max</th>
<th>V</th>
<th>V'</th>
<th>AV'</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.75</td>
<td>162</td>
<td>145</td>
<td>547</td>
<td>0.1</td>
<td>5400</td>
<td>33</td>
<td>33</td>
<td>6.3</td>
</tr>
<tr>
<td>3.25</td>
<td>38</td>
<td>1016</td>
<td>4385</td>
<td>0.3</td>
<td>27000</td>
<td>24</td>
<td>47</td>
<td>4.4</td>
</tr>
<tr>
<td>2.75</td>
<td>51</td>
<td>275</td>
<td>545</td>
<td>0.1</td>
<td>2300</td>
<td>15</td>
<td>80</td>
<td>6.5</td>
</tr>
<tr>
<td>2.25</td>
<td>43</td>
<td>192</td>
<td>441</td>
<td>0.2</td>
<td>2020</td>
<td>19</td>
<td>22</td>
<td>3.5</td>
</tr>
<tr>
<td>1.75</td>
<td>27</td>
<td>134</td>
<td>210</td>
<td>0.1</td>
<td>720</td>
<td>10</td>
<td>45</td>
<td>6.5</td>
</tr>
<tr>
<td>1.25</td>
<td>23</td>
<td>34</td>
<td>64</td>
<td>0.1</td>
<td>210</td>
<td>0</td>
<td>3</td>
<td>10.9</td>
</tr>
<tr>
<td>Total</td>
<td>344</td>
<td></td>
<td>1539</td>
<td>0.1</td>
<td>27000</td>
<td>17</td>
<td>38</td>
<td></td>
</tr>
</tbody>
</table>

V and V' expressed in percentage of the total volume. 
AV' expressed as percentage of increased precision.
Fig. 2. Predicted volume of polluted soil at the Vlijmen site. Both the upper (fig. 2a) and the lower surface (fig. 2b) are displayed. The actual volume is calculated by subtracting the lower surface from the upper surface.
The volume of contaminated soil in each of the layers was determined by predicting the concentration towards the 0.125 $m^3$ blocks (fig. 2a, 2b). For each layer the blocks where the predicted concentrations exceeded the B-level were added, yielding the volume of polluted soil per layer. Addition of these volumes for the six layers yielded $V$. To determine $V'$, blocks were added where the predicted concentration plus the kriging standard deviation exceeded the B-level.

Summary statistics for the six layers are given in table 1. The pollution decreases with increasing depth, but high values are measured at isolated points in each of the layers. The high value of the standard deviations, as compared to average values, indicate a highly skewed distribution of concentrations. Because the predicted values are expected to be high around the center of the pollution, universal kriging was applied. Because the spatial uncertainty adds to the total volume determined to be polluted, the volume $V'$ is larger than $V$ for each of the layers.

The effects of applying a more regular sampling pattern were analyzed by relocating the measurements over the area and observing the change $AV'$ in the value of $V'$. Notice that the value of $V$ is determined by the actual measurements, whereas the difference between $V$ and $V'$ is calculated by means of the kriging standard deviation, and hence is determined by the spatial structure and the data configuration alone, and not by the actual measurements. The average kriging standard deviation for 250 randomly located observations has been determined. For each layer a reduction in the uncertainty was observed, ranging from 4% to 11%. Despite the relatively large number of observations, the uncertainty of the volume $V$ (expressed by $V'$) remains large, due to the high spatial uncertainty. Therefore it was concluded from this study that observations need to be taken with the smallest possible sample size (support) in order to minimize spatial mixing and hence the associated uncertainty.

In this study the role of GIS did not necessitate interactions. Procedures allowed automated computations without any interaction with experts. GIS was used for visualization of calculated volumes of polluted soil, using advanced geostatistical procedures in the context of measured, quantitative pollution levels.

**Cadmium pollution in the Kempen area.** The soil of the Kempen area in the south-eastern part of the Netherlands and the adjacent north-eastern part of Belgium is polluted with cadmium and zinc (23). The pollution was caused by nearby zinc factories, which began operating in 1892 and until 1973 have produced an uncontrolled discharge of cadmium and zinc. During this period a highly contaminating thermic production process was applied. An area of approximately 60 $km^2$ in the Netherlands and of 140 $km^2$ in Belgium was surveyed during the 1980s. The Dutch part is located around the municipalities of Budel ($\pm 18$ $km^2$) and Weert ($\pm 40$ $km^2$), approximately 10 km east of Budel.

In this part of the survey, 2020 allotment gardens were sampled to measure the cadmium content of the topsoil, i.e. 0-30 cm below the surface (24). Each sample consisted of a mixture of 8 cores taken from the same garden. Of these observations, 43 were coded as 'missing', but were in fact measurements below the detection limit of 0.4 mg/kg dry matter. For the subsequent geostatistical analysis 1781 observations have been used, the other 196 data, selected at random, were reserved in advance as a test set to measure the effects of using prior information on an independent data set. The data were stored in a raster GIS.

The first purpose of this study was to contour the cadmium content. This was difficult because the majority of the observations were just above the detection limit, causing large variability without much spatial structure. The second purpose was to test the significance of the distance from the allotment gardens to the factory and the distance from the gardens to zinc cinder roads as explanatory variables for the amount of cadmium. The third purpose was to evaluate the necessary number of observations to extend the inventarization to neighboring municipalities, being the major cost factor in this analysis.
In the municipality of Budel the cadmium contents were on average 1.5 times as high as in the municipality of Weert. According to the guide lines for soil sanitation practices, in 28% of all the cases there was no pollution, in 71% of all the cases there was a light pollution and in 1% of the cases there was a moderate pollution. A stratification of the study area was applied.

The spatial variability was modelled by means of semivariograms. Ordinary kriging was applied to map the cadmium contents (fig. 3a). Next, stratified semivariograms were determined for each of the two strata. In order to compare stratified kriging with ordinary kriging, predictions towards the points in the test set were carried out. The mean squared error (MSE), defined as the average of the squared differences between observations and predictions, and the mean variance of the prediction error (MVP) were calculated (table 2). An overall MSE value of 0.186 remained more or less unchanged irrespective of use of prior information (0.191 and 0.189, using stratification according to municipalities and to zinc cinder roads, respectively). However, the largest gain was observed when focusing attention on the individual strata: an MSE value of 0.170 for the strata within 100m of a zinc cinder road and an MSE value as low as 0.083 for the relatively homogeneous stratum of Weert. Finally, multiple indicator kriging was applied to determine the probability distribution of cadmium at unvisited locations. A map was produced displaying probabilities that the B-level (2.5 mg cd per kg dry matter) is exceeded (fig. 3b). The interpolated map shows values ranging from below 1 ppm to approximately 8 ppm, without assigning any precision to this map. The probability map of exceeding the B-value, however, is based upon the interpolated values for threshold values. It shows probability close to 0 outside the two municipalities, due to the low standard deviation. Close to the urban centers in the region, higher probabilities are calculated (even close to 1) for the B-level to be exceeded. Several isolated spots at a larger distance from the two urban centers were distinguished also that have clear positive probabilities, but generally the two maps show a similar pattern. It depends upon the application which of the two maps is most suited.

Sample spacing was determined as a function of the average kriging standard deviation. It appears that the 1400 observations in Weert could be reduced to, say, 100, without seriously affecting the precision of the interpolated map. This number is sufficient to properly estimate the semivariogram (6) In contrast, denser sampling might be needed for the Budel area to obtain a map of sufficient precision. Extension of the current sampling schemes to neighboring municipalities should be based upon the most likely distribution of the pollutant: for a spatial distribution comparable to that of Weert, a far less intensive sampling scheme may be applied than by a spatial distribution comparable to that of Budel. If the sampling scheme distributes the observations more or less evenly over the area, predictions with a sufficient precision may be obtained.

<table>
<thead>
<tr>
<th>Stratification</th>
<th>MVP</th>
<th>MSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstratified</td>
<td>0.26309</td>
<td>0.18644</td>
</tr>
<tr>
<td>Municipalities</td>
<td>0.23770</td>
<td>0.19149</td>
</tr>
<tr>
<td>Budel</td>
<td>0.40943</td>
<td>0.35332</td>
</tr>
<tr>
<td>Weert</td>
<td>0.12215</td>
<td>0.08259</td>
</tr>
<tr>
<td>Zinccinder roads</td>
<td>0.20486</td>
<td>0.18940</td>
</tr>
<tr>
<td>Present</td>
<td>0.36883</td>
<td>0.17057</td>
</tr>
<tr>
<td>Absent</td>
<td>0.09706</td>
<td>0.20178</td>
</tr>
</tbody>
</table>

709
Fig. 3. Two maps of the cadmium polluted area in the southern Netherlands. The first map shows the predicted cadmium amount, the second map shows the probabilities that the 5 ppm threshold value is exceeded.
The analysis of the usefulness of deterministic information in this area showed a significant reduction of the cadmium content with increasing distance from the zinc forge in the municipality of Budel. This significance does not extend to the municipality of Weert, probably because the measured concentrations were lower, and hence were more likely to be influenced by accidental influences than by the distance from the factory. The cadmium contents are significantly influenced by both the distance from the factory (at least in the municipality of Weert) and by the presence of zinc cinder roads.

GIS was used in this study for interpolation and visualization purposes. An interactive use of GIS to critically evaluating the effects of sampling density during data collection would have lead to a considerable reduction in costs. This study shows that a combination of a GIS and statistical and geostatistical procedures may provide valuable information that extends well beyond the scientific frontier.

**Spatial variability of nitrate leaching applied to fertilizer scenario calculations.** Nitrate and fertilizers are applied on a broad scale by farmers all over the world. Determination of the optimal amount is a major issue: too little nitrate leads to sub-optimal yields, whereas excessive application leads to leaching to the groundwater and hence pollution. National governments regulate the maximum allowable amount of nitrate and fertilizers. To do so, scenarios for nitrate application have been developed, depending upon land use and soil type. A GIS was applied in this study to measure and visualize the effects of land use scenarios.

In the center of the province of North-Brabant in the Netherlands six fertilizer scenarios were compared to model the effects of land use types on the amount of nitrate leaching to the ground water, representing current and forthcoming limitations on the use of fertilizer and manure imposed by the national government, all of the fertilizer scenarios had been developed by the governmental institutions.

The nitrate leaching model RENLEM served as the basis of the study. To apply RENLEM, spatial information in the form of soil maps, a classified land use map and groundwater maps were necessary. In addition, soil profile data for each soil unit, obtained from the soil map legend, were applied to obtain the sequence of the soil layers, the thickness of the soil layers, and per layer organic carbon content [%], pH, loam content [%] and bulk density [kg/m^3]. The maps were generalized to handle the large number of combinations appearing on the three maps: the 1:50,000 soil map, originally showing 31 units, was generalized to 8 major soil types on the basis of pedogenetic and soil physical properties of the units. The ground water level map of the same scale was generalized from 7 to 2 different units, by distinguishing only the wet soils (original classification GT 2-5) from the dry soils (original classification GT 6-7; for a legend of GT classification refer to (26)). The classified land use map of the Netherlands contains 17 different map units. By combining different units 8 forms of land use remained. Generalization was carried out using GIS. After generalization, the maps were combined, resulting in a relatively complex map with 128 different mapping units, of which 105 had a positive area (Table 3).

The fertilizer scenarios applied in this study are based upon the Decree for Using Animal Manure, established by the Dutch ministry for the environment VROM. Scenario 1 applies to current land use. The scenarios differ from each other in respect to the time of the year for application of fertilizer on grass (spring or autumn), the type of animal manure (pig or cow), the change in atmospheric deposition as compared to the current amount (100% or 50%) and the so-called BGDM-phases which impose limitations on the use of animal manure for different types of land use, the so-called P-levels (Table 4b). The P-levels are a strong limit on the use of animal manure for regions which are sensitive for nitrate leaching. The active period indicates when the regulations are in effect.
Table 3. Sizes of the different areas stratified according to soil type, land use and water table class (WT)

<table>
<thead>
<tr>
<th>SOIL</th>
<th>WT</th>
<th>grass</th>
<th>arab</th>
<th>maize</th>
<th>agric</th>
<th>pine</th>
<th>decid</th>
<th>heather</th>
<th>road</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ia</td>
<td>1</td>
<td>15.4</td>
<td>2.3</td>
<td>10.6</td>
<td>0.0</td>
<td>0.0</td>
<td>3.9</td>
<td>0.0</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1155.4</td>
<td>192.6</td>
<td>680.1</td>
<td>99.8</td>
<td>66.1</td>
<td>74.8</td>
<td>2.2</td>
<td>132.2</td>
</tr>
<tr>
<td>Ib</td>
<td>1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1108.1</td>
<td>133.9</td>
<td>621.9</td>
<td>125.2</td>
<td>456.6</td>
<td>180.4</td>
<td>6.9</td>
<td>284.1</td>
</tr>
<tr>
<td>Ic</td>
<td>1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>77.1</td>
<td>5.4</td>
<td>44.5</td>
<td>23.1</td>
<td>181.9</td>
<td>33.6</td>
<td>12.8</td>
<td>64.8</td>
</tr>
<tr>
<td>Id</td>
<td>1</td>
<td>236.9</td>
<td>20.5</td>
<td>92.0</td>
<td>11.4</td>
<td>4.4</td>
<td>11.6</td>
<td>0.3</td>
<td>67.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>458.6</td>
<td>69.6</td>
<td>302.8</td>
<td>61.4</td>
<td>13.0</td>
<td>29.6</td>
<td>2.2</td>
<td>200.7</td>
</tr>
<tr>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10.3</td>
<td>0.8</td>
<td>16.2</td>
<td>5.8</td>
<td>2.9</td>
<td>2.8</td>
<td>4.9</td>
<td>16.6</td>
</tr>
<tr>
<td>III</td>
<td>1</td>
<td>1017.9</td>
<td>185.2</td>
<td>584.9</td>
<td>84.0</td>
<td>8.2</td>
<td>37.9</td>
<td>0.6</td>
<td>198.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>39.6</td>
<td>10.0</td>
<td>33.3</td>
<td>1.8</td>
<td>0.2</td>
<td>3.75</td>
<td>0.0</td>
<td>33.1</td>
</tr>
<tr>
<td>IV</td>
<td>1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>9.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>10.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>9.7</td>
<td>3.9</td>
<td>3.1</td>
<td>4.6</td>
<td>152.9</td>
<td>5.4</td>
<td>5.3</td>
<td>19.1</td>
</tr>
<tr>
<td>V</td>
<td>1</td>
<td>3.2</td>
<td>0.6</td>
<td>9.2</td>
<td>2.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>15.0</td>
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<tr>
<td></td>
<td>2</td>
<td>527.7</td>
<td>47.7</td>
<td>467.3</td>
<td>84.0</td>
<td>30.6</td>
<td>34.3</td>
<td>0.9</td>
<td>476.8</td>
</tr>
<tr>
<td>urban</td>
<td></td>
<td>17.8</td>
<td>0.0</td>
<td>1.8</td>
<td>19.8</td>
<td>3.6</td>
<td>1.0</td>
<td>0.4</td>
<td>315.0</td>
</tr>
<tr>
<td>assoc.</td>
<td>1+2</td>
<td>236.8</td>
<td>40.6</td>
<td>140.6</td>
<td>25.4</td>
<td>6.4</td>
<td>12.6</td>
<td>2.9</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Soil types:
- Ia. Haplaquod with peaty top soil (shallow peaty podzol soil)
- Ib. Haplaquod with hydromorphic characteristics ('Veld' podzol soil)
- Ic. Haplaquod without hydromorphic characteristics ('Haar' podzol soil)
- Id. Haplaquod with a thin anthropogenic top layer ('Laar' podzol soil)
- II. Haplorthod (Moder podzol soil)
- III. Humaquept ('Beek' earth soil)
- IV. Udipsamment (Vague soil)
- V. Plaggept ('Enk' earth soil)

Land use types:
- Arab. Arable land
- Agric. Other agricultural land
- Pine Pine forest
- Decid. Deciduous forest
Table 4. Description of the six fertilizer scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Phase</th>
<th>Fertilizer on grass</th>
<th>Manure on maize</th>
<th>Atmospheric N-deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>spring</td>
<td>pig</td>
<td>100%</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>autumn</td>
<td>pig</td>
<td>100%</td>
</tr>
<tr>
<td>III</td>
<td>1</td>
<td>spring</td>
<td>cow</td>
<td>100%</td>
</tr>
<tr>
<td>IV</td>
<td>3</td>
<td>spring</td>
<td>pig</td>
<td>100%</td>
</tr>
<tr>
<td>V</td>
<td>P</td>
<td>spring</td>
<td>pig</td>
<td>100%</td>
</tr>
<tr>
<td>VI</td>
<td>1</td>
<td>spring</td>
<td>pig</td>
<td>50%</td>
</tr>
</tbody>
</table>

*Amount of nitrate applied for the different phases, stratified according to land use:

<table>
<thead>
<tr>
<th>Phase</th>
<th>Grass</th>
<th>Maize</th>
<th>Farm</th>
<th>Other Farms</th>
<th>Forest/Heather</th>
<th>Active period</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>250</td>
<td>350</td>
<td>125</td>
<td>70</td>
<td>0</td>
<td>'87-'91</td>
</tr>
<tr>
<td>III</td>
<td>125</td>
<td>125</td>
<td>125</td>
<td>70</td>
<td>0</td>
<td>'95-</td>
</tr>
<tr>
<td>VI</td>
<td>110</td>
<td>75</td>
<td>70</td>
<td>70</td>
<td>0</td>
<td>P-susceptible areas</td>
</tr>
</tbody>
</table>

Table 5. Calculated leaching for scenarios I-VI for each soil type

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Area</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ia</td>
<td>20.9%</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Ib</td>
<td>47.4%</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Ic</td>
<td>3.6%</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Id</td>
<td>13.4%</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>0.4%</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>0.3%</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>1.9%</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>12.1%</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Land use

| Grass   | 46.4%| 6 | 6  | 6   | 5  | 5 | 5  |
| Maize   | 28.5%| 6 | 6  | 7   | 2  | 2 | 2  |
| Farmland| 6.8% | 6 | 6  | 6   | 6  | 3 | 5  |
| Other farming | 5.1% | 2 | 2  | 2   | 2  | 2 | 2  |
| Pines   | 8.7% | 2 | 2  | 2   | 2  | 2 | 1  |
| Deciduous forest | 4.1% | 1 | 1  | 1   | 1  | 1 | 1  |
| Heathland| 0.4% | 2 | 2  | 2   | 2  | 2 | 1  |

1 = 0 - 50 4 = 150 - 200 7 = 500
2 = 50 - 100 5 = 200 - 250
3 = 100 - 150 6 = 250 - 500

leaching in [kg N/ha.y]
Table 5 summarizes the calculated nitrate leaching for different soil types, forms of land use and water tables. Application of scenario 2 leads to slightly increased nitrate leaching, whereas application of scenario 3 shows an even greater increase. Scenarios 4 and 5 give the strongest reduction in nitrate leaching, which in particular apply to maize crops (covering 28.5% of the area) and, to a lesser degree, to other arable crops (covering 6.8% of the area). Scenario 6, focusing on reduced output, does not show any substantial effects. Because none of the other forms of land use are substantially affected by a choice for any of the scenarios, it could be recommended to apply scenario 5, putting strong limitations on the maximum amount of fertilizer for each different land use forms. In respect to the soil types, the calculated differences are minor. The only conclusion that could be drawn was that the Veldpodzol and Haarpodzol soils (soil types Ib and Ic) as well as the Enkeerd soils (soil type V), covering almost 70% of the area, are somewhat less sensitive for nitrate leaching than the other soils.

A GIS is an indispensable tool for this type of studies. First, it was necessary to link spatial information with a nitrate leaching model. A tractable number of combinations of land use and soil type was obtained. Available maps of a regional scale can be managed. Next, it provided possibilities to combine expert knowledge concerning soils and satellite images with land use scenarios. And finally it was helpful for the visual display of the effects of applying land use scenarios.

The procedures followed in this study are appropriate at a regional scale. Spatial variability within the combined mapping units, however, is as yet not accounted for. This study applies to the regional level. Making decisions at this level as a next step involves economical, political and social considerations as well.

Discussion. A GIS is necessary to choose an appropriate method of sampling, of interpolation and to properly select models. Current research shows that interaction with experts could be replaced by expert systems. The first step towards a GIS with expert systems is currently being developed for spatial sampling. These systems were not applied in the case studies above. The expert system SOILSURD (14) was developed to supply optimal sampling schemes, optimality being defined in terms of economic costs and minimized variance. This system mimics the statistical expert on design of a sampling scheme. A statistical expert system may be useful for studies similar to the first case. Optimal designs can be determined for each separate layer. Minor adaptations are required to include prior information on the spread of waste materials such as debris and the remnants of old buildings and the physical requirements of the sanitation devices. It might be interesting, but probably less successful, to apply a statistical expert system to studies comparable to the second case, e.g. to determine an optimal scheme to measure the average pollution in, say, a municipality. But the presence of many physical obstacles could prove prohibitive. It may be used successfully, however, to define a sampling scheme for each garden separately, yielding different random schemes for the different gardens, an approach to be realized using global positioning systems. In contrast to the first two cases, a study comparable to the third study should be modified completely to allow the use of a statistical expert system. As long as soil units are determined on the basis of the representative profile without taking replicate samples within units, little to no benefit may be expected. On the other hand, a soil scientific expert system including the rules applied by a soil surveyor when deciding upon the optimal location for a representative spot, might be far more beneficial.

In the three cases analyzed in this study, point data were interpolated towards areas of land. Current interpolation procedures either apply a geostatistical approach (1st and 2nd case), or apply another carrier of spatial information, like the soil map (3rd case). A crucial interactive point during the processing of data in a GIS is distinguished when a choice for geostatistics is weighed against the use of a soil map (compare 2nd and 3rd case, which both focus at problems at the
regional scale). In the 2nd case, little gain was to be expected from the use of soil maps, because the deposition was mainly caused by wind contamination, and cadmium does not interact so much with the (sandy) soils that show little pedogenetic variation. In the 3rd case, however, where nitrate leaching to the ground water was analyzed, the different soil types have a larger impact on the amount of final mapping and the maps in a generalized form were used successfully.

When applying geostatistics, identification of the stationarity of the pollutant is of importance as is illustrated by the first case. It was fairly obvious that some form of non-stationarity was likely to exist, especially since the pollution was expected to be high around the center of the terrain and typically lower at larger distances from the center. Procedures to determine the probability distribution at unvisited locations must exist as well, as was demonstrated by the second case. Such maps may yield a substantial contribution to environmental decision making, for example to the issuing of certificates of being uncontaminated, if the area is with ε% not polluted or proceeding with cleaning-up activities as long as the value of α is less then 50. It should be decided, however, where the critical limit should be placed: a $P = 95\%$ certainty that an area is clean (and allowing a 0.05 probability that the C-level is exceeded), requires a different modelling of risks than a $P = 99.9999\%$ value, that is accepted for other risks (such as ionizing radiation), and necessitates the use of extreme value theory.

Risk analysis is for the larger part determined by the levels that protect the environment from too high stresses of heavy metal loads, fertilizers and pesticides. In each of the three cases these levels have been used. During an environmental investigation a geostatistical analysis of the data is usually appropriate in the stage that sufficient observations are available to estimate the semivariogram. On the one hand the levels that are to be predicted are important, but exceedance probabilities of each level are important as well as was shown in the second case. Risk evaluation is up until now completely characterized by environmental and health standards, providing a most valuable means to apply geostatistics. Such standards allow a quantitative analysis of the risk of soil contamination and soil stress, in particular by means of probability statements.

Conclusions. The advantage of using a GIS is most evident for studies of a relatively large area, for which much prior information is available. For the very small areas, closed computer systems will yield information with a sufficient level of precision and the additional information obtained by interaction is likely to be insignificant. If many comparable small sites are investigated, however, details of the individual sites may be collected in a database, hence requiring interactivity when combinations are made using a GIS.

Research of soil sanitation activities is supported by translating scientific results into a decision making process. Of particular importance is the choice for an appropriate level of aggregation within a GIS. The development of expert systems to determine sampling schemes is a first step. These systems could function in an optimal way, if an on-line access is established between the many engineering stations, the national centers for the environment and the scientific research stations.

Further development of GIS should aim to mimic the total process of soil sanitation from the recognition of a polluted area to the moment of sanitation. One is inclined to choose a particular scale, say the large scale cases as exemplified by case 1. Such a system must possess the possibilities to include different alternatives, as mentioned in fig. 1. It must include soil, hydrological and economical models as well and should be flexible enough to include many practical limitations. It would be extremely complex, but it would offer a substantial support in solving important real-world problems.

Studies carried out at different scales showed that the choice for the observations was of particular importance for dealing with spatial variability. Different uses of GIS at different scales
stressed the universal applicability of flexible information systems.

Acknowledgement This study was carried out with a grant from the Netherlands Integrated Soil Research Programme (PCBB). The authors wish to express their gratitude to the Engineering offices Oranjewoud, Oosterhout, and DHV, Amersfoort, and to the Open University for providing the data sets applied in this study.

Literature cited


A World Soils and Terrain Digital Database: Linkages

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Introduction.

As a significant and dynamic component of the Earth system, soil has come to the forefront of the environmental agenda during the past decade as it has never done previously. Whether we are considering soil as a source and sink of greenhouse gases, a contaminant of water resources, a medium for the production of food for a rapidly expanding human population, a non-sustainable resource under current management systems, or a site of environmental degradation, the community of soil scientists faces a formidable challenge to provide credible, usable and timely soils information to resource managers and policy-makers.

As members of the first human generation to have the tools to study the Earth as a system, we soil scientists must address seriously our obligation to provide to the user community the kinds of data and information about soils resources which that community needs to make rational decisions about resource and environmental management and policy. In this context, "user community" may be defined as any individual, group, organization or agency (local, national, regional, global) whose decision-making processes require an input of information about soil resources. These information requirements for a specific user might be quite simple, e.g. percent organic matter for a selected local soil, or they might be complex, e.g. fate of a specific pesticide applied to a soil, including the persistence and rate of chemical change of the pesticide.

The requests for digitized soils data (cartographic and descriptive) have increased dramatically during the past five years as government agencies and industries have developed GIS capabilities and wish to add soils data layers to their resource databases. These requests are coming from users who may need different spatial scales ranging from detailed local scales to global scales. Often, when soil scientists cannot meet the demands for digitized soils and other resource databases, these demands may be filled by contracting with those who may know GIS technology quite well but have a limited understanding of soils and problems associated with transferring soils data from one spatial scale to another and who have no understanding of the many different soil classification systems.

For soil science, the year 1986 was important in a decade of important "global change" events. Early that year the U.S. National Aeronautics and Space Administration (NASA), after two decades of research and development of Earth observing systems and collaborative support of both domestic and international scientists, announced its new thrust--"Earth System Science: A Program for Global Change." In its schema illustrating the components, processes and interconnectedness of the Earth system, NASA displayed prominently the role of soils (1).
In August 1986 at the 13th Congress of the International Society of Soil Science (ISSS) in Hamburg, approval was given to a proposal to develop a world SOils and TERrain (SOTER) digital database at a scale of 1:1 M. This approval by the ISSS was a reaction in part to the fact that questions related to the environment and global change had finally reached the top of both the political and scientific agendas. Society had begun asking for credible environmental information from the science community and for effective action from political decision-makers. Both groups began to focus more attention on questions of environmental degradation, sustainable development, toxic threats in the environment, global deforestation, ozone depletion, desertification and global warming. At the Hamburg Congress, ISSS also established a Working Group under Commission V on a World Soils and Terrain Digital Database.

Another event in 1986 important to the soil science community was the creation of the International Geosphere-Biosphere Programme (IGBP) by the International Council of Scientific Unions (ICSU) during its Annual Meeting in September of that year. With a permanent secretariat in Sweden, IGBP since its inception has initiated and organized many different core projects, working groups, and international meetings to consider a broad range of changes occurring in the Earth system.

Perhaps the IGBP core project which is of greatest interest to soil scientists is the Global Change and Terrestrial Ecosystems (GCTE) project. Of the 27 IGBP Global Change Reports which have been published since 1986, five are of particular significance to the soil science community.


Each of these activities, events and publications emphasize the importance of the linkages which soils have with all other major components of the Earth System and to the importance of soils in buffering change and/or in healing the scars caused by natural disasters or human intervention. One of the serious failures of the soil science community is that we have failed to deliver to resource decision-makers and policy-makers a unified, standardized, accurate, reliable relational soils and terrain digital database at all of the spatial scales necessary to serve the information needs for local, state, national, regional and global planning and modeling.

An important message which continues to emerge from many activities related to improving our understanding of the Earth system and to the monitoring and assessment of terrestrial ecosystems is the critical need for a more reliable, relational global database for soils and terrain. One of many expressions of this need is exemplified by a Workshop in 1992 sponsored by the IGBP-DIS (Data and Information System) which brought together an international, interdisciplinary group of scientists representing the soil science community and the global modeling community (7). The objectives of this workshop were to a) appraise the global coverage, nature and reliability of soils information; b) initiate a dialogue between global change modelers and soil
scientists; c) consider the strategy for creating a global, georeferenced database of pedon data suitable for global change modeling studies, and d) consider the methodology for scaling up from local to regional to global data sets.

**Materials and Methods.**

*Development and Testing of Procedures for Implementing SOTER.*

With funding provided by UNEP, the SOTER Project began in 1987. From the beginning of the Project, a clear decision that SOTER would not seek to develop a new system of soil classification has been strictly followed. Rather, the concept for creating a SOTER world soils and terrain database has been to use any existing soils and terrain maps which meet the quality requirements of SOTER, regardless of the classification system used for generating the map. One of the first tasks of SOTER was to establish a standard procedure to be used for (a) translating soils cartographic and descriptive data into a universal legend and (b) correlating cartographic and descriptive soils and terrain data across political boundaries.

The first SOTER Procedures Manual (8) was used at a workshop in Montevideo for training participating soil scientists from Argentina, Brazil and Uruguay to translate and correlate existing soil maps for a pilot area of 250,000 km² in those countries.

Another of the early tasks of the SOTER Project was to identify the soils and terrain parameters or characteristics which are required for inclusion in the SOTER Database. An initial list of these parameters was developed. This list of parameters has been tested extensively in the field and has been modified with each new revision of the Procedures Manual.

After being tested in the field in several countries and four revisions of the SOTER Procedures Manual, the 1993 version of the Manual, now considered operational, was issued as a common publication of UNEP, FAO, ISSS, and ISRIC (9). FAO is preparing its own issue that will appear in its World Resources series.

**Cartographic Base for SOTER Database.**

At the time of the generation of most existing soil maps, no thought was given to the idea that they might one day be digitized and integrated into a geographic information system (GIS). The SOTER database is a GIS and in the future will be integrated with numerous other layers of spatial data, possibly including data representing geology, hydrology, topography, climatology, demography, vegetation, land use, and socio-economic parameters. This integrated use of soils and terrain maps requires that cartographic accuracy be followed to the greatest extent possible and feasible. The conversion of many existing soil maps to meet acceptable cartographic quality standards is not a trivial matter.

One of the early considerations for SOTER was that of selecting a cartographic base of acceptable quality to serve as a base map to which soil maps could be registered and integrated. The SOTER Project accepted the recommendation of the Joint Working Group of the
International Geographical Union and the International Cartographic Association (10). The mission of this working group was to select from among available 1:1 M world maps, the most appropriate one for a world digital database for environmental science (WDDES). The map which was selected by the Joint Working Group was the Operational Navigation Charts (ONCs) series developed and published by the Defense Mapping Agency (DMA) of the United States. Although the decision was made in 1988 by SOTER management to use the DMA/ONC map series as a 1:1 M map base for SOTER, the ONCs were not yet in digital format. Since that time, the DMA let a contract to have the ONCs digitized, and the complete digitized set was published in 1992 and made available on compact disks (11).

Results and Discussion.

SOTER Activities Since the 1990 International Soil Congress.

During 1991 and 1992 progress was made in the continuing testing and revision of the SOTER Procedures manual and in the solicitation of financial support to expand the SOTER Project.

In 1993 three new SOTER studies were initiated. In March 1993 a SOTER workshop met for training and formulation of an implementation plan for the development of a SOTER database for Kenya (KENSOTER). This two-year project is being financed by FINNIDA (International Development Agency of Finland) and UNEP and executed by the Kenya Soil Survey and ISRIC.

In 1993 funding to support an extension of the LASOTER project was approved by UNEP. The Instituto Nacional de Tecnologia Agropecuaria (INTA) in Argentina and the Dirección de Suelos y Aguas (DSA) in Uruguay, together with ISRIC, will expand the area covered by previous Project activity to 460,000 km² in Argentina and to a full coverage of Uruguay, upgrading the existing database according to the new Procedures Manual. SOTER procedures will be applied at a scale of 1:100,000 in a window of about 7000 km² in each country.

The first country in Europe for which a SOTER database will be implemented is Hungary. HUNSOTER is to be executed by the Research Institute for Soil Science and Agricultural Chemistry of the Hungarian Academy of Sciences (TAKI). One of the objectives of HUNSOTER is to test the multipurpose applicability of the SOTER database.

Several other countries have expressed an interest in the SOTER concept. SOTER methodology will be implemented in Bolivia in a natural resources mapping and land use planning project. Project proposals have been formulated for SOTER implementation in Russia and other countries in Central and Eastern Europe. The development of a SOTER database for North America is under consideration.

Another important activity in which the SOTER Project (ISRIC) is involved is the revision of the FAO-Unesco Soil Map of the World (FAO, 1974) for Central and South America, a joint project of UNEP, FAO and ISRIC. This revision is to be coordinated by FAO. The effort will include the creation of a SOTER database for the continent at a scale of 1:5 M with correlation activities implemented by ISRIC.

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Data and Information Management for the SOTER Project.

Since the initiation of the SOTER Project with financial support from UNEP, coordination and management of the Project has resided at ISRIC. The level of funding has determined the rate of expansion of SOTER into other countries and regions of the world. Now that the 1993 version of the SOTER Procedures Manual is available and has been accepted by FAO as an operational document, it is anticipated that the rate of SOTER activities and expansion may accelerate.

Global Change Data and Information System.

As a part of the U.S. Global Change Research Program (GCRP), a U.S. government Interagency Working Group on Data Management for Global Change (IWGDMGC) was founded in 1988 to establish inter-agency linkages and to coordinate environmental data management among agencies. The goal of the U.S. Global Change Data and Information Management Program is to make it as easy as possible for researchers and others to have ready access to and use of global change data and information. Soils and terrain data will eventually become an important component in the directory of data sets accessible through this Program.

Two U.N. agencies with strong interests in soils and terrestrial ecosystems are FAO and UNEP. Since 1960 FAO has played a key role in promoting and providing technical leadership in national and global soil mapping (12, 13, 14, 15, 16). During the past decade both of these agencies have moved to develop their capabilities in GIS and digital cartography. The FAO-Unesco Soil Map of the World has been available in digitized format for at least five years. For global modelers who wish to integrate soils data into their models, this digitized Soil Map of the World is essentially the only soil map available. For many objectives of the modelers, this digitized map does not provide the quality or detail about soils which the modelers require.

In 1985 UNEP established GRID (Global Resource Information Database) to provide an environmental data management support service to UNEP, to other UN specialist agencies, international organizations and national governments (17). Through a network of cooperating centres in Brazil, Japan, Kenya, Nepal, Norway, Poland, Switzerland, Thailand and the United States, GRID archives, collates and disseminates information in digital format extracted from maps, satellite images, aerial photographs, statistical tables and other sources.

Current Global Soils Modeling Activities.

Since the creation of IGBP in 1986 there has been an increasing demand for the integration of disparate data sets of environmental data. This has resulted in a proliferation of global modeling activities in universities, research institutes, and in national and international government agencies.

Numerous global modeling efforts involving the use of soils data have been initiated during recent years. Some of these studies use point data only, especially in the modeling of the variability of soils as sources and sinks of carbon (18). Others use the digitized FAO-Unesco
Soil Map of the World or other digitized soil maps to derive a wide range of national and global thematic maps and descriptive data, such as distribution of soil carbon, status of land degradation, variability of soil productivity potential, agroecological zoning and other themes. Some use relational databases which attempt to integrate both spatial and point data (19).

Call for Completion of a 1:1 M World Soils and Terrain Digital Database in This Century.

Expressions of the need for a 1:1 M world soils and terrain digital database come from many quarters.

1. The Global Change Research Community. A development in 1993 of importance to soil scientists was the signing of a Memorandum of Understanding (MoU) by four agencies of the United Nations (FAO, UNEP, Unesco, WMO) and the International Council of Scientific Unions (ICSU). Under the MoU, the signatories agreed to cooperate in the scientifically based design and planning phase of the Global Terrestrial Observation System (GTOS). GTOS is expected to be complementary to and mutually supportive of GOOS (Global Ocean Observation System) and GCOS (Global Climate Observation System).

The long range objective of GTOS will be to provide the observational framework and data basis for a) detection and understanding of the impacts of regional and global change on terrestrial and freshwater ecosystems, including their biodiversity, as well as responses of ecosystems to such change and of their role in causing change; b) evaluation of the impacts and consequences of global change on terrestrial ecosystems components and the environment; c) forecasting, prediction and early warning of future terrestrial changes and their impacts; and d) validation of global models of ecosystem processes and change.

One of the data sets essential to GTOS for accomplishing its mission is a global dataset for soils and terrain. At all spatial scales of sampling or observing components and processes in terrestrial ecosystems, soils are intimately related to variability and stability/instability of an ecosystem. An understanding of the physical, chemical and biological properties and processes in soils is essesential for quantizing the contributions which soils make to changes in the Earth system.

Global change modelers continue to document the need for more reliable and complete global data sets, including those of soils and terrain (20, 21, 22, 23, 24).

2. International Development Organizations and Agencies. It has only been during the past two decades that the technology has emerged which allows us to acquire, analyze and interpret remarkable quantities of data about land resources. Recently the CGIAR (Consultative Group on International Agricultural Research) has expressed a serious interest in having access to the SOTER Database to supplement the remarkable datasets about agricultural resources which more than a dozen international agricultural research centers around the world have acquired in their research during the past thirty to forty years.

3. National Soils and Environmental Management Agencies. Early results from the SOTER Project have brought numerous requests from participating countries for completion of the
translation, correlation and input of soils and terrain data for their entire countries into the SOTER database. Other countries have initiated proposals for the inclusion of their soils and terrain maps to be included in the SOTER database.

For many countries the SOTER methodology provides a model for procedures which can be used to develop national soils and terrain digital databases at a more detailed scale than the SOTER global database.

Even in highly developed industrial nations where detailed soils maps are available, the challenge continues to be to find more efficient and effective means of delivering desired soil information to those who need it. In the U.S. a large and long-term investment is being made in developing a relational soils database accessible to users electronically from their remote computer terminals for delivery of soils map and descriptive information at three levels of detail (25):

1. Scale: 1:1 M, national level database, known as NATSGO
2. Scale: 1:250 K, state level database, known as STATSGO
3. Scale: 1:15,840 or 1:20,000, local level database, known as SURGO

Improving Future Delivery of Better Information on Global Soil Spatial Variability.

The number of scientists, agencies, academic institutions and research centres with interests in spatial modeling of Earth resources at national, continental and global scales is increasing rapidly. The disciplines involved in this modeling and their objectives are diverse. A SOTER world soils and terrain digital database will fulfill the need for one of the important components of the Earth system. The availability of such a database is imperative for the credible representation of spatial variability of global soils and terrain resources. In preparing for the implementation of an operational SOTER, planners must take into account several important factors.

Factor 1. Accessibility of data. In recent years the commercialization of and proprietary restrictions which deny access to natural resources data have placed severe restrictions on the development of uniform, standardized complete global databases. The future of SOTER is dependent upon the open and free access to soils and terrain data on a global basis. Another issue related to accessibility is the continual change and improvement of data storage and reading media. Many datasets acquired and archived just a decade ago are no longer easily accessible because current technology for storing and reading the datasets is not able to access the archived data. It is important that this serious problem be addressed.

Factor 2. Integration of data. Many examples of governmental agencies which have undertaken projects requiring a combination and harmonization of data from many sources, different disciplines, and a wide range of spatial and temporal scales can be cited. A study of several national and global projects, each of which required the integration of disparate data sets, was recently released by the U.S. National Academy. This study provides recommendations which address the major problems encountered in the integration of disparate data sets related to changes in the environment and the human contribution and response to such change.
In the implementation of SOTER it must be clearly understood that SOTER data (cartographic and descriptive) will be integrated with many other databases (geology, hydrology, topography, demography, land cover, land use, economics, other) for a broad range of objectives related to global change, land productivity, land degradation, global carrying capacity, global warming, sustainable development and other resource management problems. In the process of integration of soils and terrain data with other datasets, every effort must be made to preserve as much as possible the true representation of soil spatial variability and the relationships of that variability with other data layers with which the soils data are being integrated.

Factor 3. Global linkages. Increasing consideration and effort is being given to establish national and global information "super highways." A considerable amount of progress has been made in the conceptualization, design and prototype testing of networking of environmental databases nationally and globally (26, 27, 28). With the rapid progress which is being made in electronic transmission of large data files, it is reasonable to envision the capability within the next decade of including SOTER and other resource databases in global networks for easy access by an interdisciplinary, international community of users.

Factor 4. Role of remote sensing in data acquisition for SOTER. Aerial photography and images from sensors on polar-orbiting Earth observation satellites provide invaluable data for detecting and delineating mappable soil differences. A limited amount of research has been reported on the use of reflective bands of spectral data from meteorological satellites for the study of soil patterns. However, from the few studies which have been reported, positive results have been suggested in delineating meaningful soils differences at reconnaissance levels with reflectance data from the AVHRR (Advanced Very High Resolution Radiometer) of the NOAA-10 (National Oceanic and Atmospheric Administration) satellite with its spatial resolution of one km. This scale lends itself to use for SOTER in those areas of the world where adequate soil mapping has not yet been completed. It is important that more research be conducted in a wide range of geographical and soil regions. The very modest cost of AVHRR data, relative to that of other satellite images, makes it an attractive source of data for soil studies.

Literally tens of thousands of satellite multispectral images from all land areas of the world at spatial scales ranging from 10 to 80 meters are in archival storage and may be useful to the SOTER Project in the future. These images may be used to supplement or instead of aerial photographs for delineating spatial variability of soils in those areas where there are inadequate or no soil maps.

Factor 5. Relational soils and terrain databases. It is important that from soils and terrain databases accurate relationships can be drawn between the cartographic data or spatial variability and the differences in chemical, physical and biological properties of soils among different mapping units. It is also important that the database management systems be so designed that relationships can be derived among soils and terrain datasets at different spatial scales, ranging from detailed maps to reconnaissance soil surveys. This is an area which requires much more research. The SOTER procedures provide the linkages of the universal legend for the
cartographic data and descriptive data with the classification system with which the soils were originally mapped. These relationships must be preserved and expanded.

Factor 6. Global modeling. Currently there is an active and diverse global modeling community. However, as emerging hardware/software/methodology technologies become more easily available and easier to use, the number of scientists engaged in modeling components and processes in the Earth system can be expected to increase dramatically. During the past decade great emphasis has been placed on the development of spatial database technology, both hardware and software. More attention is being shifted now to the use of spatial databases with multiple layers of resource data as tools for decision-making and policy-making. In a real sense, global modeling is taking on two different meanings. One is the modeling of the Earth system. The other is the "global" use of these emerging technologies to model ecosystems, biomes, or watersheds from local to global scale. Research is needed to address the efficient transfer to and use of this technology by the user community for "modeling" their databases and improving their decision-making.

Factor 7. Changing and emerging technologies. It goes without saying that hardware, software, and methodologies related to the design, structure and use of spatial databases will continue to change. It is difficult to imagine what the capabilities of the technology will offer ten years hence. However, the SOTER database and its management system must be designed so that they may be upgraded and updated as the technology advances and when it is appropriate to do so.

Literature Cited.
Creation and use of a European Soil Geographic Database

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Abstract

For the Commission of the European Communities (CEC), in particular its Directorates General of Agriculture (DG VI), Environment (DG XI) and Research (DG XII), a thorough knowledge of soils and their use and protection is of vital importance. European agronomic research is carried out with this objective in mind, and has led to the publication of the 1:1,000,000-scale Soil Map of the European Communities (EC) in 1985.

This map was largely based on national soil data collected as part of an unfinished FAO program started in the 1970s. However, for reasons of supra-national harmonization, only part of the data could be used. Since then, the CORINE program (DG XI) has digitized the soil map, finishing version 1.0 in 1986. It was intended to use specific parameters for thematic subjects, such as zonation of erosion susceptibility of southern Europe, or the creation of agro-meteorological models as part of the MARS project (DG VI).

As the digitizing of the map provided insufficient data, a version 2.0 was made by incorporating the remaining, unpublished, data from the FAO archives. Since then, the database was further modernized by adding new attributes for a better characterization of mapping and typological units, resulting in version 3.0. Pedotransfer rules were also developed, using expert-judgement input, to estimate parameters that are needed for answering thematic problems such as erosion and pollution. This database, which is managed by a Geographic Information System, is under constant development by the "Soil and GIS" CEC Support Group.

Recently, the CEC has decided to extend the database to cover Central and Eastern European countries and to develop it using the same strategy as that adopted for the EC countries. The final aim is to obtain a spatialized soil database that is valid for all Europe.

It is also obvious that it is becoming increasingly imperative to achieve harmonization with the other main World programs, such as those operated by FAO and UNEP.

I - Introduction

Problems of land use and soil conservation require increasingly accurate information on the properties and geographical location of soils. An important point is to obtain harmonized data for highly diverse regions (12, 21). In Europe, as part of the activities of the Commission of the European Communities (CEC), the knowledge of soils, and their use and protection, mainly concern the Directorate General of Agriculture (DG VI), but also the Directorates General of Environment (DG XI) and of Research (DG XII).

Until recently, spatial soil data were mainly available as paper-printed soil maps, which are graphically constrained and thus cannot hold an infinite quantity of information. They also have to present a simplified view of reality in order to be readable. Finally, most users will agree that maps are commonly correct, but still may be difficult to read (31, 34).
It is well known that a general knowledge of soil distribution within a given area is one of the basic requirements for natural resources evaluation. European programs of the CEC on soil knowledge and management are included in such wider-ranging programmes as:

- in agricultural production domain (DG VI), by means of the Soil Map of EC at 1:1 M., and the MARS project
- in environment domain (DG XI), by means of CORINE program, now European Environment Agency.

In this paper, we will discuss the main steps that were taken to create the European Soil Geographical database in the framework of these two major programmes.

II - The Soil Map of the European Communities

For many years, agronomical research was organized by DG VI in different Programme Committees with precise objectives, coordinated by the Permanent Committee of Agronomical Research (PCAR). The Programme Committee for Soil Science first was called "Land Use" and later became "Land and Water Use and Management". Between 1972 and 1985 it worked successively on the following points: 1) inquiries in EC countries to define the main problems affecting land management; 2) drafting of the EC Soil Map (scale 1:1,000,000); 3) organization of "Workshops" where soil conservation took an increasingly important place; 4) introduction of computerization in data processing; 5) research into land evaluation, land degradation and conservation

Before dealing with the European Soil Geographic Database, a short historical description of the soil mapping effort is needed, the present 1:1,000,000 scale EC Soil Map being the fruit of more than 30 years work.

1952 Studies are made of the different soil classification systems in Europe, with a view to eventual harmonization and common work.
1965 The first result was the publication of the FAO soil Map of Europe at scale 1:2,500,000 (13).
1970s Work started under the auspices of FAO on the Soil Map of Europe at scale 1:1,000,000. The legend was designed at the same time as that of the World Soil Map at scale 1:5,000,000, which was published in 1975 (14).
1974 Because of financial problems, the work was stopped by FAO and the map has never been published. However, the archives were stored until now.
1978 The CEC (DG VI) decided, with agreement of the FAO, to revive the work for the countries of the European Communities.
1985 Publication of the present Soil Map of the EC at scale 1:1,000,000 (7). In 1986, the territories of Austria and Switzerland were added to the map at the initiative of UNESCO and the International Soil Science Society (8).

III - The EC geographic database for soil landscapes

The main objective of CORINE (Coordinated Information on the European Environment - DG XI) is the creation of a Coordinated Information System on the state of the Environment and Natural Resources of the European Communities. This implies setting up a homogeneous framework for collecting, storage, presentation and interpretation of environmental data on the EC countries (4). Another major programme that needs soil data is the MARS project of DG VI (Monitoring Agriculture by Remote Sensing), which includes different "Actions", especially Action 3: making yield-forecast models (25). To make new (or improve existing,) agrometeorological models, MARS needs databases on physical and agronomical conditions, which in themselves depend on the use of remote-sensing data to monitor crop and forecast yields.
3.1. Version 1.0 of the spatial soil database. The CORINE programme resulted in the computerization of the EC Soil Map in 1986, constituting the first spatialized soil database (Version 1.0). This work consisted in digitizing contours and indicating, for each polygon, the number of the corresponding soil association and the nature of the possible phase. No more data were used than were drawn on the map. This database thus was created as part of research into, and the storage and handling of soil parameters that must be considered for both agricultural production and land protection. Several versions were made, considering the increasing needs of these domains, but the first version of the database was rapidly applied to two major problems that required the use of multi-parameter combinations:

- A first project (DG XI CORINE programme) tried to make a zonation of the southern part of the EC, in terms of susceptibility of soil to erosion, associated with another zonation dealing with land quality. The methodology consisted in combining the principal factors of Wischmeier's "universal equation of earth losses" with a procedure adapted to Mediterranean conditions. The climatic erosivity 'R' was estimated from specific indexes; the erodability of soils 'K' was calculated from values attributed to texture, depth, stoniness and organic matter; and the slope 'S' was ranked as 4 classes. Combination of the three values leads to 3 classes of "potential" erosion risk; combined with two values of vegetation cover this then gives 3 classes of "actual" erosion risk. This work made it clear that the existing base at that time was far from complete.

- The second problem requiring zoning concerned "Buffering" capacity and susceptibility to acid rain. Here, zoning was based on the primary attributes of the first version of the database, and mainly on the FAO soil name. Swedish scientists compiled the necessary data from "EFTA" Europe, including data from the older 1:5 M-scale World soil Map. Different geological types, soil types, land uses and amounts of rainfall were combined with a weighting procedure in order to obtain 5 broad classes of relative sensiveness, related to critical load values.

3.2. Version 2.0 of the spatial soil database. To provide satisfactory answers to the problems as stated the database had to be improved. A ready source of additional data could be found in the archives (Table 1), stored at Ghent University (Belgium), which had not been used because of map harmonization. Data on parent material and percentage of land-use were among the new attributes introduced, leading to an improved Version 2.0 of the soil database, whose main attributes were:

FAO Soil Name (7, 14); Topsoil texture class (1: Coarse to 5: Very Fine); Slope (a: Level to d: Steep); Phase (7); Parent Material (10); Land Use (10); Surface percentage of STU in SMU.

Table 1: Example of the data available in FAO archives

<table>
<thead>
<tr>
<th>EC Soil Mapping Unit number</th>
<th>Soil Typological Unit (FAO)</th>
<th>Composition (%)</th>
<th>Texture</th>
<th>Slope</th>
<th>Phase</th>
<th>Elevation (m)</th>
<th>Parent material</th>
<th>Land use</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>Bd</td>
<td>90</td>
<td>2</td>
<td>c</td>
<td>Stony lithic</td>
<td>300-600</td>
<td>Residual stony loam from schists</td>
<td>Forest, pasture, arable land</td>
</tr>
<tr>
<td>57</td>
<td>Lgs</td>
<td>75</td>
<td>4</td>
<td>c</td>
<td>Stony lithic</td>
<td>250-400</td>
<td>Residual loamy clay of marl</td>
<td>Arable land, pasture, forest</td>
</tr>
<tr>
<td>58</td>
<td>Ql</td>
<td>80</td>
<td>1</td>
<td>c</td>
<td>Stony lithic</td>
<td>300-450</td>
<td>Residual sand of sandstone</td>
<td>Forest, arable land</td>
</tr>
<tr>
<td>8</td>
<td>Lo</td>
<td>75</td>
<td>2</td>
<td>c</td>
<td>Stony</td>
<td>250-380</td>
<td>Residual stony loam</td>
<td>Pasture arable land</td>
</tr>
</tbody>
</table>
The geographical database consists of three geographical "objects" (29): 1) mapping polygons that show the geometry of soil units; 2) Soil Mapping Units (SMU) that contain polygons of the same soil type; 3) Soil Typological Units (STU) formed by the main soil types contained in the SMUs. SMUs and STUs are respectively described in two tables, showing horizontally the list of units and in columns the attributes describing such units.

As part of the MARS project, the combination of specific soil parameters led to the first draft of a Water Storage Capacity Map needed for agrometeorological models (26). However, this map was not really satisfactory and demonstrated that the existent database was not still sufficient.

3.3. The "Soil and GIS" EC Support Group. The database as described above and managed by a Geographic Information System (6), was progressively created by a Support Group of the CEC called "Soil and GIS", organized by the MARS project. The participants were experts of different EC countries and the main objectives were:
- Selection of Pedological Factors that interfere with spatial and temporal yields variations.
- Discussion about the suitability of Models in relation with Data Precision.
- Proposals for further work to complete the available information from soil maps and associated databases (new "Attributes").

3.4. Version 3.0 of the spatial soil database. The database has been improved by adding new attributes that enable a better characterization of the Mapping and the Typological Units (Version 3.0). These new attributes are:
- Depth to textural change (classes from 1: 20/40 cm, to 5: No change)
- Subsurface textural class (classes from 1: Coarse, to 5: Very Fine)
- Obstacle to roots (classes from 1: no obstacle, to 4: between 20 and 40 cm)
- Presence of an impermeable layer (classes from 1: absent, to 4: within 40 cm)
- Water regime (classes from Dry to Very Wet (10))
- Water management (10)
The only national input were the data earlier produced by the EC countries and stored in the Ghent archives. In many countries, however, the state of knowledge on the soil landscape had seen considerable evolution since the original work was undertaken. National consultations were therefore needed and the relevant part of the database was sent to soil scientists in each country, for review, correction and update. In several countries this led to a complete recompilation of large parts of the map; in other countries the changes needed were less fundamental.

In addition to this major correlation effort, an analytical database of soil profiles for the most representative units of the European territory was designed, and is in the process of being created (30).

Figure 2: The different steps in creating the EC Soil Geographic Database.

IV - Creating a knowledge database

A method was designed for translating data stored in the database into data needed for environmental purposes (10, 35). This method is based on the concept of pedotransfer function (3). Due to the qualitative nature of the data, such functions are simple tables and we call them "pedotransfer rules". The combined pedotransfer rules are like an expert system that enables automatic interpretation of the soil map and its associated database. The advantage of this method is that interpretations are explicit and can themselves be managed in a database, which we call a knowledge database. The rules can be
updated when necessary, either by adding new data in the future, or on the basis of particular features of certain regions.

4.1. Output attributes. Pedological output attributes were selected on the basis of the environmental parameters needed for the problems faced, e.g.: the hydrology of soil types for predicting catchment response to rainfall and a standard percentage of run-off; the location and sensitivity of wetlands; soil buffering capacity for predicting soil susceptibility; vulnerability of ground and surface-water to pollution by agrochemical products and farm waste; soil erosion potential, etc. Table 2 gives an overview of the attributes required to develop expert systems for the derivation of thematic maps of major environmental parameters. The attributes selected for this work are listed in Table 3. They are grouped into four classes that correspond to attributes of biological, chemical, mechanical and hydrological nature. For each output attribute of the pedotransfer rules, we have indicated the necessary input attributes for making the estimates.

Table 2: Attributes required to establish a database of major environmental parameters.

<table>
<thead>
<tr>
<th>ENVIRONMENTAL PARAMETERS</th>
<th>ATTRIBUTES REQUIRED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicting catchment overflow hazard</td>
<td>- Depth to a slowly permeably layer</td>
</tr>
<tr>
<td></td>
<td>- Depth to a gleyed horizon</td>
</tr>
<tr>
<td></td>
<td>- Hydrogeologic class</td>
</tr>
<tr>
<td></td>
<td>- Presence of a raw peaty topsoil</td>
</tr>
<tr>
<td></td>
<td>- Maximum packing density</td>
</tr>
<tr>
<td>Location and sensitivity of wetlands</td>
<td>- Hydrogeologic class</td>
</tr>
<tr>
<td></td>
<td>- Soil-wetness class</td>
</tr>
<tr>
<td></td>
<td>- Depth to a slowly permeable layer</td>
</tr>
<tr>
<td>Soil-buffering capacity</td>
<td>- Depth to bedrock</td>
</tr>
<tr>
<td></td>
<td>- Topsoil-texture class</td>
</tr>
<tr>
<td></td>
<td>- Maximum CEC class</td>
</tr>
<tr>
<td></td>
<td>- Maximum base saturation</td>
</tr>
<tr>
<td>Vulnerability of groundwater to pollution by agrochemical</td>
<td>- Soil class</td>
</tr>
<tr>
<td>products and farm waste</td>
<td>- Hydrologic class</td>
</tr>
<tr>
<td></td>
<td>- Topsoil-texture class</td>
</tr>
<tr>
<td></td>
<td>- Depth to bedrock</td>
</tr>
<tr>
<td></td>
<td>- Depth to a gleyed horizon</td>
</tr>
<tr>
<td></td>
<td>- Depth to a slowly permeable layer</td>
</tr>
<tr>
<td></td>
<td>- Soil adsorption capacity</td>
</tr>
<tr>
<td></td>
<td>- Soil porosity class</td>
</tr>
<tr>
<td></td>
<td>- Presence of a raw peaty topsoil</td>
</tr>
<tr>
<td>Vulnerability of surface water to pollution by agrochemical</td>
<td>- Slope class</td>
</tr>
<tr>
<td>products and farm waste</td>
<td>- Hydrogeologic class</td>
</tr>
<tr>
<td></td>
<td>- Depth to a gleyed horizon</td>
</tr>
<tr>
<td></td>
<td>- Depth to a slowly permeable layer</td>
</tr>
<tr>
<td></td>
<td>- Soil adsorption capacity</td>
</tr>
<tr>
<td></td>
<td>- Soil porosity class</td>
</tr>
<tr>
<td></td>
<td>- Presence of a raw peaty topsoil</td>
</tr>
<tr>
<td>Soil-erosion potential</td>
<td>- Slope class</td>
</tr>
<tr>
<td></td>
<td>- Topsoil-texture class</td>
</tr>
<tr>
<td></td>
<td>- Topsoil organic carbon content</td>
</tr>
</tbody>
</table>
### Table 3: Name and classes of selected output attributes with their required inputs.

<table>
<thead>
<tr>
<th>OUTPUT ATTRIBUTES</th>
<th>INPUT ATTRIBUTES</th>
<th>OUTPUT (CLASSES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topsoil organic carbon content (0-25 cm)</td>
<td>FAO soil name - Regrouped land-use class</td>
<td>H(igh): &gt; 6.0%</td>
</tr>
<tr>
<td>Presence of a raw peaty topsoil</td>
<td>FAO soil name</td>
<td>Y(es)</td>
</tr>
<tr>
<td>Soil-profile differentiation</td>
<td>FAO soil name</td>
<td>H(igh): 1.1-2.0%</td>
</tr>
<tr>
<td>Topsoil mineralogy</td>
<td>Parent material - Type of differentiation</td>
<td>Chemical or Geochemical (MC): Chemical and Mechanical (ND): No Differentiation</td>
</tr>
<tr>
<td>Topsoil cation exchange capacity</td>
<td>Topsoil-texture class</td>
<td>L(ow): &lt; 15 cmol(+).kg(-1)</td>
</tr>
<tr>
<td>Subsoil base saturation</td>
<td>FAO soil name - Regrouped land-use class</td>
<td>M(edium): 50-75%</td>
</tr>
<tr>
<td>Subsoil cation exchange capacity</td>
<td>Subsoil mineralogical class</td>
<td>H(igh): &gt; 50%</td>
</tr>
<tr>
<td>Subsoil base saturation</td>
<td>FAO soil name - Subsoil mineralogical class</td>
<td>H(igh): &gt; 75%</td>
</tr>
<tr>
<td>Depth to bedrock</td>
<td>FAO soil name - Phase</td>
<td>S(hallow): 0-40 cm</td>
</tr>
<tr>
<td>Depth to a gleyed horizon</td>
<td>FAO soil name</td>
<td>S(hallow): 0-20 cm</td>
</tr>
<tr>
<td>Depth to impermeable layer</td>
<td>FAO soil name - Subsoil packing density</td>
<td>S(hallow): &lt; 80 cm</td>
</tr>
<tr>
<td>Hydrologic class</td>
<td>FAO soil name - Elevation</td>
<td>D(eeep): 80-120 cm</td>
</tr>
<tr>
<td>Available water capacity of topsoil</td>
<td>Topsoil-texture class</td>
<td>V(ery) H(igh): &gt; 190 mm</td>
</tr>
</tbody>
</table>

**BIOLOGICAL ATTRIBUTES**

- FAO soil name
- Regrouped land-use class
- Accumulated mean temp.

**CHEMICAL ATTRIBUTES**

- M(edium): 2.1-6.0%
- V(ery) L(ow): < 1.0%
- Y(es) N(o)

**MECHANICAL ATTRIBUTES**

- FAO soil name
- Regrouped land-use class
- Topsoil-texture class
- Subsoil-texture class

**HYDROLOGICAL ATTRIBUTES**

- R, C, S, L, H, M (10)
- D(eeep): 80-120 cm
- V(ery) D(eeep): > 120 cm
4.2. Standard structure of pedotransfer rules. Pedotransfer rules are described by a table containing input attributes from the geographic database and output attributes that were established through expert knowledge. The structure of a typical table is given in Table 4. The columns on the left correspond to values taken by input attributes; the central columns provide estimated values and their "confidence level"; and the right-hand columns contain management attributes and the reference of occurrence, i.e. author, date of last update, and a pointer for access to explanatory notes. The lines indicate the possible occurrence of the rules, based on the values (or combinations thereof) for the input attributes in the geographic soil database.

Table 4: Standard table for describing a pedotransfer rule.

<table>
<thead>
<tr>
<th>INPUT ATTRIBUTES</th>
<th>OUTPUT ATTRIBUTES</th>
<th>REFERENCE ATTRIBUTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional Codes</td>
<td>Class</td>
<td>Confidence level</td>
</tr>
<tr>
<td>1, 2, 3, n</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3. Confidence level. A rule is the result of expert knowledge and is not necessarily 100% reliable for all occurrences. It was thus proposed to add to each occurrence a confidence level that is attributed to the estimated output value. Four classes are proposed, ranging from "high", via "medium" and "low" to "very low". When the definition of input attributes enables the direct evaluation of an output attribute, the level is "high". However, if it is known that a very strong variation exists in the values of an output attribute, the "low" level is retained. "Very low" is used in the case of missing input attributes.

To warn the users against improper use of pedotransfer rules, it was decided that the confidence level of an output value should be the minimum of the confidence levels of the input attribute and its corresponding occurrence.

4.4. Mapping method: creating a legend for SMUs. Each estimate of an attribute in space is saddled with the problem of its map representation, which should provide documents for helping in decision making that are easier to use than a simple table with numbers. The data that derive from the model are complex and cannot be shown directly on a map. A choice thus has to be made for simplifying the information and providing a document that is as close as possible to reality.

As most Soil Mapping Units (SMU) contain several Soil Typological Units (STU), it may be impossible to show multiple data on the map. A simple solution to this problem is to select for each SMU the so-called dominant STU, representing the greatest surface percentage. Certain SMUs are very complex and contain up to 11 typological units. In this case, the dominant unit may represent only a small percentage of the association, thus leading to errors when reading the map.

To avoid this problem, it was proposed to assign a representation character to each of the classes of an attribute. The classification operation can be done on the level of STUs, and it will be easy to calculate the surface percentage taken up by each class. The selection of the dominant class will enable a much more precise representation of reality than the choice of a dominant STU. (32).

Only a small percentage of the surface of the European Communities corresponds to pure SMUs. For that reason, we have proposed to produce a set of maps that show "confidence level" as well as maps showing the "purity" concerning a specific subject. Figure 3 is an example for Soil Water Storage Capacity.
Figure 3.1: Distribution of Soil Water Storage Capacity.

![Distribution of Soil Water Storage Capacity](image)

Figure 3.2: Confidence levels.

![Confidence levels](image)
For the moment, we have limited ourselves to estimating the soil parameters necessary for environmental problems. No risk (or vulnerability) maps were drawn; such work would require the combination of soil attributes with physical (climate, relief), agronomic (agricultural farming structure) and industrial (type and place of polluting emissions) variables. Each case would also require a fine analysis of the problem, modelling of the processes, selection of the tolerance threshold, and validation through experimental field work. The development of pedotransfer rules is the preliminary work for such investigations and should facilitate a general application to local studies for all of Europe, providing a first estimate of the soil parameters needed for environmental models.

V - Extension to Central and Eastern Europe

The Commission of the European Communities wishes to favor, promote and harmonize the scientific and technical tools, as well as the databases of the different countries of continental Europe, in order to integrate them progressively in the Western European fabric, particularly in the domain of soil knowledge (5, 22, 23).

Building upon the work on the MARS project in the EC countries, the Joint Research Centre has asked INRA, and more precisely the SESCPF, to study the possibility of extending this work into the Central and Eastern European countries, covering Austria, Switzerland, and other neighbouring countries such as Slovenia, Croatia and Albania.
5.1. The Strategy. It was decided to use the same strategy as that used for the EC countries. This consists in starting from the FAO archives stored at Ghent University, and proceeding in three steps:
- Harmonization of the available maps and corresponding descriptive tables.
- Digitizing of the documents to ensure the possibility of making easier corrections.
- Participation of the concerned national soil survey services in correcting and updating of the documents.

5.2. Analysis of available data. The archives stored at Ghent University of the unfinished FAO project concerning a Soil Map of Europe at scale 1:1,000,000 have been analysed. The different documents were graciously made available by Professors R. Tavernier (+) and E. van Ranst.

5.3. The work completed. The following tasks were carried out: digitizing of contours, semantic capture, and the making of thematic maps.
- Digitizing of contours
The cartographic documents were digitized by scanner. Use of the data in Arc/Info GIS software enabled the creation of the database framework. An information layer includes the storage of contours under vector form, and the identification of each closed contour (polygon) in terms of Soil Mapping Unit (SMU). Each step is followed by a control phase, which means that three sets of controls were applied to each cover, i.e. contour control, label control and SMU control.

Figure 4: State of progress of the Soils European Database.
- Semantic capture

The descriptive tables were coded with the same conventions as those used for the EC database. However, the EC database list of codes being incomplete for the new countries, a number of new codes has been added, particularly for soil names and parent materials.

- Thematic maps

Three themes were selected to help the different countries with their work:
- Distribution of principal soil types following the FAO nomenclature.
- Parent materials of the principal soil types.
- Surface texture of the principal soil types.

Figure 5: Strategy used for setting up the Databases for EC, Central and Eastern Europe.

Those works have been made till now for Eastern part of Germany, Poland, Bulgaria, Hungary, Czech and Slovak Republics and Rumania.

5.4. Contribution of extending the EC Database to Central and Eastern Europe. Extension of the EC database to Central and Eastern Europe has led to real enrichment because of the introduction of several new elements. Of these, two groups seem to be essential:
- It has been necessary to introduce into the database parent-material types that are characteristic of the geology and geomorphology of Central and Eastern Europe. The influence of a periglacial climate is stronger in these countries than in Western Europe, e.g. the large amount of moraine material in Poland and Eastern Germany.
- New types of pedogenesis evolution ("Soil Name") and subdivisions in the nomenclature used, had to be added to the database. Such complements are mostly linked to pedoclimatic regimes specific for these regions, such as the appearance of Leptic Podzols, Chernozems, and great expanses of soils with vertic or halomorphic (Solonetz) features.

These additions open new perspectives for the potential use of the European geographical soil database in its larger sense. However, at the same time several coordination problems have appeared as well concerning the harmonization of geographic details, the quality of attributes for semantic definitions, and the coordination at national boundaries.

Another item is the extension of the "soil profiles database" for the EC countries to Central and Eastern Europe. However, here we face a problem of differences in analytical methods, which first will have to be compared before making an attempt at harmonization. To do this, it will first be
necessary to make an inventory of the main protocols in such countries for mechanical, physical, chemical, physico-chemical and mineralogical analysis. Once this has been completed, it may be possible to prepare a general framework and adequate "pro-formas".

VI - Perspectives

In the short term, one of the priorities is to rectify a problem noted during the process of computerization: comparison of the original digital map with the printed version showed geometric distortion that appear to derive from the differences between the projection systems of the various maps. This problem results in misalignments of up to 3 km in some areas. This may not be highly significant for Europe-wide applications, but will need to be corrected. Aesthetically, this could be corrected by rubber-sheeting the soil dataset along coastlines, but this would probably produce a false impression of spatial accuracy since the same errors also exist further inland. It is therefore planned to re-align the entire map on the basis of a hydrographic dataset, probably the one included in the Digital Chart of the World, and this with the help of EUROSTAT (EEC Luxemburg).

The GIS Support Group has proposed other developments of the Database, suggesting that both the parent-material referential and the soil-typology system could be modified. The former would require the development of a new system that more closely reflects the geomorphologic heritage, providing additional data on the behaviour of materials for environmental purposes. Modification of the soil-typology system would entail switching from the presently used "old" FAO legend to its new version (15). In many cases, SMU limits would have to be redrawn, to reflect the splitting or merging of classifications.

It is also scheduled to extend the work to more detailed databases, corresponding to larger scales and located in vulnerable regions of Europe. Scale transfer studies would be of great interest for this work (2).

At present, development of the Soil Geographic Database is being coordinated by the MARS Project in cooperation with the European Environment Agency, DG XI and VI, and EUROSTAT that has accepted the responsibility for distribution of the Database. However, the needs for updating, development, refinement and maintenance of the database will continue beyond the presently projected lifespan of the MARS Project, which ends in 1998; it will have to reflect the needs of its user community. A full analysis of these needs should be made and the Database should be managed to reflect their evolution. Moreover, as new data are collected at country level, these should be incorporated as well. In order to meet these continuing needs, a structure must exist for ongoing contact and feedback with individual experts in the field as well with national soil services. To this end, the prospects are investigated for establishing a more permanent Soil Bureau within the Joint Research Centre, in support to the CEC (5).

VII - Conclusions

The final aim of the work is to create a spatialized soil database for the whole European territory. This database would provide sufficiently good answers to the different kinds of problems affecting agricultural production (DG VI, MARS), or those concerning the protection of the European environment (DG XI, European Environment Agency), as well as for "Global Change" simulations. Another aim is to make "Relational Databases", including the relationships between the typological units of a landscape and describing the main transfers within the soil cover, thus opening the possibility to build "Spatial Organization Models" (16, 29).

In a world context, different works have been completed or are in progress under the auspices of international organizations such as FAO or UNEP, e.g. the GLASOD and SOTER programs, or the
GEMS (17) and GRID (18) organizations. Some of these, such as the SOTER program, are managed by ISRIC in Wageningen (1, 20). It is obvious that a harmonization with these main world-wide programs appears to be an increasing necessity (19). The rational structuring in a computerized form of our knowledge concerning the principal soils of Europe, will lead to a further improvement in the management of European soil resources.

Acknowledgements. We thank very much the CEC CORINE and MARS Projects and all members of the "Soil and GIS" Support Group of CEC for their support and contribution to our work.

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Soil-space organization model and soil functioning units in Geographic Information Systems

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ABSTRACT

Computer-based techniques, and in particular Geographic Information Systems, enable the management, analysis and easy restitution of soil data. Older data in map format that should be converted into geographic database format, thus should first be computerized. However, such work may well be insufficient due to the limitation of a conventional map representation. Therefore, a new structure of pedological information is proposed as relational tables that correspond to the main conceptual subjects used during conventional cartographic work. This "Soil-space organization model", or SSOM, is a computerized framework for coherent description of the geographical variability of soils. It makes no pre-judgement on the type of processing of such data. However, it stresses the importance of starting with the determination of the type of soil organization, such as the identification of spatial units and their relationships. Design of a cartographic representation from this model is then the last stage, requiring the selection of (combined) attribute(s), map scale and graphic patterns. To test the method, it was applied to the soil landscape of the Picardy region in north-eastern France after description of the relational tables.

1. INTRODUCTION

Map representation of a continuous domain such as soil, conventionally uses choropletes maps (18), composed of juxtaposed polygons. This method provides the possibility of showing the main discontinuities of the soil cover that can be seen as a pseudo-continuum (33). A delineation indicates a pertinent structure of the environment as compared with its use (38), despite controversy about the soil-boundary concept (19).

Regardless of the means used to arrive at such a subdivision of space, the data considered as most relevant must be conveyed in map format. This can be done by showing the maximum of soil characteristics for each polygon, using graphic techniques (6), or alphanumeric codes (21). A complementary technique uses a legend with an additional report in which, using the same symbols, similar soil units are grouped according to a predefined classification. Details of the soil characteristics then can be available in this legend or in the text and graphics of the additional report.

The use of colours, graphic patterns or icons to indicate the relevant soil features of a region provides readers with a means for understanding the spatial distribution of soils and their relationship with other environmental parameters, such as geology or landscape. Hanson (29) asserted that maps have the rudiments of a vocabulary. However, one of the limitations of this method lies in the graphic constraints imposed by publication means. Beyond a certain, fairly restricted, number of different colours or
patterns, the eye can no longer distinguish the diversity of information (51). The problem is that many soil types have to be shown, and that their spatial variability is high (9), particularly when the final maps are of medium- to small scale. Finally, the documents thus obtained are difficult to use, which is an inconvenience that has caused misunderstanding and underutilization of cartographic work in soil science (21, 46, 56).

A possible answer to this problem was proposed with the help of computers, digitizing the maps and managing the data with Geographic Information Systems (GIS). These tools made it possible to digitize published maps (44, 45). However, the numerical processing of documents that were not designed for this purpose, generally cannot lead to high-quality information. A computerized framework is needed that can describe the complexity of the soil cover and store unlimited data (36). Fortunately, most soil mappers have in mind intuitive soil-landscape models (33), which are more complete and accurate than their map representations.

In this paper, we try to translate the soil mapper's knowledge into a numerical and logical form, using a relational-database model. The objective is not only to store all basic field data, but to retain the main features of the soil cover as deduced by the soil mapper's judgement. Thus, the proposed concepts within the so called "Soil-space organization model" (SSOM) are extensions of concepts included in conventional soil-mapping work. In particular, we use a discontinuous representation of the soil cover and this paper does not take into account the background of mathematical methods which enable continuous modelling of spatial variability (59).

2. METHOD: A PROPOSED RELATIONAL MODEL

A conventional soil map is composed of (i) plotted outlines, (ii) a legend according to a soil typology, and (iii) an explanatory booklet giving descriptions of soil units and assumptions on pedogenetic processes. Minutes and archives are very precious documents, which contain the basic descriptions that were used for grouping soil units and drawing soil boundaries. Soil mapping is more than just plotting on a topographical background the results obtained from soil samples according to a soil taxonomy: soil maps can be regarded as models (7).

Mapping comprises a search for coherence between observations, in order to identify soil bodies, explain their spatial relationships, and their previous or present functioning, and this in combination with other environmental features such as geology or climate (49). This aspect of present functioning between soil types that form part of the same landscape unit, is particularly well shown by the importance of an exact "structural analysis" (13, 48).

A computer structure presented as a descriptor of soil-cover knowledge, should thus be capable of receiving all data acquired for a single region, in an organized and necessarily simplified manner. To do so, it is necessary to start with definitions of "conceptual objects" and descriptions of their relationships.
2.1. Definition of conceptual soil-space objects

2.1.1. The horizon. Soils are three-dimensional units that are continuous in space (50). The most obvious structure, when looking at a soil profile along a transect, is the presence of parallel layers that normally are called "horizons". The recognition of diagnostic horizons is at the root of many soil classifications (1, 2, 24, 55). We have chosen the horizon as the basic element of the data model (58). It is a conceptual horizontal soil volume that has a very small vertical dimension (z) when compared to the horizontal dimensions (x and y) that can be several kilometres (Figure 1) (15, 28). The framework proposed in this first step may be independent of general soil taxonomy and the manner in which the horizon was defined. The essential point is that characteristic features can be provided for each conceptual horizon, such as granulometry, limestone content, pH, etc., and this as precisely and completely as possible.

Figure 1: division of the soil cover into elementary volumes (from 28)

2.1.2. The Soil Typological Unit (STU). Certain soil characteristics cannot be assigned to horizons, such as the depth of groundwater, or parameters of the root system. In addition, the use of soil does not involve one horizon, but several combined horizons that most commonly are superposed. For this reason, the soil cover is generally subdivided into conceptual vertical volumes, which we call Soil Typological Units (STU) (Figure 1). They are mainly defined according to the type and organization of the horizons that are found within them. This approach has been widely used in soil-mapping programmes, as expressed in the idea of "Soil Individual" (41), "Elementary Soil Area" (25) and "Soil Series" (22, 37, 52, 54). A very interesting manner to define an STU is to use the common origin of soils, involving the
concept of "genon" proposed by Boulaine (10).

The specific structure of an environment according to a vertical or horizontal subdivision, commonly can be recognized without precisely defined geographical boundaries of each of these subdivisions (41). Using predefined general typologies may be insufficient because they do not fit natural soil bodies (47). Usually, the structure of the soil cover is defined by studying large-scale toposequences or small areas, and maybe using statistical methods. As a result, the two conceptual objects that are retained, i.e. the "Horizon" and the "Soil Typological Unit", are primarily defined according their own internal characteristics, such as texture, organic content, permeability, etc. They may constitute a regional typology that late can be linked with general soil taxonomy (3, 5).

In the database, the objects are shown as two tables, each line respectively representing a horizon (first table) or an STU (second table). Each column contains an attribute that gives a coded description of a soil property that is specific for the object under consideration (Figure 2). For each property, the modal value is requested and completed by an estimation of unit intravariability (i.e. a purity level of the unit). As such data are rarely quantitative, but qualitative, their statistical use must be based on the soil mapper's experience.

2.1.3. The Soil Mapping Unit (SMU). When sufficient data are available, it is possible to define the spatial extension of an STU in a geographical sense, even though horizons are rarely defined on maps, except when they are very large (14). It may not be possible to define an STU at the selected level of precision, in which case it is proposed to group several STUs into a "soil association". A Soil Mapping Unit (SMU) is thus defined as a coherent segment of the soil mantle, mainly described by one or several geometric polygons. Some internal attributes may be attached to it (area, number of STU, etc.).

This method was widely used in many national and international mapping programs, at small and medium scales (16, 20, 23, 57). In most cases, the number and variability of parameters to be handled are so large, that preference was given to the dominant pedogenetic processes. The main decision underlying such grouping is related to the selected publishing scale of a map, for which reason we use the expression "mapping unit" for a soil association. This is a similar concept to that of the "mappon" proposed by Boulaine (11). However, an SMU should correspond to a pedological province (53) with a "more or less regular pattern always in the same interrelations": (4). Obviously, an SMU may contain only one STU, in which case it will be considered as a pure unit. The attributes describing SMUs in the database, as well as those they have in common with STUs in a single SMU, are recorded in tables (Figure 2).

2.2. Relationships between soil spatial objects
2.2.1. The relationship between Horizon and STU. Most STUs contain several horizons. Moreover, a single horizon can in theory belong to several STUs. The two entities "Horizon" and "STU" are thus interrelated and their relationship is described in a specific table (Figure 2), which comprises all data describing how horizons are arranged within an STU. For each STU it contains, for instance, the list of component horizons; each STU-Horizon couple itself is defined by the depth at which the horizon appears, and its thickness and type of distribution within the STU, e.g. the type and shape of boundaries between horizons. This type of description covers the idea of a horizon as proposed in the work of "structural analysis" by Boulet et al. (14).
2.2.2. The relationship between STU and SMU. The listing and organization of STUs within an SMU is described by another relational table, indicating their rate and mode of spatial distribution (31, 42), e.g. surface percentage, shape index, localization, boundary contrasts, neighbouring relationships, etc. (Figure 3). In this way, symbolic codes can be used as a substitute for geometric lines. This organization model enables the description of "geographical patterns", thus integrating the concept of combination as
proposed by Fridland (26) and developed by Boulaine (12). The same STU can belong to several SMUs, for instance in the case of a dominant soil in an association that forms an inclusion in a neighbouring association.

Figure 3: example of attributes used to describe STU relationships within an SMU

<table>
<thead>
<tr>
<th>Some attributes applicable to SMU-STU relationships</th>
<th>Abstract Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>% STU/SMU area</td>
<td>![10%], ![50%], ![90%]</td>
</tr>
<tr>
<td>Localization</td>
<td>![Random], ![Regular], ![Localized]</td>
</tr>
<tr>
<td>Shape</td>
<td>![Disk], ![Blade], ![Including]</td>
</tr>
<tr>
<td>Pattern</td>
<td>![Simple], ![Complex], ![Very complex]</td>
</tr>
<tr>
<td>Neighbouring</td>
<td>![A-B], ![A-B, B-C, A-C]</td>
</tr>
<tr>
<td>Boundary contrast</td>
<td>![Very sharp], ![Sharp], ![Progressive]</td>
</tr>
<tr>
<td>Origin of the differentiation</td>
<td>![Geology], ![Relief], ![Vegetation]</td>
</tr>
</tbody>
</table>
2.2.3. The relationship between SMU and Polygon. From the geometrical point of view, an SMU is composed of one or more polygons that are described by the coordinates of their component arcs. A last relational table defines the membership of a specific polygon to a certain SMU.

2.3. Notion of Soil Functioning Unit (SFU)

Before contemplating cartographic representation at a given scale, it may be of interest to group STUs into Soil Functioning Units (SFUs), in order to describe relationships between STUs belonged to several SMUs. In this way, an SMU is not attached to the geometric dataset. The objective is to focus on the STU relationships that highlight past and present soil-formation processes. Several SFUs can overlie each other according to various soil processes.

Such a grouping corresponds to the concepts of "sequence" (22, 40), or "soil systems" (8, 15), in which STU distribution is not random but according to pedogenetic laws of varying complexity, e.g., soil-landscape laws (35, 60). Some authors suggested a spatial organization of soils (12, 26, 32), but a more complete form is to describe the pedogenetic laws that govern soil-forming processes. To reach this ideal goal, the tacit knowledge usually used in soil survey has to be written in a literal form or with schematic diagrams (34). Computer methods then apply the variables, used for describing SMUs and the relationships between STUs within an SMU, to the notion of SFU, e.g., the surface percentages of STUs within SFUs, shape, localization, boundary contrast, pattern, origin of the differentiation. This is the first step to formalize soil-space organization and its relevant laws, and should help the predictive modelling for soil surveys as suggested by Hewitt (30).

2.4. Adopted terminology

The structure of the proposed database makes no pre-judgement on how the "objects" were earlier defined or grouped. It provides a descriptive framework for the organization of spatial data. The combined tables describing conceptual objects, defined according to their internal characteristics, are called a "semantic base", whereas the combined tables describing conceptual objects defined according to their geographical characteristics, are called a "geometric base". The combined relational tables used for describing a type of object within other types of objects, can be called a "topologic base". This makes it possible to describe geographical organization without necessarily having a geometrical description.

3. APPLICATION TO A TYPICAL SOIL LANDSCAPE IN FRANCE

The present methodology was used for two soil-inventory programs. A first draft structure was adopted to digitize archives data from the 1:1,000,000 European soil map (43). This first work showed the loss of information due to the restrictions of map representation (20). Many soil units were grouped together in order to limit the complexity of the legend. This grouping was done with a preference to the dominant pedogenetic process. With such a procedure, many data could not be shown on the map, nor even mentioned in the explanatory notes. Update work is now in progress at the European level, as collaboration between several national soil survey staffs (17, 39).
Figure 4: schematic block diagram illustrating the concepts of SMUs, STUs and SFUs
Example of a loamy calcareous landscape in Picardy (France)
The structure database presented in this paper was improved as part of a second programme named IGCS (French acronym for soil inventory, management and conservation). The objective of IGCS was to create a general database covering the French territory at the 1:250,000 scale. Practical application of the IGCS work was made possible through the development of the DONESOL software (27).

Figure 5: relational tables related to the block diagram of Figure 4
(Definitions are given in the text (§ 2.) and on Figure 2)
A typical soil landscape studied during the IGCS program was selected to show a concrete example that constitutes a fragment of a loamy calcareous soil landscape in Picardy (north-eastern France). We have illustrated the structure of the soil cover as a block diagram (Figure 4). Related to this block diagram, we filled out the schematic tables of the Figure 2, with examples of descriptions and relationships of soil objects (Figure 5). To give an exhaustive description here of all attributes would be redundant and boring, and only one attribute per table is given to illustrate the methodology.

3.1. Horizon description

The main horizons we observe are:

Ap: Silty loam, medium organic matter content, crumbly to platy structure
E: Silt to silty loam, low organic matter content, particulate structure.
Bt: Silty clay loam, very low organic matter content, subangular blocky structure, common clay coating.
L: Loess, silty loam, no organic matter, particulate to massive structure, with some vertical dissociation faces.
C: Cretaceous chalk, low or no organic matter content, crumbly to blocky structure.

It is obvious that a same type of horizon can belong to different STUs.

3.2. STU description

A toposequence shows from top to bottom of the relief the following STU succession: an Orthic Luvisol (T1) developed on the loess cover; the same Luvisol with its E horizon removed by erosion (T2); a Rendzic-Leptosol on chalk (T3); passing abruptly into a similar Leptosol (T4) but here developed on a periglacial chalk shoreline; a Calcaric or Eutric Cambisol (T5), differentiated in old loamy colluvium; and finally in the axis of the thalweg a Fluvisol on recent colluvium.

3.3. STU-horizon relationships

For each STU, the present horizons are indicated. The real depth of each horizon is a relational attribute, since it describes the object envelope. As a horizon can belong to different STUs with respective different depths, we cannot attribute a proper depth to that horizon.

3.4. SFU description

The SFUs that we can determine in this landscape are mainly two. The first (F1) is due to old Quaternary sedimentation of loess, with a geomorphological redistribution that is related to periglacial conditions. The second (F2) is presently active and consists of degradation of the superficial structure under rainfall, and erosion due to concentration of runoff.
3.5. SFU-STU relationships

The succession from top to bottom leads to the presence of different types of boundaries between STUs. They can be progressive between complete and eroded Luvisols, or between Eutric Cambisols and Fluvisols, or they are more abrupt between Luvisols and Rendzic Leptosols. Rainfall on clay causes hardening because of the closure of soil pores, a decrease in infiltration, and an increase in runoff and erosion, with accumulation of soil in the lowest parts of the relief. Such hydraulic functioning defines an SFU that groups STUs (2 to 6), which are affected by such water and particle transfer.

3.6. SMU description

Except in the case of scales of 1:5,000 and larger, it is practically impossible to show on a map all STUs that were grouped into three SMUs: i.e. the Luvisols (T1)+(T2); the Rendzic Leptosols related to chalk outcrops in the slope (T3)+(T4) with some small inclusions of Cambisol (T6); and the association of Cambisols and Fluvisols at the bottom of the slopes (T5)+(T6). Each STU belongs to only one SMU, except STU T6 that mainly belongs to SMU M3, but also belongs SMU M2. It is indeed impossible to draw the boundary between T6 and T4 at a small scale; this limit is thus generalized by introducing some T6 inclusions into M2.

3.7. STU-SMU relationships

The percentage of occupied areas is the minimum essential information that must be shown, but the other parameters of intra-unit variability should be noted as well, if possible. In many cases, an SMU is in fact an SFU, the cartographer having wished to highlight the organization laws.

3.8. Polygon description and polygon-STU relationships

Polygons are grouped in SMUs in order to avoid the repeating of information. However, it is quite possible to only one SMU for a polygon, if this is useful.

4. CONCLUSIONS

Before computerized techniques were used, a soil map had to fulfil two functions: that of "memorization", managing a maximum of data, and that of "communication", transmitting a minimum of pertinent data for a given problem. The method we propose has been designed around a clear distinction between these two functions.

The model handles the first function of data "memorization" by proposing a computerized framework of collecting geographic data. The future use of this type of framework should be seen as independent from the objective of map representation at a given scale, in order to avoid any limitation in the memorized data. The second, "communication", function thus forms a final step, which translates into a selection of pertinent data and a clear map representation. This step is a standard GIS function.
Furthermore, the proposed method opens new possibilities to describe the relationship between soil bodies defined as soil-typological units. Such relationships may be active today or be residuals from past pedogenetic processes. This approach leads progressively to the description of the soil distribution laws that explain the present structure.

The work in progress is only a first approach that will need a better harmonization than the present one. The proposed framework is a possible solution favouring a certain type of knowledge structuring, such as the concepts of horizon, STU, SMU or SFU. Other solutions are possible with the help of geostatistics, and/or by introducing geographic data that are not strictly pedological, but are systematically known for a given region, like remote-sensing data or a digital terrain model (61). The proposed method has the advantage of handling widely used concepts for conventional map-making at small and medium scales, but respecting certain essential elements such as the three-dimensional structure of the soil cover.

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Sistema de Información Geográfica, Suelos de Uso Agrícola y Operación de los Distritos de Riego

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RESUMEN

Los Distritos de Riego (DR) requieren del manejo de grandes volúmenes de información para realizar en forma adecuada y oportuna sus actividades de operación, conservación y administración. Por tal motivo, se hace necesario que éstos se apoyen en el uso de equipo moderno y técnicas que permitan el manejo masivo de la información, que utilizadas como herramienta, los ayuden a optimizar la integración, análisis y manejo de la información generada como resultado de su funcionamiento.

Los equipos de cómputo actuales proveen a sus usuarios una gran capacidad de procesamiento de datos en forma rápida y confiable y aunque los Distritos de Riego se han empezado a dotar de estos equipos, en la mayoría no se ha obtenido su máximo provecho, ya que no se cuenta con sistemas de información adecuados para el procesamiento de sus datos.

En este trabajo se presenta un ejemplo de un Sistema de Información Geográfica (SIG) para los DR, el cual fue desarrollado para el DR 085, La Begoña, Gto. La metodología obtenida en este distrito, se encuentra en proceso de transferencia, con las adaptaciones pertinentes, para el DR 026, Bajo Río San Juan, Tamaulipas, tomando en cuenta las necesidades de manejo de información del personal técnico del distrito y de las Asociaciones de Usuarios que en él existen y que básicamente están encaminadas al aprovechamiento, manejo y uso eficiente del agua y del suelo para lograr su máxima productividad.

En términos generales, el SIG abarca los siguientes aspectos:

- Padrón de usuarios, con las características y datos que marcan las leyes y reglamentos en vigencia.
- La información específica más importante desde el punto de vista del funcionamiento del DR, por lote: agrología (textura, series de suelos, drenaje, salinidad, microrrelieve interno) infraestructura hidroagricola, que son prácticamente datos constantes, y operación, que son datos con una variación periódica por ciclo.
La información cartográfica, a la cual se relacionan las dos anteriores; corresponde a los planos por sección, catastrales y de infraestructura.

Con un programa de cómputo especialmente diseñado para ello, se ha procesado todo el padrón de usuarios; con otro lo que corresponde a la información estadística constante y variable; con ARC/INFO, paquete comercial apropiado, se hizo la digitalización de la información cartográfica, catastral y de infraestructura por sección, y se hizo la relación entre todas las bases de datos para su despliegue de los aspectos más importantes, en forma gráfica y numérica.

**SISTEMA DE INFORMACION GEOGRAFICA PARA EL DR 085**

El funcionamiento general de los Distritos de Riego y la toma de decisiones que permita un buen uso y manejo de los recursos de que disponen, se apoya fundamentalmente en el conocimiento y análisis de la información que en ellos mismos se genera. Las actividades inherentes que las diversas áreas técnicas realizan, se programan y ejecutan de acuerdo a dos tipos básicos de información: la numérico-estadística, que conjunta el desarrollo histórico, como resultado de esas actividades, y de cuyo análisis es posible obtener índices, parámetros y tendencias; y por otra parte, como una manera de resumir esta información y de hacerla más objetiva y evidente, se plasma en forma gráfica en diversos planos, en los que los conceptos más importantes pueden ser más fácilmente apreciables y refuerzan el aspecto cualitativo de la información.

Así, se tiene información numérica-estadística de: Padrón de Usuarios, superficies sembradas, regadas, cosechadas, rendimientos, volúmenes de agua distribuidos, láminas de riego, eficiencias, etc; por otro lado información descriptiva agrológica sobre: texturas, microrrelieve, drenaje, salinidad, niveles freáticos, series de suelos; y por último información cartográfica como: plano de infraestructura hidroagrícola, catastral, topográfico, agrológico, etc.

Los actuales sistemas de cómputo (SIG), proporcionan la rapidez y exactitud de ejecución de registro y procesamiento de grandes volúmenes de información. Este avance en la computación, permite relacionar datos de tipo geográfico o espacial con sus datos estadísticos o descriptivos, función básica en un SIG; consideran además un gran número de disciplinas y diversos procesos y aplicaciones en cada una de estas; por ejemplo, un SIG permite registrar toda la información referente a las características físicas y químicas que un suelo presenta como son: textura, serie, salinidad, drenaje, microrrelieve interno; permitiendo realizar diversos análisis y generar diversas capas de información y a partir de ésta nuevos planos, Al sobreponer estas capas, es posible identificar las diferentes características existentes en un área geográfica, y con ésto contar con mayores elementos al participar en la planeación y programación de las actividades que en el DR se realizan.; ejemplo de ésto, es que cuando se dispone de información confiable y oportuna ya sea representada mediante mosaicos temáticos.
o reportes en papel, se estará en posibilidad de elaborar un adecuado plan de cultivos y de riegos para ciertas superficies que cumplen con las características requeridas por cada una de los cultivos establecidos. También, conociendo (mediante un SIG) la información sobre la evolución de las sales en un suelo agrícola, será posible conocer las acciones más adecuadas para realizar su conservación o su mejoramiento, entre otras múltiples aplicaciones.

Con base a lo anterior, la Comisión Nacional del Agua, a través de la Gerencia de Distritos de Riego, dependencia a cuyo cargo está todo lo referente a la administración de los distritos, solicitó al Instituto Mexicano de Tecnología del Agua el desarrollo de un Sistema de Información Geográfica para ser aplicado en los Distritos de Riego del país.

Para el desarrollo del SIG se seleccionó un DR que presentara mayor factibilidad de ser el centro piloto para el desarrollo e implementación del SIG, así como para realizar la evaluación de sus alcances y bondades una vez concluido. Esta selección se hizo en función de las características de cada distrito, de las cuales las determinantes para la selección del sitio fueron, que el DR fuera relativamente pequeño y compacto, con superficie de riego bien definida, sin problemas de tenencia de la tierra, cercano al IMTA para una frecuente comunicación. De este modo se eligió al DR 085, “La Begoña” en el estado de Guanajuato.

El primer paso consistió en el análisis de las actividades de procesamiento de información que se llevan a cabo dentro del distrito para determinar cuales de esas actividades eran las más viables de implantar dentro del SIG.

La información seleccionada para ser incluida dentro del SIG fue la siguiente:

- Plano catastral por sección de riego. Contempla la división catastral, la infraestructura hidráulica y la ubicación de zonas urbanas y vías de comunicación.

- Padrón de Usuarios. Documento donde se encuentran todos los usuarios con derecho a riego dentro del área del distrito, con sus diversas características.

- Información específica. En una parte se incluyen aspectos relativamente constantes como agrología (textura, drenaje, microrrelieve interno, salinidad, series), topografía e infraestructura hidroagrícola, y en otra información sobre operación y aspectos afines que sí puede tener una variabilidad periódica.

La información correspondiente al Padrón de Usuarios relacionada al plano catastral, es la base para la relación con el resto de la información. El campo de cuenta y subcuenta registrado dentro del padrón es la llave para relacionar toda la información entre sí. (Figura 1)
A toda la información disponible (estadística y cartográfica) se le hizo un análisis, depuración y actualización en forma exhaustiva para posteriormente ser capturada e integrar la base de información geográfica.

El siguiente paso fue la selección del software a utilizar para el desarrollo del SIG; los requisitos para su selección fueron los siguientes: que pudiera usarse en computadora personal bajo el ambiente DOS y que el manejador de bases de datos, tanto geográfico como descriptivo, reconociera el formato del manejador de bases de datos comercial dBase, ya que los DR cuentan con un programa de cómputo para el procesamiento de la información del Padrón de Usuarios desarrollado en Dbase, el cual sería utilizado como un componente del SIG. Para el manejo de la información específica se decidió desarrollar una aplicación en Clipper, el cual es un manejador de bases de datos compatible con Dbase que permite el desarrollo de sistemas. Para capturar la información geográfica y la relación de los datos descriptivos con su respectiva localización espacial dentro del plano, se seleccionó el software comercial Arc/Info.
El Padrón de Usuarios, es el documento fundamental en un DR, de éste se derivan programas y acciones a realizar, se dimensionan presupuestos, costos, cuotas, tiempos de ejecución, valor y volumen de producción, etc. Este documento registra cada una de las personas físicas o morales que hacen uso de los servicios de riego, drenaje, domésticos, industriales u otro tipo que se proporcione con sus obras, y además de los nombres de los usuarios, contiene las superficies físicas y netas de riego o de drenaje de las parcelas o lotes beneficiados, y los datos complementarios para su identificación y localización dentro del área del DR. La información contenida en el Padrón de Usuarios fue capturada mediante el Sistema para el Manejo de Padrones de Usuarios (SIPAD), elaborado para la Gerencia de Distritos de Riego.

Para la captura y procesamiento de la información específica se desarrolló el módulo de Información Específica. Este módulo comprende a nivel de lote o predio, los siguientes conceptos:

- Agrología y Topografía: textura, serie, salinidad, drenaje y microrrelieve interno.

- Infraestructura: material de construcción del canal o tipo de dren, capacidad, status y estado de conservación en drenes y canales por separado. Tipo de obra, capacidad, status, estado de conservación y tipo de estructura aforadora en tomas-granja y tomas directas.

La digitalización de la información cartográfica se hizo con el propio paquete ARC/INFO, mediante el uso de una tableta digitalizadora. Los planos de los cuales se digitalizó la información fueron proporcionados por el DR a escala 1:10,000 cada uno corresponde a una sección de riego. Durante la digitalización se integró el número de cuenta y subcuenta de cada lote para realizar la relación con los datos descriptivos.

La integración de los datos descriptivos y geográficos se lleva a cabo dentro de Arc/Info y esta parte representa la principal aplicación del Sistema de Información Geográfica. Para facilitar el manejo de los dos tipos de información se programaron un conjunto de macros dentro del lenguaje SML de Arc/Info. Estos macros constan de una serie de menús de opciones que al seleccionarlos ejecutan comandos de Arc/Info para realizar una tarea específica.

Ya con los datos integrados se pueden llevar a cabo las siguientes tareas:

- Despliegue en pantalla y en forma impresa del plano general del DR, digitalizado con división por secciones de riego, a diferentes escalas.

- Despliegue en pantalla y en forma impresa de planos catastrales y de infraestructura correspondientes a todas las secciones de riego a diversas escalas.

- En pantalla, como interrelación de datos, las características, según SIPAD, de cada predio de los planos catastrales de cada sección de riego, previamente seleccionado.
- En pantalla, ampliación (zoom) de una superficie seleccionada del plano catastral de cualquier sección previamente seleccionada, en la que cada predio está identificado por su número de cuenta.

- Es posible desplegar en pantalla la cartografía digitalizada de las secciones del distrito, en forma individual, así como para un predio o grupo de ellos, consultar sus características según el Padrón de Usuarios y la información estadística capturada mediante el SIE y desplegar los mosaicos de: tenencia de la tierra, ejidos, cultivos, texturas, salinidad, drenaje, microrrelieve, índice de productividad del agua neta y bruta y series de suelos. Cada mosaico presenta un tema, en donde se definen sus conceptos mediante colores y simbologías.

- Impresión de cada uno de los mosaicos arriba mencionados a diferentes escalas.

- Para reforzar la información gráfica de los aspectos operativos, como ya se mencionó, se tiene la posibilidad de obtener mosaicos de cultivos, IPA Total e IPA Neto. El IPA (Índice de Productividad del Agua), se define aquí como la productividad económica por el uso del agua, en miles de pesos por millar de metros cúbicos utilizados (netos), y es un indicador de la eficiencia económica del uso del agua. Plasmar este índice en forma de mosaico, da una buena aproximación de la distribución espacial de los ingresos, lo que si se correlaciona con los demás mosaicos, apoyará la detección y análisis de áreas con problemas que estén afectando negativamente la producción agrícola y por tanto, el ingreso de los productores.

AGROLOGÍA Y TOPOGRAFÍA

Dentro de la información usada en un distrito de riego, la que se refiere a las características del suelo representan gran importancia ya que junto con el agua representan los principales recursos para la producción. Dentro del SIG se consideran varias capas de información que describen las características físicas del suelo, las cuales se encuentran clasificadas por cada uno de los predios. Estos temas son los siguientes:

Textura. Se refiere a la proporción de partículas de arena, limo y arcilla que existen en el suelo. En la figura No. 2 se muestra un ejemplo de la distribución geográfica de cada clasificación. Las clasificaciones usadas son las siguientes:

- Arena
- Arcilla
- Limo
- Migajón arenoso
- Migajón arcilloso
- Migajón arcilloso limoso
Figura 2. Distribución espacial de texturas.

Serie. Unidad básica en el sistema de clasificación de suelos que reúne características físicas, químicas y morfológicas similares en el perfil con excepción de la textura de la capa arable o superficial. Las series utilizadas dentro del SIG son las definidas localmente para el DR 085 y un ejemplo de su distribución se muestra en la fig. No.3.

Figura 3. Distribución espacial de series de suelos.
Salinidad. Se refiere al contenido de sales solubles en el suelo, que al rebasar ciertos niveles puede perjudicar el crecimiento y desarrollo de las plantas. Un ejemplo de su distribución se muestra en la figura 4. Las clasificaciones usadas son:

- Sin problemas
- Ligeramente salino
- Moderadamente salino
- Altamente salino
- Máxima salinidad

Figura 4. Distribución espacial de salinidad.

Drenaje. Se refiere a la capacidad del suelo para eliminar el agua en exceso o almacenarla en cantidades útiles para el crecimiento y desarrollo de las plantas. La figura No.5 muestra la distribución de las clasificaciones. Las consideradas dentro del SIG son:

- Sin problemas
- Ligeramente afectado
- Moderadamente afectado
- Fuertemente afectado

Microrrelieve interno. Representa la conformación topográfica del terreno (figura 6). Se usaron las siguientes clasificaciones:

- Plano
- Ligeramente accidentado
Figura 5. Distribución espacial del drenaje.

Figura 6. Distribución espacial del microrrelieve.

- Moderadamente accidentado
- Fuertemente accidentado

La combinación de varias capas de información puede dar una idea aproximada sobre las acciones más acertadas cuando se requiere tomar decisiones al planear el aprovechamiento de los recursos con que se dispone, en este caso el suelo agrícola.
Por ejemplo, si se sobreponen al plano de la cuadrícula el plano catastral, el de texturas, el de drenaje, y el de salinidad, se podrá conocer el conjunto de características existentes a nivel de parcela si se quiere ser muy puntual y a nivel de sección de riego si se quiere abarcar una superficie mayor; a partir de esta sobreposición de capas de información, se podrá saber la localización exacta de cada uno de los usuarios que constituyen a la sección, la existencia y el grado de salinidad en cada uno de los predios, la profundidad de la capa arable, si en éstos existen encharcamientos de agua, si es arena, limo o arcilla; en general, si en conjunto representan un serio problema para el desarrollo y crecimiento de los cultivos o si es benéfico para el establecimiento de una gran diversidad de éstos (figura No.7).

Figura 7. Distribución espacial de cultivos.

Las clasificaciones incluidas en cada uno de los mosaicos de información, son sólo algunas de las existentes en el catálogo, de tal manera que si una sección de riego requiere presentar otras clasificaciones, estas ya están dadas de alta y sólo sería cuestión de registrarlas mediante la clave correspondiente.
RESUMEN

La planeación y ejecución de las diferentes actividades que se llevan a cabo dentro de un Distrito de Riego para su administración, operación y conservación, están basadas en información sobre diferentes aspectos técnicos, naturales y organizativos que se relacionan con el área geográfica donde éste se localiza. Así se tiene, por ejemplo, información del Padrón de Usuarios, asociada al plano catastral, o información agrológica relacionada a su distribución geográfica dentro del distrito.

Los Sistemas de Información Geográfica poseen un conjunto de procedimientos que permiten manejar una base de datos con información geográfica asociada a su información descriptiva.

Este artículo trata sobre un Sistema de Información Geográfica desarrollado para el Distrito de Riego No. 085, "La Begoña" en el estado de Guanajuato. El sistema recibe como entrada, información sobre Padrón de Usuarios, agrología, topografía e infraestructura y la relaciona a su predio correspondiente dentro del plano catastral. Entre las aplicaciones más importantes se tiene la generación de mapas de información temática con los cuales es posible hacer diversas sobreposiciones, realizar múltiples análisis y obtener nuevos criterios para la ejecución de las tareas con mayor precisión. Las salidas del sistema consisten en la impresión de planos a diferentes escalas para cada una de las capas de información, así como la generación de tablas sobre las mismas.

Palabras clave: Sistemas de Información Geográfica, SIG, Distritos de Riego, Operación, Conservación, Administración, Arc/Info, Cómputo, Bases de datos.

ABSTRACT

The planning and execution of the different activities carried out within an Irrigation District for its administration, operation and conservation, is based in information about different technical, natural and organizative aspects, which is related with the geographical area where it is located. In this way, for example, information about the Users Census is associated to the cadastral plain, or agrological information is related to its geographical distribution within the district.

The Geographical Information Systems has a set of procedures which allow to manage a geographical information data base associate to its descriptive characteristics.

This article treats about a Geographical Information System developed for the Irrigation District No. 085, "La Begoña" at the State of Guanajuato. The system receives as input, information about users census, agrology, topography and infrastructure and relates it to its corresponding property within the cadastral plain. Among the most important applications, it is the generation of thematic maps, which is possible to make diverse overlays in order to accomplish multiple analysis and obtain new criterions for the execution of the tasks with higher precision. One of the main results of the system consists in the printing of plains at different scales for each one of the layers of information, as well as the generation of tables about the same.

Key words: Geographical Information Systems, GIS, Irrigation District, Operation, Conservation, Administration, Arc/Info, Computation, Data Bases.
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Description of Soils, in Tabasco, Mexico Using Geographic Information Systems


Introduction. The agriculture of Mexico is restricted by climatic and soil factors. This represents an important challenge for researchers in locating geographical zones with the best yield potential and to apply the suitable technology. In this sense, it is necessary to know the geographical conditions where some characteristic factors are repeated in regional cultivable areas. This study is part of the National Project "Growth Potential of Plant Species ", to reorganize the soil use and to produce each specie with largest advantage. In this paper Tabasco state, México is used as example.

A Geographic Information System (GIS) is a database management system for map-oriented data. For any region, a set of maps can be added to the database as digitized images to represent different data topics describing the region. Within each data topic, homologous regions are identified, and attributes describing those regions are stored in tables that reference the map of the specific data. GISs then offer several features for manipulation of the graphical and tabular data. For instance, if data for field boundaries, crop and soil type, are included in a GIS for a given farm, GIS could quickly calculate and display on a map with all regions with a selected crop planted in heavy clay soils. Alternatively, if weed histories were available in a map form, all fields planted with high risk areas could be displayed to help farmers in early weed control decisions. However, like any database, a GIS is static and contains no domain specific knowledge to help its users manipulate their database. Recently, researchers have attempted to integrate GISs with expert systems to make them much more powerful (6, 7).

Geographic Information Systems are computer databases that organize information in a spatial framework. This allows the analysis of data based on part on location. A pilot project has been set up in the Yuma Valley to explore the use of GIS and study the influence of crop sequences, weeds, urban areas, and insect vector populations on the incidence of virus diseases of vegetables. The goal is to learn to collect field observations so that long term regional trends can be understood and visualized. Such information can then be used in management plans (5).

The Instituto Nacional de Investigaciones Forestales y Agropecuarias (INIFAP), is the Agricultural Research Service in the country. INIFAP worked, the growth potential of plant species in 12 important crops, using the GIS, IDRISI and Arc/Info in Puebla state, Mexico (4). While the Tamaulipas state's government, studied the actual soil use, using remote sensing, the objective was to have evidence for the environmental decision and major crop changes (2).
Recent developments in remote sensing and Geographical Information System technologies allowed the examination of ecological patterns at spatial scales larger than it was previously possible. At the same time, there has been increased appreciation for the importance of processes at small spatial scales in the structure of populations and communities (3).

The objectives of this study were: 1) To establish a geographical database of soils and elevations, with flexibility to generate specific products. 2) To identify and select soil types, with high growth and yield potential for plant species, and high potential of soil degradation. 3) To offer actions to reorganitize the use of the soil, based on an increment of crop productivity.

Materials and Methods. The variables considered in the description of soils from Tabasco, México, using Geographic Information Systems were characteristics as topographic and edaphic. Topographic information was used from the Digital Elevation Model of Instituto Nacional de Estadística Geografía e Informática (INEGI). Elevation information was taken every 30 arc seconds for latitude and longitude. A grid, with an elevation value every 900 x 900 meters was made. This model was also used to determine the slope of the land.

The edaphic information of a map (scale 1:250000) with soil classification system FAO/UNESCO (1) of INEGI was digitized by the GIS ARC/INFO. The first database was used to obtain altitude and slope images. The second was used to obtain soil units, physical and chemical phases, texture and soils depth, cities and water reservoirs images. All images were handled with the GIS IDRISI. For each soil unit and subunit, elevation, slope, city and water reservoirs, a map was generated with geographic position and areas in hectares. These images were edited with DPAINT.

The Hardware used was:

1. GTCO Roll-Up Digitizer (16 button cursor). It converts the position of the transducer into data for computer processing. Data output from the digitizer is in the form of an XY coordinate pair pinpoint the location of the cursor on the tablet surface.
2. Computer PC 80486, 50Mhz, 8 Mb RAM and 1.2 Gb Hard Disk.
3. Color graphics printer HP PaintJet XL.

The software used was:

1. The Geographic Information System, ARC/INFO. For digitizing the edaphological information map.
2. The Geographic Information System, IDRISI. For the entry, storage, management and display of raster images.
3. dBASE III Plus. To create the database of polygon outlet the digitizer.
4. DPAINT, For editing the output images.
Results and Discussion. The results of elevation, slope and edaphic database in Tabasco state are presented. The most frequent elevation in this state, are less than 100 masl (96.6%) and this image is presented in the Figure 1. The most frequent slope is less than 4% (96.43%) in Tabasco state, and it is presented in Figure 2. The clay texture soil is the most frequent (69.66%) in state’s area. Eighty two percent of state’s area has deep soils and the rest of the state has physical phases and litosol soils, Figures 3 and 4. The areas with water reservoirs in Tabasco was 83,835 hectares (3.49%) and its geographical localitation is presented in Figure 5.

Using GISs, it is possible to overlay state’s images with requirements of crops and to establish limits in the areas where the growth potential of crop is optimum, including its geographic locations and areas in hectares. An example is shown with Bannana crop, in Table 1. In this table, the reduction of the potential is noted when more requirements are added, having in Tabasco state only 589,923 hectares (24.56%) with potential zones for banana.

<table>
<thead>
<tr>
<th>REQUIREMENTS</th>
<th>LEVEL</th>
<th>AREA (Ha.)</th>
<th>AREA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevations</td>
<td>0 - 400 masl.</td>
<td>2'320,002</td>
<td>96.60</td>
</tr>
<tr>
<td>Slope</td>
<td>&lt; 4%</td>
<td>2'315,061</td>
<td>96.39</td>
</tr>
<tr>
<td>Litosol soils</td>
<td>No</td>
<td>2'306,961</td>
<td>96.05</td>
</tr>
<tr>
<td>Citys</td>
<td>No</td>
<td>2'306,394</td>
<td>96.03</td>
</tr>
<tr>
<td>Deep soils</td>
<td>No</td>
<td>1'921,887</td>
<td>80.02</td>
</tr>
<tr>
<td>Water reservoirs</td>
<td>No</td>
<td>1'840,968</td>
<td>76.65</td>
</tr>
<tr>
<td>Texture soils</td>
<td>Medium and sands</td>
<td>589,923</td>
<td>24.56</td>
</tr>
</tbody>
</table>

The overlaying images of the crop requirements, generated an image with the best areas for this crop. Figure 6.

Fourteen soil units and thirty nine soil subunits from the primary soil were registrated. The predominate soil unit, was gleysole with 1'398,465 hectares, (58.21%), Figure 7. This units are considered if soils than presented periods with excessive water in some periods of the year, and it is necessary to include drainage systems for their use in agriculture. Gleysol’s subunits are presented in Tabla 2.
FIGURE 1.- ELEVATIONS IN TABASCO

ELEVATIONS

| < 100 masl |
| > 100 masl |

FIGURE 2.- SLOPE EN TABASCO MEXICO

SLOPE

| < 4 % |
FIGURE 3.- CLAY TEXTURE IN TABASCO MEXICO

FIGURE 4.- DEEP SOIL IN TABASCO MEXICO
FIGURE 5.- WATER RESERVOIRS IN TABASCO, MEXICO

FIGURE 6.- POTENTIAL AREAS FOR BANANA IN TABASCO, MEXICO
There are Vertisol soil units in 269,568 hectares (11.22%), Figure 8, its subunits are: vertisol pelico and vertisol cromico, with 235,872 hectares (9.82%) and 33,696 hectares (1.40%), respectively.

Table 2.- Gleysol's subunits in Tabasco, México (area and percentage)

<table>
<thead>
<tr>
<th>SUBUNITS</th>
<th>AREA HECTARES</th>
<th>PERCENTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERTICO</td>
<td>645,327</td>
<td>26.86 %</td>
</tr>
<tr>
<td>EUTRICO</td>
<td>616,815</td>
<td>25.68 %</td>
</tr>
<tr>
<td>MOLICO</td>
<td>72,333</td>
<td>3.01 %</td>
</tr>
<tr>
<td>PLINTICO</td>
<td>38,718</td>
<td>1.61 %</td>
</tr>
<tr>
<td>HUMICO</td>
<td>18,144</td>
<td>0.75 %</td>
</tr>
<tr>
<td>CALCARIO</td>
<td>7,128</td>
<td>0.30 %</td>
</tr>
</tbody>
</table>

Others soil units were: luvisoles (3.07%), cambisoles (6.07%), regosoles (3.32%), litosoles (1.71%), and fluvisoles (1.97%). All these soil units represent 85.57% of the state's area. Others less important soil units in Tabasco state were: rendzina, histosol, zolonchac, feozem, acrisol, arenosol y andosol.

This study can be important to organize the soil resources in Tabasco state, and to plan areas and crops for better use of soil conditions; for example, the requirements of soil units for rice are: gleysoles, vertisoles and fluvisoles, and Tabasco state has 1,715,256 hectares with this soils. The GIS shows an image with the geographic localization of this areas. Figure 9.

Conclusiones. Geographic Information Systems are computer based tools that can help to collect, store, retrieve, change, and manipulate, spatial information from the soil database in a small region, state or a country.

This study can be important to organize the soil resources in Tabasco state, and to take this as start point of sustainable development. These results are important in the conversion of areas and crops to the best use of soil conditions.
FIGURA 7.- GLEY SOL SOIL IN TABASCO MEXICO

FIGURA 8.- VERTISOL SOIL IN TABASCO MEXICO
Figure 9.- CROP RICE'S UNITS SOIL IN TABASCO, MEXICO

Literature Cited.


Improving the Representation of Soil Spatial Variability in Geographical Information Systems: A Paradigm Shift and its Implications.

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Abstract.
Soil information is being increasingly used in Geographical Information Systems (GIS) in analysis, assessment and modelling of natural resources and phenomena. In this paper it is argued that the conventional approach to representing continuously varying soil spatial data of in GIS, using conventional classification and discrete mapping concepts, is in anachronic discordance with GIS modern technology. This paper points out at the need for a paradigm shift from classification and choropleth mapping, products of information generalization, in favour of retaining ungeneralized "hard" point-data in the database, and process these with a range of quantitative techniques for spatial estimation in GIS. The interpolative algorithms for estimation would be recalled as required in the GIS for the production of ad-hoc thematic maps of soil. The algorithms are based on recent geostatistical and mathematical techniques that offer a great potential for estimation and map generation. Such techniques are briefly reviewed in this paper and the technical and practical implications of the paradigm shift are discussed.

Introduction.
The current paradigm in understanding and representing soil spatial variability is based on conventional soil survey output, i.e. soil classes with sharply-defined boundaries and discrete soil mapping units. Mapping and natural resources agencies are spending considerable large sums of money in developing spatial databases in GIS, which essentially convert this kind of spatial representation of soil variability from paper maps to digital form. The consequences of literally transporting the shortcomings of such models of reality into GIS and using them combined with other environmental information demand serious consideration. Significant errors may accrue in interpretations resulting from analysing information based on assumptions of sharp or crisp boundaries of soil classes and internally-uniform soil polygons, when combined with other kinds of environmental information in GIS.

An alternative to the current paradigm relies heavily on the power of modern computer and database technology for storing ungeneralized point-data from the field and on applying to them recent geostatistical theory and techniques for estimation and generation of thematic maps. This alternative paradigm is by no means new. Earlier forms of it have been discussed before (e.g. Giltrap, 1983). However, only until recently, a relatively wide range of predictive techniques for estimation of both, ratio and categorical variables of soil, and for dealing with uncertainty.
and ambiguity in soil data have emerged and have been tested. The abundant experience generated from the application of these techniques that is reported in the soils literature, supports the view that a paradigm shift is possible.

The problems generated by generalization of soil information are discussed first together with the current models for representation of soil variability in GIS. A brief review of the range of geostatistical and other quantitative techniques for estimation of soil variables is presented. Their use in representations of soil variability in the GIS is addressed later, together with a discussion of the technical and practical implications of a shift in the paradigm of soil spatial variability representation for GIS.

Natural variation in soils and conventional representations.

The soil mantle is essentially a multivariate entity. Its unit of observation is the soil profile which represents a point on the landscape. Its description and characterization generates point-data. The multiple soil characteristics change at different spatial and temporal scales. Thus, soil variability is generally complex. For instance, the variability of a given soil property that is present in an area of one or more hectares may already be present in one square metre, (Beckett and Webster, 1971). Usually, variability increases with the size of the are sampled. But usually, at any given scale, more variability can be resolved by continuing sampling recursively at yet bigger scales.

In order to deal with such complexity, and with the relatively large volumes of data generated from field soil surveys, soil specialists were compelled to generalize soil information into manageable units of information that facilitated comprehension and communication in a pre-computer era. Information generalization occurs in two stages: (a) classification, and (b) mapping.

Soil classification uses crisp discrete threshold values of diagnostic variables or differentiae to allocate a soil sample (profile or auger) to a class. Class limits are sharp and discrete, yet by imposing an arbitrary breath of class and by letting the class be represented by a central concept (typical profile) the original field information is generalized. The second stage of generalization involves the finding of the spatial extent of the soil class. In reality, since most soil changes are not abrupt, the mapping of the continuous variation of the soil landscape into parcels of land with discrete boundaries involves information generalization and the inclusion of soils from other classes in the form of "impurities".

The problem.

What we term as soil is not a simple entity but, rather, a multivariate complex. Yet it is conceptualized and studied in terms of soil "individuals" (i.e. profiles) within which the multivariate nature of soil is forced into univariate discrete units. The units resulting form soil survey: soil classes and soil mapping units (i.e. soil polygons) are also discrete. For most practical applications these units are treated as though they were:

(a) Mutually exclusive.

(b) Internally homogeneous in all soil properties.
In reality, it has been shown that soil mapping units are disappointingly heterogeneous. Hence of low quality. In some instances the average "purity" of a soil map has been found to be not much larger than 50%. (Beckett and Burrough, 1971). The soil often varies in more continuous and complex ways than what is represented by the simple and rigid models offered by choropleth maps. Soil classes and the areal units mapped by conventional soil survey produce an incomplete, often unsatisfactory and even misleading picture of soil variation over the landscape. Moreover, a soil map is a rather inefficient means for the storage of soil information. Giltrap, (1983) has documented that only 6-7 bits of information can be retrieved from a soil map, once the information has been generalized, for every 100 bits of original point-data recorded in the field. This amounts to a serious information "loss" of about 90% due to generalization.

Clearly, the problem is that the models of soil spatial variability being digitized into GIS and stored in spatial databases, fail to recognize the rigid, yet imprecise and inaccurate nature of soil boundaries in a choropleth map, and the internal variability of soil polygons. The gloss of computer technology many times is taken by the inexperienced user as lending some form of implicit legitimacy to the soil mapping units displayed on the computer monitor.

**Current GIS data models for representing soil spatial variability**

In GIS the spatial variability of soils can be recorded following two approaches (i.e. data models).

a). The Raster data model. On the one hand, the continuous soil variation in the two dimensional space can be partitioned into really small regular units of the smallest size possible forming a grid of regular cells, with the expectation that the resulting cells or pixels are internally homogeneous. Obviously, the finer the pixels the more homogeneous but the larger the storage and processing requirements. So, the pixel size (its resolution) results from a compromise between storage and internal homogeneity of pixels.

One of the main advantages of this model is that, by increasing the pixel resolution, it could potentially deal with cells of such small size that homogeneity within the cell could be safely assumed. The map scale and the complexity of the phenomenologically-determined variability would indicate the most appropriate cell size (resolution) or level of partitioning. The most important disadvantage is the relatively high demand on memory storage that raster structures place on the computer for relatively small gains in resolution. It is important to note also that in this data model only one attribute (soil variable) can be displayed at a time. This corresponds to the attribute value in each cell. Thus, the multivariate nature of soils cannot be displayed simultaneously in other ways that by overlaying all the P raster layers necessary to represent the P soil properties characterizing a sample site. The raster data model is not commonly used for representing conventional soil survey spatial data. Grids are more frequently used in special cases where thematic mapping of individual soil properties (e.g. salinity) is required.

b). The vector data model. Partitioning the variability of soils can be done through the conventional procedure of classification and mapping from soil survey as indicated above. Soil spatial variability can be represented by various artifacts. Goodchild (1992) provides a useful list that can be adopted with slight modifications:
The collection of randomly or regularly located sample points (profiles or augers);

- Isorhythmic lines represented by a polyline this are "contours" with a given rate of variation indicated by the contour interval;
- An irregular array of triangles with the value of soil property recorded at every vertex (triangulated irregular network model);
- An irregular array of polygons where the value of each polygon, in this case a categorical value representing the soil class, is assumed constant within each polygon.

The latter is the most commonly used GIS representation of soil variability in current practice. The areas defined by the mapping unit delineations are represented by polygons with digitized crisp boundaries and with assumed maximum internal homogeneity. The sequence of points which is used to construct the polyline that defines the polygon is described by a vector of coordinate tuples (X,Y). Such approach to represent the continuous variability of soil properties in terms of discrete boundaries of "stepped" multivariate classes represents, obviously, an oversimplification of the true nature of soil variability. The polygon representation of variability is a data model of discrete entities. The problem with interpretations derived from this type of data model is that other quantitative or GIS models address the behaviour of such discrete entities rather than the continuum from which they were generated and of which they are abstractions.

The marrying of powerful and modern computer and information technology with oversimplified and obsolete concepts of soil variability represents a gross anachronism of cartographic concepts from last century, implemented in modern technology of the 20th century. Some of the negative consequences of using this type of representation of soil variability have been already pointed out above.

Both, the raster and vector data models are only useful views of reality. They are mental models of geographical variation that facilitate comprehension of what is potentially an infinitely complex world. However, of the two, the raster data model appears more suitable for representing continuous spatial variation of soils. The main problem is, then, how to generate raster representations of variability from "raw" soil point-data at particular sites. This represents a problem on spatial estimation known also as spatial interpolation, and there is a range of quantitative techniques which could operate on point-data for the generation of raster maps.

Quantitative tools for estimation, prediction and modelling of soil spatial variability.

Analytical quantitative tools for modelling and estimation of spatial phenomena, e.g. soils, have proliferated since the advent of computers and digital data processing (Webster 1977). As far as soil science is concerned, some of the most promising and exciting developments, however, have taken place only since the last decade with the application of Regionalized Variable Theory Matheron (1965, 1971), and the generic field of Geostatistics to modelling, estimation and representation of soil spatial variability. This section concentrates on recent developments on the application of Regionalized Variable Theory and Geostatistics to soil science, for they hold a promising potential for improving representations of soil spatial variability when coupled with developments in GIS technology.
Regionalized Variable Theory.

In studies of soil variation, it is appropriate to conceive a measurement of soil property $z$ at a given location $z(x)$ as being made at a point. The positional error in the location of that point, for the purposes of any likely analysis, is relatively small and negligible, and can be considered irrelevant.

Mathematically, the soil is a multivariate or vector field. Some variables may be measured on continuous (interval or ratio) scales, while others, such as soil class, may be discrete (nominal or ordinal). In principle, it is possible to determine the value of any soil property $z$ at any location $x$. Thus, an infinite number of sample sites would be required to capture geographical variation over a finite area completely. In soil survey practice, soil properties can be observed or measured only at a discrete number of locations. Therefore, prediction or estimation of values at unvisited locations during survey is essential.

Regionalized Variable Theory (RVT) is the basis of Geostatistics. It offers a range of techniques resulting from a robust body of theory to provide optimal estimation. Soil scientists have used such techniques and an abundant literature exists which is related to its application in soil science.

A regionalized variable $z(x)$ is a random variable that takes different values $z$ according to its location $x$ within some region. It can be considered a particular realization of a random variable $Z$ for a fixed location $x$ within the region. The realizations of a regionalized variable have two components: a structural or systematic component $m(x)$ and a random component $e(x)$. Thus:

$$z(x) = m(x) + e(x)$$

(1)

Stationarity.

If the systematic component is the same over the entire region, that is, if the expected value of the random function $z(x)$ is the same at all locations throughout the region it no longer depends on position $x$, so it is said to be first-order stationary when:

$$E[z(x)] = m$$

(2)

and

$$E[z(x) - z(x+h)] = 0$$

(3)

where $h$ is the vector of separation distances between the sample locations. Second-order stationarity demands that for all vectors $h$ the variance of the increment $z(x) - z(x+h)$ be finite and independent of position within the region:

$$\text{VAR}[z(x) - z(x+h)] = E[(z(x) - z(x+h))^2] = 2 \gamma(h)$$

(4)

Half of the variance $2 \gamma(h)$ is the semi-variance $\gamma(h)$ which depends exclusively on the vector of separating distances between points. Equations 2,3 and 4 are the "Intrinsic Hypothesis" (IH). The model of soil variation under stationarity is therefore:

$$z(x) = m + e(x)$$

(5)
Spatial dependence in soil.
Values of z at virtually the same location x are expected to be more alike than values for sites h distance apart (x+h), and as h increases the discrepancy between values increases too. This phenomenon describes the dependence of the values on distance or space. Spatial dependence is a fact of life in geographical variation. Regionalized variables and, almost invariably, soil properties exhibit spatial dependence. This can be quantified by semi-variances and by their plot against lag spacings h known as the semi-variogram.

The semi-variogram.
Structural analysis of spatial dependence can be quantified by the semi-variogram assuming the intrinsic hypothesis. The semi-variogram describes the spatially dependent component of the random function Z. The semi-variance at a given lag h is estimated as the average of the squared differences between all observations separated by the lag.

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N} [Z(x_i) - Z(x_i + h)]^2$$

where there are N(h) pairs of observations. The semi-variogram is central to geostatistical analysis and to the elucidation of the structures of spatial variability of soils in a given area. Its accurate estimation is critical in the success of spatial interpolation and the generation of raster maps, in that its estimated parameters are used in the solution of the system of equations for the various forms of Kriging interpolation. The reliability of the semi-variances depends on N(h) the number of pairs of point-data for a given lag. Thus it depends on the sampling density that the survey could afford.

Given a fixed sampling effort, the soil scientist would attempt to estimate a pre-survey or "reconnaissance" semi-variogram with minimum sampling effort and then use it as a diagnostic tool to determine what is the most promising spatial interpolation technique or other predictive means to use, given the situation of sampling effort and complexity of variability.

Spatial interpolation: optimal methods.
A family of techniques derived from RVT which are a form of weighted local moving averaging and termed as Kriging in its various forms is being used extensively by soil scientists as spatial predictor, and hence, for reconstruction of the continuum of spatial variability of a given soil property over an area, starting from point-data. Kriging in its various forms is optimal in the sense that it provides estimates of values at unvisited sites together with a measure of the prediction error, known as the estimation variance. Isorhythmic or raster maps made by block or other forms of kriging are alternatives to conventional soil maps where properties can be measured at relatively close spacings. Kriging depends on first computing an accurate semi-variogram, which measures the nature of spatial dependence for the property. Estimates of semi-variance are then used to determine the weights applied to the data when computing the averages, and are presented in the kriging equations.
**Point Kriging.**

This is the simplest of the Kriging techniques. The essential equations are reviewed here for reference to other variants of Kriging. The set of sampling points can be represented as \( z(x_1), z(x_2), z(x_3), \ldots, z(x_n) \). The estimate of a value \( z \) at any point \( x_0 \) can be given by:

\[
z_0 = \lambda_1 z(x_1) + \lambda_2 z(x_2) + \cdots + \lambda_n z(x_n)
\]

or

\[
z(x_0) = \sum_{i=1}^{n} \lambda_i z(x_i)
\]

the coefficients or weights \( \lambda_i \) take into account the known spatial dependence expressed in the semi-variogram. The estimates are unbiased in that,

\[
\sum_{i=1}^{n} \lambda_i = 1
\]

and the estimation variance is minimum and given by:

\[
\sigma_z^2 = \mu
\]

where \( \mu \) is the matrix of semi-variances between the point to estimate and every other point and \( \mu \) is the Lagrange parameter used in the optimization. Other important computational and analytical aspects of the application of the technique can be found in Journel and Huijbregts (1978), and Burgess and Webster (1980).

**Block Kriging.**

This could be understood as an extension of point kriging. It provides average estimates for discrete areas or blocks instead of point estimates. Such blocks can be set to coincide with the pixel size of a desired raster map. The estimated value of property \( z \) for any block \( V \) is a weighted average of the observed values \( x_i \) in the neighbourhood of the block:

\[
z(V) = \sum_{i=1}^{n} \lambda_i z(x_i)
\]

The minimum estimation variance for block \( V \) is:

\[
\sigma_V^2 = \sum_{i=1}^{n} \lambda_i \gamma(x_i, V) + \mu - \gamma(V, V)
\]
where $\gamma(x_i, V)$ is the average semi-variance between sample points $x_i$ in the neighbourhood and those in the block $V$, and $\gamma(V, V)$ is the average semi-variance between all points within $V$ (i.e. the within-block variance). An important fact to consider is that the estimation variance of block kriging is always less than that of punctual kriging because the within-block variance is removed from the error term. Block kriging is an improvement over point kriging in terms of estimation. Considerable improvements in average estimation precision can be made with block kriging over point kriging. Moreover, the maps produced by block kriging appear to be smoother. This is due to the smoothing of local discontinuities.

Block kriging can produce thematic raster maps of individual soil properties by optimal interpolation. These maps would accurately depict spatial variation with a known estimation error if an accurate semi-variogram can be estimated, and when the block size is set to be conveniently equivalent to the pixel size required for the resolution desired in the raster map.

**Co-regionalization and Cokriging.**
This is a method for estimating one or more variables of interest using data from several variables by incorporating both, spatial correlation and intervariable correlation. In practical terms, a soil property which was not sufficiently sampled to yield good estimates can be improved in its estimation by considering the spatial correlations between this variable and other better-sampled variables. This is called "the undersampled problem".

The cokriging equations are expressed in terms of the variograms and cross-variograms. The cross-variogram of two variables $z_j$ and $z_k$ is defined by:

$$\gamma_{jk}(h) = \gamma_{jk}(h) - \frac{1}{2} \text{Cov}[z_j(x+h), z_k(x)]$$

where Cov denotes the covariance. If $Z(x) = [Z_1(x), ..., Z_m(x)]$ denotes the values of variables 1,...,m at location $x$, and there are $x_1...x_n$ sample locations with data $Z(x_1)...Z(x_n)$. Then, the cokriging estimator is a linear combination of all available data values of all the m variables in co-regionalization, and is given by:

$$Z^*_x = \sum_{j=1}^{m} \sum_{k=1}^{m} \lambda_{jk} Z_{jk}$$

where the $\lambda_{jk}$ are the weight matrices. If each component of $Z(x)$ satisfies the intrinsic hypothesis, then this estimator is unbiased.

The great potential of Cokriging in estimation and representation of soil spatial variability is obvious and stems from its ability to consider intervariable relationships to be transported to
spatial co-regionalizations. This technique exploits these relationships between variables or co-
regionalizations to estimate the one soil property of interest for which there are no sufficient data,
on the basis of existing information for the other related variable. In a certain way, a similar
operation could be performed in GIS alone. A raster map could be calculated from an existing
map through a mathematical expression relating both maps. The mathematical model could be
built in GIS as a map calculation expression, with the existing map as an independent variable.
However, cokriging offers the quantitative optimal approach, with knowledge of the nature of the
cointegration.

Disjunctive Kriging (DK) and mapping the conditional probability.
In many applications of soil information, particularly in the environmental assessment and the
agronomic fields, it is not only necessary to know the values of a soil property at given locations
but the probability of exceeding some predetermined threshold values which may be related to
environmental standards or expected land-use outputs as in land evaluation (see, for example,
Yates, et al, 1986; Webster and Oliver, 1989; Staritsky et al., 1992; Stein, 1992; Finke and Stein,
1992). Disjunctive kriging provides such a predictive tool.

Disjunctive kriging (DK) provides estimates of values of random variables spatially distributed
by combining data non-linearly and with minimum variance. This technique is as good or even
better than linear estimators in the sense of minimum variance and exactness of the interpolation.
DK also provides an estimate of the conditional probability that a random variable located at a
point or averaged over a block in a two-dimensional space is above some specified cutoff or
tolerance level, and this can be written in terms of the probability distribution or the density
function. Data are transformed using Hermite polynomials to a normal distribution, and this
transformation produces a stationary bivariate normal distribution for all pairs of data. The
bivariate distribution allows for the calculation of the conditional probabilities of exceedance or
shortfalls from a specified critical threshold. Soil spatial variability can be represented by

The difference of DK with simple kriging is that the latter is a Best Linear Unbiased Estimate
(BLUE) and demands that the assumptions of Matheron’s Intrinsic Hypothesis be satisfied. In
contrast, DK is a more advanced technique involving non-linear estimation that is potentially
more precise, and even more importantly, enables probabilities to be estimated.

The mathematical formulation of DK is not simple and only a summarized account is provided
here. Take the values \( z(x_1), z(x_2), \ldots, z(x_n) \) of a soil property at locations \( x_1, \ldots, x_n \);
denoting both spatial coordinates.

The equation of ordinary kriging (eq.8) may be regarded as a special case of a more general
estimator:

\[
Z_p(x_0) = \sum_{i=1}^{n} f_i[z(x_i)]
\]
where each $f_i$ is a function of $Z$ at $x_i$. In Disjunctive kriging the objective is to find the functions (in contrast to the coefficients or weights as in ordinary kriging) that minimize the estimation variance.

The assumptions underlying disjunctive kriging are that the property $Z(x)$ is the outcome of a second-order stationary process and that the bivariate probability distribution is known, and that this too is stationary throughout the region of interest.

The DK method utilizes the autocorrelation function in determining the weighting coefficients for a series of Hermite polynomials. Second order stationarity implies that the variance exists, in which case the autocorrelation can be written in terms of the semi-variogram as follows

$$\rho(h) = 1 - \frac{\gamma(h)}{\gamma(\infty)}$$

where $\rho(h)$ is the autocorrelation function, $\gamma(h)$ is the semi-variogram and $\gamma(\infty)$ is the sill value of the semi-variogram, and $h$ is the distance vector. To obtain the DK estimator, the original data $Z(x)$ must be transformed into a new variable, $Y(x)$ with a standard normal distribution. This function is invertible. The transformation guarantees the required distribution and has the form:

$$z(x) = \Phi[y(x)]$$

where the function $\Phi$ is a linear combination of Hermite polynomials, which can be defined by

$$\Phi[y(x)] = \sum_{k=0}^{\infty} Q_k H_k(y(x))$$

Where $H_k[y(x)]$ is a Hermite polynomial of order $k$, and $Q_k$ are the Hermitian coefficients which are determined using properties of orthogonality, and by numerical integration as follows;

$$Q_k = \frac{1}{k! \sqrt{2\pi}} \sum_{j=1}^{M} W_j \Phi(v_j) H_k(v_j) \exp(-\frac{v_j^2}{2})$$

where $v_j$ are specific values of $y$ and $w_j$ are the corresponding weights for Hermite integration. The DK estimator is found from a sum of unknown functions of the transformed sample values, $Y(x)$. So, the DK estimator can be found in the same fashion as in ordinary kriging. An unbiased estimator with minimum estimation variance is sought. This results in the following system of equations:
the series in $k$ can be safely truncated to no more that $M=10$ terms, and

$$Z_D^*(x_0) = \sum_{k=0}^{M} Q_k H_k[y(x_0)]$$

(20)

where $\lambda_k$ represents the estimated value of the $k$th Hermite polynomial at the estimation site.

To obtain an estimated value for the Hermite polynomial, the DK weights, $\lambda_k$, must be found by solving the linear kriging equation for each $k$.

$$\sum_{i=1}^{n} \lambda_k [p(x_i,x_j)]^k - [p(x_o,x_j)]^k \text{ for } j=1,2,...,n$$

(22)

where $\rho(x_i,x_j)$ is the autocorrelation between the two sampling points $x_i$ and $x_j$ and $\rho(x_o,x_j)$ is the spatial correlation between the point to estimate $x_o$ and the sampling points. When $k=0$ this last equation represents the unbiasedness condition. The DK variance is:

$$\sigma_D^2 = \sum_{k=1}^{K} k! Q_k^2 [1 - \sum_{i=1}^{n} \lambda_k (\rho)^k]$$

(23)

So, given a critical or threshold value $Z_c$ there is a corresponding $y_c$. So the probability that $Z_c$ is exceeded given the observed $z(x_i), i=1,2,...,n$, is:

$$P(x_0) = \text{Prob}[z(x_o) \geq Z_c | x_1(x_2),...,z(x_n)] = \text{Prob}[y(x_o) \geq y(x_1),y(x_2),...,y(x_n)]$$

(24)

The conditional probability can be written in terms of the conditional expectation. The estimated probability density function $PDF_{DK}(x_o)$ can be computed by taking the derivative of the conditional probability function with respect to $y_c$ to give:

$$PDF_{DK}(x_o) = g(u) + \sum_{k=1}^{K} H_k(u)H_k^* [y(x_o)]/k!$$

(25)
where Pf is the probability density function of Disjunctive Kriging at location Xo, g(u) is the derivative of the probability integral for the normal distribution. The last equation provides the disjunctive kriging estimate P(Xo) of the probability that the threshold is exceeded; i.e. z(xo) >= Zc. The probability may be integrated over a block B. Thus, P(B) estimates the average probability that z(xo) >= Zc within the block.

The use of prior information: point data, soil classes and maps.
Field soil surveys have produced a considerable volume of information in many parts of the world. Such surveys attempt to characterize and represent the spatial variability of soils. The major soil survey outputs are both in terms of discrete entities. These are: a). Point-data (profile or auger) data. b). Categorical data (soil classes expressed as mapping units). None of these represent satisfactorily the reality of continuous variation of soil properties which the most frequent case. This type of variables are best modelled by techniques derived from Regionalized Variable Theory which takes into account their stochasticity and their spatial autocorrelation. For soil properties whose variation over the two-dimensional space is discrete, they are best modelled as deterministic variables in the same way as the classes or mapping units in a soil map. For practical applications, usually soil information is available in both forms: deterministic (soil maps and classes) and stochastic (point-data are but realization of such continuous random function). Thus, a crucial point in studying, modelling and representing soil variability is how to make the best use of existing soil information, of whatever nature, to improve on estimation, modelling and representation of soil spatial variability in a GIS for solving practical problems.

Studies carried out at different scales of variation (Stein, 1992; Ponce-Hernandez and Beckett, 1989) have showed that major soil mapping units proved to be appropriate at the smallest scale, whereas geostatistical estimation proved to be more useful at the largest scales. Also, that point-data, geostatistical estimation and the products of conventional soil survey (i.e. soil mapping units) can be used complementarily for improving estimation and representations of soil variability (Ponce-Hernandez and Beckett, 1989). For instance, in situations where a "reconnaissance" semi-varioogram has elucidated the presence of long-term trends, non-stationarity in the data, or the presence of major discontinuities or strong anisotropies, mapping units were used to partition the data into subsets and so to split the trend or remove the impediments to geostatistical estimation. This is a more practical solution to non-stationarity and discontinuities than modelling the trend (i.e. usually polynomial), then kriging the residuals from the trend and add them back to the trend (Ponce-Hernandez and Beckett, 1989).

The model proposed by King et al (in this proceedings) conceptualizing the Soil/landscape in terms of functional units could be also a very useful starting point to geostatistical estimation. These type of complementarity combines, to a great advantage, the rigour of mathematical propositions with human intuitive models of reality. The best of both worlds.

Indicator Kriging for categorical data.
The indicator approach is relatively new in soil science. This technique can be adapted to serve as a method to describe categorical soil data, for instance, it can be used to predict the unknown classes at unvisited locations. Since great part of the recorded information during survey is qualitative (i.e. about 80%). It is difficult to interpolate these qualitative data using geostatistical techniques from RVT. Indicator Kriging appears to provide a solution to the problem of estimation and prediction of categorical variables through non-parametric geostatistics. Bierkens
and Burrough (1992) have used the "Sequential Indicator Simulation" (SIS) to assess the uncertainties in resource analyses (i.e. soil water table classes) caused by impurities in classified maps that are used as input for these analyses.

The soil mapping units or polygons can be seen as predictors (albeit usually poor) of the unknown classes at unvisited locations. The quality of these maps can only be investigated afterwards by taking randomly (in space) sufficient additional borings. The practice of drawing boundaries around clusters of equally classified borings is rather subjective.

Second, the map purity, a measure of the quality of (a particular part of) the map, can only be obtained by additional sampling. Furthermore, the map purity which is thus obtained is spatially invariant within one map unit and independent of the number of borings taken and the classes found at the boring sites. Obviously, if a class is predicted at an unvisited location, the uncertainty of this prediction should be larger if the surrounding borings all belong to different classes. This uncertainty should decrease when more borings are placed around the location of the prediction. The "classical" method, i.e. predicting categorical data by making choropleth maps and assessing the map purity afterwards, does not account for these effects.

In the practice of land resources assessment, maps of categorical variables are often used as an important source for interpretations. Conventional land evaluation procedures assume that these maps are correct. The errors in land resources assessment caused by impurities in the input maps are seldom taken into account. An important reason for this is the lack of a comprehensive statistical model to predict categorical data and to estimate the uncertainties of these predictions. Bierkens and Burrough, (1992) used indicator kriging to estimate the conditional probability of occurrences of classes of categorical data, given the classes found at the original sampling sites. Bierkens and Burrough (1992) provide an excellent description of what he terms the Sequential Indicator Simulation which in essence is a non-parametric estimation of spatial distributions (Journel, 1983). The theoretical development considers at a certain location \( x_0 \) in an area, a random variable \( N(x_0) \) which can take any of the values \( \{U_1, \ldots, U_m\} \). Where \( N(x_0) \) is the event of finding a given soil class \( U \) at location \( x_0 \), and \( U_m \) are the soil classes \( U \). The cumulative probability distribution function, (cpdf) given by:

\[
F_{U_0}(U;x_0) = P[N(x) \in \{U_1, \ldots, U_k\}]
\]

is the probability of \( N(x_0) \) at location \( x_0 \). The function \( N(x) \), \( x \) in \( \mathbb{R}^n \) is considered a random field consisting of categorical variables (i.e. soil classes). If \( n \) observations or field checks on the classes are available, the occurrence of a class may be predicted by estimating the conditional probability on each of the \( m \) classes, given the \( n \) observations. Thus, an Indicator Random Function or indicator transform \( I(U_k;x) \) of \( N(x) \) is defined as:

\[
I(U_k;x) = \begin{cases} 
1 & \text{if } N(x) \in \{U_1, \ldots, U_k\}; \\
0 & \text{if } N(x) \in \{U_{k+1}, \ldots, U_m\}\end{cases}
\]
The indicator transform has important properties:

\[ E[I(U^x)] = P[N(x) \in (U_1, \ldots, U_k)] - F_N(U^x) \]  

(28)

The expected value is the first order cumulative probability distribution function of \( N(x) \). And:

\[ E[I(U^x) \cdot I(U^x')] = P[N(x) \in (U_1, \ldots, U_k)] \]  

(29)

where:

\[ N(x') \in (U_1, \ldots, U_k) = F_N(U^x') \]  

(30)

The second moment of the Indicator Random Function is a measure of the spatial connectivity of the mapped classes. Thus, the conditional expected value of \( I(U_i; x) \), given a set of classified soil inspections in the field (auger borings) \( \{n_i; x_i : i \in (n)\} \) is given by:

\[ E[I(U^x) | n_i x_i : i \in (n)] = P[N(x) \in (U_1, \ldots, U_k) | n_i x_i : i \in (n)] \]  

(31)

From this equation it can be seen that the conditional probability can be estimated by estimating the corresponding indicator conditional expected value \( E(I(U_i; x)) \). The derivation of the conditional expectation can be rather complex. Instead, it can be approximated by a function of simple Kriging weights, assuming that \( I(U_i; x) \) is a second order stationary function. The kriging weights are obtained by solving and Indicator Simple Kriging System using the stationary Indicator Covariance Function \( C_I(U_i; h) \) for the threshold \( U_i \):

\[ \sum_{i \in (n)} \lambda_i (U^x) \cdot C_I(U^x_i - x_j) = C_I(U^x_i - x_j), \quad \forall j \in (n) \]  

(32)

where \( k = 1, \ldots, m-1 \).

The indicator variograms can be inferred from the indicator data using the estimator:

\[ \gamma_I(U_i; h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [I(U^x_i) - I(U^x_i + h + \Delta h)]^2 \]  

(33)

being \( n(h) \) the number of pairs of indicator data that are at a distance \( h + \Delta h \) apart. Thus, for every soil class \( U_i(i=1, \ldots, m) \) the probabilities on a certain soil property value (SV) are known by: \( P(SV = z | U_i) \). Then the probability distribution of a soil property value at an unvisited location \( x \) can be estimated with:

\[ P(SV(x) - z) = \sum_{i=1}^{m} P(SV = z | U_i) \cdot P^*(N(x) - U_i) \]  

(34)

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Thus, for a set of validation points (augers) the average purity of a map (AMPe) over all
validation points can be estimated from:

$$\text{AMPe} = \frac{1}{N} \sum_{i=1}^{N} P_i$$

Hence, AMPe values can be compared to observed average map purity to provide an evaluation
of the accuracy of the indicator simulation procedure. The potential of the indicator kriging
function for predicting categorical variables and its utility for assessing the purity of maps
representing soil spatial variability in GIS is only beginning to be realized.

**Fuzzy Sets for representing uncertainty in soil classes and maps.**

The development of Geographical Information Systems and digital mapping has encouraged the
conversion of analogue (paper) maps to digital maps. Many agencies, national and international
are spending large sums of money on the development of such spatial databases in digital form.
However, the maps being digitized correspond to discrete spatial units with "crisp" boundaries,
which attempt to encapsulate the multivariate and continuous nature of soil variability. Once in
digital form in the GIS, these polygons are, reclassified, overlaid, recombined and new
interpretive maps are generated from them. The quality and usefulness of such maps clearly
depends on the quality of the maps from which they were generated. The problems of sharply
delineated, internally homogeneous units of soil for representation of soil spatial variability are
quite evident and have been outlined all throughout this paper. They have been summarized by
Burrough (1989) as: (a) Internal purity of mapping units; (b) spatial variation within soil mapping
units; (c) measurement error of attributes and entities, and (d) imprecisely formulated data
 descriptions.

Fuzzy sets (Zadeh, 1965; Burrough, 1989) can be an effective technique for characterizing classes
or soil units with a type of imprecision which is appropriate for entities which should not have
sharply-defined or crisp boundaries. A fuzzy set \( Y \) in \( X \), where \( X = \{x\} \) is a space of objects, is
the set of ordered pairs:

\[
Y = \{(x, \mu_Y(x)) : x \in X\}
\]

\[
\mu_Y(x) \hspace{1cm} 0 \leq \mu_Y(x) \leq 1
\]

where \( \mu_Y(x) \) is the "grade of membership" of \( x \) in \( Y \), usually in the range
where 1 represents full membership to the set. The Semantic Import Model is an a priori
membership function to compute the grade of membership or simply the membership function.
It is given by:

\[
\mu_Y(x) = \frac{1}{1 + \gamma(x-c)^2} \hspace{1cm} \text{for } 0 \leq x \leq P
\]
where $y$ is the parameter governing the shape of the function, and $c$ defines the value at the central concept of the class (e.g. the "typical" profile of the soil class). The position of the "crossover" point and the form of the membership function can be easily controlled with these two parameters. For "crisp" boundaries $\mu_y(x) = 0$ for $x<b$; and $\mu_y(x) = 1$ for $x>=b$; where $b$ defines the exact boundary condition for membership to a class.

Membership functions can be drawn for different soil properties within soil profiles or augerings and use such functions for fuzzy operations to answer simple or complex queries. Land suitability assessments based on Fuzzy operators with crossover values representing the critical values of land-use requirements, give better results than the strict Boolean approach (crisp boundaries) with operators "OR", "AND", etc. (Burrough, 1989).

Membership functions can be drawn for different soil properties within soil profiles or augerings and use such functions for fuzzy operations to answer simple or complex queries. Land suitability assessments based on Fuzzy operators with crossover values representing the critical values of land-use requirements, provide more realistic results than the strict Boolean approach (crisp boundaries) with operators "OR", "AND", etc. We would concur with Burrough, (1989) that the strength of the fuzzy set approach is that it is based on the premise that nature, or at least our perception of it and our language about it, may be inherently vague and imprecise, and therefore the fuzzy approach makes no attempt to represent it otherwise.

A paradigm shift in representing soil spatial variability.
Considerable evidence has accumulated through research into spatial variability of soils, to indicate that the old paradigm of information generalization through the two stages: classification and mapping of soils, results in incomplete, inadequate and sometimes misleading descriptions and representations of soil spatial variability. The inclusion of sharply-delineated, internally-homogeneous, integrative units of soils into large digital databases in GIS, currently developed or under development in many parts of the world, carries the serious risk of assuming validity and high quality in these maps when displayed through the gloss of digital technology. The indiscriminate use of such representations of soil variability in GIS analysis, without questioning their quality and validity, inevitably, will have a negative impact on the quality and usefulness of the new maps and products derived from the original maps through GIS analysis.

The pre-computer paradigm of information generalization prevalent even in current cartographic representations of soil variability by conventional soil survey output, found its justification, in the past, due to the lack of computer power, media and algorithms, to store, manipulate and analyze large volumes of point-data generated from those surveys. However, today’s computer technology has the power, memory sizes and algorithms for data manipulation and analysis, which is sufficient to seriously challenge the need for continuing with models of spatial variability based on information generalization through classification and choropleth mapping. This situation represents a major anachronism between technological developments and conceptual backwardness.
A paradigm shift must occur to prevent the serious information losses and errors that accrue through generalization of soil information. Perhaps more importantly, to avoid the frequent abuse of discrete representations (i.e. soil classes and discrete mapping units) through analysis with other types of data in GIS. The shift must occur towards retaining "raw" point-data in the databases of GIS and combine these with a collection of predictive algorithms, (e.g. the various forms of kriging) for spatial interpolation and prediction in the two-dimensional space. Thematic raster maps generated by the application of interpolative algorithms to raw point-data, can be generated by request, on an ad-hoc basis. A diagram illustrating the processing of point-data under the new paradigm is illustrated in figure 1.

Paradigm-shift in soil variability representations in GIS: implications.

The methodological and practical implications of the paradigm shift in representing soil spatial variability for GIS could be many. However, among the most important are:

a). The use of existing or prior information: i.e. soil maps and soil classifications. For instance, in situations where the underlying spatial variability does not meet the intrinsic hypothesis of geostatistics, or where the random component of variability is exceedingly large to the expense of spatial dependence which may be negligible, or where there are discrete and abrupt changes in soil brought about by discontinuities in the landscape, soil mapping units and classes can be of great help in partitioning trends or stratifying variability for semi-variogram calculation and for spatial interpolation. The benefits of the complementary use of soil maps and geostatistical estimation have been sufficiently demonstrated and discussed, e.g. Ponce-Hernandez and Beckett, (1989).

b). Estimation of a pre-survey or "reconnaissance" semi-variogram (RSV) for use as a diagnostic tool. Perhaps the most crucial aspect in the paradigm shift of spatial variability representation in GIS, is the ability to estimate a reliable pre-survey semi-variogram (RSV) with minimum point-data (i.e. pre-survey sampling effort), and to use the structures of such RSV to decide on the best technique for spatial estimation, i.e the form of kriging interpolation, map polygons, classes or suitable combinations of the above. On this point rests the applicability of the family of techniques described above, and the possibility of generating, inside or outside the GIS, ad-hoc thematic raster representations of soil properties on request. This amounts to the desaggregation of the multivariate nature of soil data into the univariate spatial representations of thematic information.

c). Improvement on predictive techniques. The various forms of kriging interpolation described above, and other forms of prediction in the spatial and temporal domains are not perfect yet. They will, no doubt, be improved in their predictive capacity and other new techniques will come to complement the present ones, given the exciting developments that are taking place, particularly in the applications of Regionalized Variable Theory to soil studies. However, the body of theory and bulk of techniques for spatial estimation that are present can now support the paradigm shift from the production of generalized discrete information to the ad-hoc production of continuous representations of soil properties. Currently, in the form of thematic raster maps.
Figure 1: Generation of thematic raster maps from interpolated grid cells derived from spatial interpolation of point-data.
d). Database development. It is highly debateable whether to continue investing effort and resources in the development of digital databases with generalized soil information represented by soil classes and soil polygons as entities in the database, or whether to concentrate on developing a database of stored point-data coupled by an interpolative algorithms base consisting of improved techniques for reconstructing spatial variability of soils from spatial interpolation.

Currently, many national and international agencies are involved in digital database development into GIS. Therefore, there is a sense of urgency in bringing this debate to the scientific community. This paper aimed at contributing to such debate in an attempt to bring clarification into what is the most appropriate path to follow.

e). Improvements in software and in hardware devices. The paradigm shift may bring considerations about improving hardware devices, storage of raster data structures or even conceivably, an entire new data structure which could be more suitable for representing the continuous and seemingly nested structures of spatial variation at different spatial scales. To be effective, GIS software will require the inclusion of the whole range of geostatistical techniques as modules for structural analysis and estimation (Ponce-Hernandez, 1993). These two software packages are being used independently often creating non-trivial data format compatibility problems during data import either way.

Conclusions.

Conventional representations of soil spatial variability are based, for the most, on a simplistic model of natural variation consisting of sharply-defined, internally-homogeneous soil units (polygons) and crisp class boundaries. These entities are the result of a two-stage process of information generalization. Such model is inappropriate for GIS representation and analysis for it encourages false assumptions about data accuracy and quality.

Regionalized Variable Theory has provided soil scientists with a body of theory from which powerful techniques for elucidating the structures of spatial variation of soils and for estimation have been derived. The values of both, ratio and categorical variables whether at points or at small areas (blocks), can be optimally estimated by the various forms of kriging interpolation, and the variance of those estimations be known. The probabilities that the values of a given soil property exceed a meaningful threshold value can also be computed. Membership functions indicating the degree of membership to a category, e.g. a soil class, may be calculated to represent uncertainty, ambiguity and other forms of "fuzziness" present in soil data. Some of these techniques, e.g. Indicator Kriging, fuzzy sets, may also be used to assess and model errors in spatial databases in GIS.

The state of knowledge about the theory, methods and techniques to reconstruct continuous variation in the two-dimensional space from point-data, or from other outputs from soil survey is such, that it would support a paradigm shift in the way we perceive, collect, store and process soil information. The shift would move from the current paradigm of generalization of point-data into sharply-bounded and internally-homogeneous soil classes and map units, to a paradigm of retaining and storing ungeneralized point-data and ad-hoc reconstructions of continuous
representations of the spatial variability of soil properties by means of a set of algorithms for interpolation and estimation operating on them. The advances in computer technology and database design permit now the storage and processing of the large volumes of data generated from survey and their representation and analysis in GIS.

References.


A World Reference Base for Soil Resources

Convener: Alain Ruellan (France)
Co-convener: Charles Leo Jacques (Mexico)

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Foreword

A. Ruellan, Convenor, Chairman of the WRB Working Group.

To celebrate the occasion of the XVth International Congress of Soil Science, a first draft of the complete "World Reference Base for Soil Resource" is presented to all participants.

This monograph is the result of 14 years of international work, with the participation of numerous specialists and the strong support of ISSS (mainly commission V), FAO, ISRIC, and UNESCO.

It must be emphasized that the present publication is to be regarded as a working document rather than an end product, and that further contributions and reactions are sought to widen the basis of the WRB.

Since 1986, I have had the responsability of chairing the WRB Working Group. This has been a very pleasant and interesting task because of the enthusiastic participation of all contributors. I would like to thank each one of them, and to make special mention of R. Dudal, who has been the secretary of the group, and O. Spaargaren, who prepared this version of the "World Reference Base for Soil Resource".

During the XVth International Congress of Soil Science, the Working Group will meet to discuss the WRB in its entirety. The Symposium ID 22 is only an illustration of WRB, its objectives and its principles.
Why a World Reference Base for Soil Resources

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A world reference system for soil resources is a tool for the identification of pedological structures and their significances. It serves as a basic language in soil science and facilitates:

- the scientific communication;
- the implementation of soil inventories and transfers of pedological data: elaboration of different systems of classifications having a common bases, of maps, etc...;
- the international use of pedological data, not only by the soil scientists but also by other users of the soils and of the soil science, such as geologists, botanists, agronomists, ecologists, farmers, foresters, civil engineers, architects, etc...; the objective is to improve upon:
  . the use of soil data for the benefit of other sciences (geology, ecology, agronomy, sociology, etc...);
  . the evaluation of soil resources and of the potential use of the different types of soil cover;
  . the monitoring of soils, particularly soil development which is dependent on the way soils are used by the human communities;
  . the validation of experimental methods of soil use for sustainable development, without destruction of the soil potential, and, if possible, to improve on them.
  . the transfer of soil use technologies from one region to another.

The credibility of soil science suffers from the lack of a generally accepted system of soil classification. It seems imperative that an international agreement should be reached for the distinction and definition of major soil groupings, at least for one or two categories at the highest level of generalization. The great diversity of soils in different countries seems to justify national systems at the lower levels. It is indeed hardly possible that one overall system can adequately serve global, regional and local objectives at the same time. A two-pronged approach may further facilitate the establishment of an international consensus with regard to the major soil groupings which constitute the world's soil cover.

The objective of the WRB, World Reference Base for Soil Resources, is to provide scientific depth and background to FAO's Revised Legend of the Soil Map of the World (1990), so that it incorporates the latest knowledge relating to the global soil resources and interrelationships. To include some of the most recent pedological studies and to expand use of the system from an agricultural base to a broader environmental one, it was recognized that a limited number of important changes to the 1990 legend was necessary.

WRB is not a new international soil classification system, but a base for a better correlation between national systems of soil classification. The morphological characterization of soils is emphasized rather than a purely analytical (laboratory) approach. Lateral aspects of soil and soil horizons distribution, as characterized by topo- and chronosequences, receive appropriate attention.
Introduction to the World Reference Base for Soil Resources

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Abstract. The World Reference Base for Soil Resources (WRB) is the successor to the International Reference Base for Soil Classification (IRB). Its task is to apply the IRB principles of definitions and linkages to the existing classes of the revised FAO legend (4) with as main objective to provide to it scientific depth and background, so that the latest knowledge relating to global soil resources and interrelationships is incorporated.

It is proposed that the WRB comprises 29 major soil groups. Three new major soil groups, i.e. Cryosols, Stagnosols and Umbrisols, are introduced compared to the revised FAO legend, while Greyzems are deleted and Plinthosols and Podzoluvisols renamed Sesquisols and Glossisols, respectively. The FAO terminology of diagnostic horizons and properties is retained and diagnostic soil materials were defined additionally. The WRB diagnostic horizons, properties and materials are described and defined with emphasis on field identification. Analytical criteria are given to help the identification. Some modifications are proposed to diagnostic horizons, properties and materials defined in the revised FAO legend and a number of new ones formulated. Proposed adaptions are described in the text and summarized in Table 1.

The basic philosophy of the WRB is that the final soil groups must show coherence in geographical distribution and pedogenetic character, and that soils are to be characterized by their morphological expression rather than by analytical data. In a number of proposed major soil groups this has led to divisions and in others to amalgamation. The Leptosols are given as an example. Other problems encountered are the treatment of man-influenced soils that do not qualify as Anthrosols, the Luvisol-Alisol-Acrisol-Lixisol, the Andosol-Podzol and the Acrisol/Lixisol-Ferralsol interfaces, and standardization of depths used in describing and defining soil units.

The World Reference Base for Soil Resources, like the FAO legend, continues to build on existing soil classification systems. Examples are the description, definition and subdivision of Anthrosols and Andosols. On the other hand some proposals result from new ideas not yet reflected in published classification systems.

The final result is to become a well described and defined World Reference Base for Soil Resources that is internationally acceptable by the community of soil scientists. It also intends to serve different applications in related fields, such as agriculture, geology and ecology.

INTRODUCTION

Historical background. The World Reference Base for Soil Resources (WRB) is the successor to the International Reference Base for Soil Classification (IRB), an initiative of FAO and Unesco, with the support of UNEP and the International Society of Soil Science, dating back to 1980. The IRB project was launched in an attempt to reach an international agreement on soil classification, both with regard to the principal classes to be recognized, as well as to the criteria and methodology to be applied for defining and separating them.
During the early 1980's a number of meetings were held in Sofia, Bulgaria, to discuss the
possibility of establishing such a reference base, to work out modalities for the determination
and quantification of diagnostic characteristics to be used in defining categories and classes, and
to decide on the groups of soils to be recognized at the highest level of generalization. Draft
definitions were formulated of 16 soil units for this level, viz. weakly developed soils,
swelling/shrinking soils, groundwater influenced soils, saline/alkali soils, calcic/gypsic soils,
mollic soils, umbric and shallow soils, sialic soils, fersialic soils, ferralic soils, andic soils,
surface water influenced soils, podzolized soils, histic soils, pergelic soils and anthropogenic
soils.
The IRB was taken up in 1982 as one of the proposed programmes to implement a World Soils
Policy through UNEP. The objectives and expected output were formulated as follows (cf. ISSS
Bulletin no. 62, 1982/2, pp 31-37):
Objectives
To prepare an International Reference Base for Soil Classification that will help
to identify and assess global soil resources.
To prepare a list of major soil types which need to be recognized.
To determine and quantify the diagnostic criteria to be used in the definitions of
the various classes of soils.
To prepare the definitions of the categories and classes which are recognized, and
prepare a key for their classification.
To define criteria for a further sub-division of the major soil types into more
specialized categories.
Output
An International Reference Base for soil correlation, classification and
assessment, useable also at national levels.
Furthermore it was envisaged that the International Reference Base for Soil Classification was
to be used as a base to revise the legend of the FAO/Unesco Soil Map of the World.
During the 1986 ISSS congress in Hamburg, Germany, progress was reviewed of the Working
Group RB, which had come into being within the framework of Commission V to further
elaborate the International Reference Base. It was decided to continue the IRB programme
through a core group, an extended core group and a number of selected contributors. They
would work out in more detail the definitions of the major soil groupings and relevant
diagnostic attributes, to make proposals for further subdivision at a second/third level, and to
establish correlation with existing soil units in major soil classification systems.
In 1988 a list of soil attributes, including all possible types of soil profile development was
presented during an inter-congress meeting of the ISSS at Alma-Ata, Kazachstan. Other results
were presented in 1990 during the ISSS congress in Kyoto, Japan, where six major soil
groupings were discussed in more detail at the IRB symposium, viz. the soils with calcic,
ferralic, gleyic, modic, nitic and stagnic attributes (9) and posters were presented on gypsic and
anthric soils (10). By now twenty major soil groupings were identified, viz. organic, vertic,
andic, podzic, stagnic, ferralic, nitic, luvic, lixic, fluvic, gleyic, salie, sodic, chemie, gypsic,
calcic, modic, cambic, anthric and primic soils.
In the meantime FAO had issued a Revised Legend of the Soil Map of the World (4). The
number of major soil groupings was increased from 26 to 28 and that of the soil units from 106
to 153. Some of the main changes included the amalgamation of Lithosols, Rendzinas and
Rankers into Leptosols, the split of Luvisols into Luvisols and Lixisols and, similarly, the
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separation of Acrisols into Acrisols and Alisols, the deletion of Xerosols and Yermosols, and
the introduction of Anthrosols, Plinthosols, Calcosols and Gypsisols. Some diagnostic criteria
were adapted, others were newly defined (e.g. argic and ferralic B horizons, and andic, fluvic,
gleyic, stagnic, nitic, salic and sodic properties).

Principles and objectives. Subsequent to the revision of the 1974 FAO-Unesco Legend and to
the discussions and recommendations of the Kyoto congress it was proposed to merge the IRB
and the Soil Map of the World efforts, both of which were sponsored by the ISSS. This
proposal came from the feeling that when the 20 IRB units identified, some of which were so
broad that it was difficult to prepare consistent definitions, were further refined, a list of units
would evolve almost identical to the revised FAO legend. It was also felt inappropriate to pursue
two different programmes. Other considerations were that the FAO legend had progressively
been developed to encompass the major soils of the world at three levels of generalization, that
it was widely used for actual surveys in developing and developed countries, and that the
terminology was well known and generally accepted.
The name of the IRB was changed into 'World Reference Base for Soil Resources', the
emphasis of which was to be the application of the IRB principles of definitions and linkages
to the existing FAO-Unesco-ISRIC units so as to give them more depth and validation. As
principle, soil groups would be defined in terms of a specific combination of soil horizons and,
where possible, supplement the definition of the soil groups with an account on spatial and
temporal linkages which occur in the landscape. Soil horizons were to be defined by specific
combinations of soil characteristics ('assemblages') observable in the field and supported by
laboratory analyses where necessary (9).
Thus, the main objective of the World Reference Base for Soil Resources became to provide
scientific depth and background for the 1990 FAO legend, so that it incorporates the latest
knowledge relating to global soil resources and interrelationships. More specifically, the
objectives are:
- To develop an internationally acceptable framework for delineating soil resources to
  which national classifications can be attached and related, using the 1990 FAO-
  Unesco-ISRIC Revised Legend as a guideline.
- To provide this framework with a sound scientific basis so that it can also serve
different applications in related fields such as agriculture, geology and ecology.
- To acknowledge in the framework important lateral aspects of soils and soil horizon
distribution as characterized by topo- and chronosequences.
- To emphasize the morphological characterization of soils rather than to follow a
  purely analytical approach.
Consequently, the basic framework of the FAO legend, with its two categoric levels and
guidelines for developing classes at a third level, was adopted. The broad principles that govern
this class differentiation and which were also to be applied in the WRB, are:
- At the first categoric level classes are differentiated mainly according to the primary
  pedogenetic process that has produced the characteristic soil features, except where
  'special' soil parent materials are of overriding importance.
- At the second categoric level classes are differentiated according to any predominant
  secondary soil forming process that has significantly affected the primary soil
  features. However, in certain cases soil characteristics that have a significant effect
  on use may be taken into account.
ELEMENTS OF THE PROPOSED WORLD REFERENCE BASE

The WRB major soil groups. After reviewing FAO's revised legend 29 major soil groups were distinguished for inclusion in the WRB. Compared to this legend, three new major soil groupings were proposed, i.e. Cryosols, Stagnosols and Umbrisols. FAO's major soil grouping of Greyzems was merged with the Chernozems and Phaeozems, and the Plinthosols and Podzoluvisols were renamed Sesquisols and Glossisols, respectively.

The major soil groups of the WRB considered are, in key order:

- **Histosols.** Organic soils with a histic horizon starting within 30 cm of the soil surface, either 10 cm or more thick if directly over hard rock, or 40 cm or more thick.
- **Anthrosols.** Soils strongly influenced by man having an anthric horizon 50 cm or more thick, or having a hydragric horizon sequence with a combined thickness of 50 cm or more.
- **Leptosols.** Shallow soils less than 30 cm thick or soils consisting of 90 percent or more of fragments coarser than 2 mm. Excluded are shallow soils over indurated layers of pedogenetic origin.
- **Cryosols.** Soils having permafrost within 100 cm of the soil surface that are saturated with water during the thawing period, but lack gleyic or stagnic properties.
- **Vertisols.** Clayey soils developing cracks when dry and having a vertic horizon starting between 25 and 75 cm of the soil surface.
- **Fluvisols.** Aggrading soils in alluvial, lacustrine or marine deposits showing evidence recent deposition of fluvic materials within 25 cm of the soil surface. Colluvial and other soils resulting from mass movements are explicitly excluded.
- **Solonchaks.** Saline soils having within 50 cm of the soil surface the upper limit of a salic horizon containing at least 1 percent salt more soluble than gypsum, as expressed by an electrical conductivity (EC) of 15 dS/m at 25°C.
- **Gleysols.** Groundwater influenced soils having gleyic properties (evidenced by reducing conditions and a gleyic colour pattern) within 50 cm of the soil surface.
- **Andosols.** Soils derived mainly from altered pyroclastic deposits having an andic horizon, i.e. a horizon the mineralogy of which is dominated by short-range-order minerals (e.g. volcanic glass, allophane or aluminium complexed by organic acids).
- **Podzols.** Soils having a spodic horizon, i.e. containing illuvial amorphous alumino-organic complexes.
- **Sesquisols.** Soils having a petroplinthic horizon with an upper boundary within 30 cm depth or a plinthic horizon starting either within 50 cm or 125 cm if underlying an albic horizon.
- **Ferralsols.** Highly weathered soils having a ferralic horizon between 30 and 200 cm of the soil surface.
- **Planosols.** Soils having an eluvic horizon and an abrupt textural change to a slowly permeable subsurface horizon; suffering of surface water stagnation as reflected by stagnic properties above the slowly permeable layer.
- **Solonetz.** Sodium-affected soils having a natric horizon.
- **Chernozems.** Soils with a mollic horizon, a base saturation of 50 percent or more throughout the upper 125 cm of the soil and a calcic horizon or soft powdery lime below ... cm.
- **Kastanozems.** Soils with a mollic horizon and a calcic, hypercalcic or gypsic horizon, or concentrations of soft powdery lime within ... cm of the soil surface.
- **Phaeozems.** Soils with a mollic horizon and a base saturation of more than 50 percent throughout the upper 125 cm of the soil; lacking accumulations of calcium carbonate.
Gypsisols. Soils having a gypsic or hypergypsic horizon within 125 cm of the soil surface.
Calcisols. Soils having a calcic or hypercalcic horizon within 125 cm of the soil surface.
Glossisols. Soils having an argic horizon showing with an irregular upper boundary resulting from albeluvic tonguing into the argic horizon.
Stagnosols. Surface water influenced soils having stagnic properties (evidenced by reducing conditions and a stagnic colour pattern) within 50 cm of the soil surface.
Nitisols. Deep soils having an argic horizon and a nitic horizon starting within 100 cm of the soil surface.
Alisols. Strongly weathered soils having an argic or cambic horizon and alic properties in the major part between 25 and 125 cm of the soil surface.
Acrisols. Strongly weathered soils having an argic horizon dominated by low cation exchange capacity clay minerals and a base saturation of less than 50 percent in the major part between 25 and 125 cm of the soil surface.
Luvisols. Soils having an argic horizon dominated by moderate to high cation exchange capacity clay minerals and a base saturation of 50 percent or more in the major part between 25 and 125 cm of the soil surface.
Lixisols. Strongly weathered soils having an argic horizon dominated by low cation exchange capacity clay minerals and a base saturation of 50 percent or more in the major part between 25 and 125 cm of the soil surface.
Umbrisols. Soils having an umbric horizon, not qualifying for one of the previous groups.
Cambisols. Soils having a cambic horizon or a mollic horizon and a base saturation of less than 50 percent in some part within the upper 125 cm of the soil surface.
Arenosols. Coarse textured soils being loamy sand or coarser to a depth of at least 100 cm from the soil surface lacking a sufficient degree of soil development to qualify for other groups.
Regosols. Medium and fine textured soils lacking a sufficient degree of soil development to qualify for other groups.

The WRB diagnostic horizons, properties and materials. Initially soil groups were to be defined in terms of a specific combination of soil horizons, to be named 'reference horizons' rather than 'diagnostic horizons'. Reference horizons and properties were intended to reflect genetic horizons and properties that were widely recognized as occurring in soils which could be used in the soil class descriptions but not necessarily in the soil class definitions. Besides the existing FAO diagnostic horizons new reference horizons were to be formulated, such as organic, eluvic, andic, vertic, nitic, duric, ferric, salic, gelic, plinthic, thionic, fragic, glossic and anthric reference horizons. Some of these reference horizons would replace FAO's diagnostic properties. Gleyic, stagnic, geric, fluvic, planic and leptic properties were to be retained as they reflect specific soil conditions rather than horizons.

However, the distinction between reference and diagnostic horizons created confusion and it was agreed to retain the FAO terminology of diagnostic horizons and properties. Additionally it appeared necessary to define diagnostic soil materials. This together resulted in a comprehensive list of WRB diagnostic horizons, properties and materials. A comparison between the WRB proposals and the FAO Revised Legend diagnostic characteristics is given in Table 1.

The WRB diagnostic horizons, properties and materials, where possible, are described and defined with emphasis on field identification. Analytical criteria are given to help the identification. This is in line with the WRB objectives but sometimes it has resulted in rather lengthy descriptions in which the diagnostic criteria are not clear-cut.
### Table 1. Comparison between the diagnostic horizons, properties and materials of the WRB and the Revised FAO Legend. (4)

#### A. Main differences in diagnostic horizons.

<table>
<thead>
<tr>
<th>Diagnostic horizon</th>
<th>Approximate equivalent Revised Legend</th>
<th>Differences / comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albic</td>
<td>Albic E</td>
<td>similar</td>
</tr>
<tr>
<td>Andic</td>
<td>Andic properties</td>
<td>pH (H₂O) and exchangeable aluminium added; minimum thickness (30 cm) specified</td>
</tr>
<tr>
<td>Anthric</td>
<td>Fimic A (pp)</td>
<td>new; plaggen and terric horizon replace fimic A horizon; irragric and hortic horizons introduced</td>
</tr>
<tr>
<td>Argic</td>
<td>Argic B</td>
<td>change in required percentage clay skins (10%) on horizontal and vertical ped faces; lithological discontinuity defined</td>
</tr>
<tr>
<td>Calcic</td>
<td>Calcic</td>
<td>new diagnostic thickness of 20 cm</td>
</tr>
<tr>
<td>Cambic</td>
<td>Cambic B</td>
<td>minimum content of 8% clay deleted</td>
</tr>
<tr>
<td>Cryic</td>
<td>-</td>
<td>new</td>
</tr>
<tr>
<td>Duripan</td>
<td>Duripan phase</td>
<td>similar</td>
</tr>
<tr>
<td>Eluvic</td>
<td>-</td>
<td>new</td>
</tr>
<tr>
<td>Ferralic</td>
<td>Ferralic B</td>
<td>silt-clay ratio deleted</td>
</tr>
<tr>
<td>Ferric</td>
<td>Ferric properties</td>
<td>minimum thickness (15 cm) specified</td>
</tr>
<tr>
<td>Follic</td>
<td>-</td>
<td>new</td>
</tr>
<tr>
<td>Fragipan</td>
<td>Fragipan phase</td>
<td>minimum thickness (15 cm) specified</td>
</tr>
<tr>
<td>Gypsic</td>
<td>Gypsic</td>
<td>minimum content of 15% gypsum added</td>
</tr>
<tr>
<td>Histic</td>
<td>Histic H</td>
<td>thickness specifications changed</td>
</tr>
<tr>
<td>Hydrargic</td>
<td>-</td>
<td>new</td>
</tr>
<tr>
<td>Hypercalcic</td>
<td>Petrocalcic (pp)</td>
<td>petrocalcic horizons plus calcic horizons with more than 50% calcium carbonate equivalent</td>
</tr>
<tr>
<td>Hypergypsic</td>
<td>Petrogypsic (pp)</td>
<td>petrogypsic horizons plus gypsic horizons with more than 60% gypsum; minimum thickness (10 cm) specified</td>
</tr>
<tr>
<td>Mollic</td>
<td>Mollic A</td>
<td>P₂O₅ requirement deleted</td>
</tr>
<tr>
<td>Natric</td>
<td>Natric B</td>
<td>similar; includes adaption of argic horizon</td>
</tr>
<tr>
<td>Nitric</td>
<td>Nitric properties</td>
<td>water dispersable clay and silt-clay ratio requirement added; minimum thickness (30 cm) specified</td>
</tr>
<tr>
<td>Ochric</td>
<td>Ochric A</td>
<td>similar</td>
</tr>
<tr>
<td>Petroplinthic</td>
<td>Petroferric phase</td>
<td>minimum amount of Fe₂O₃ (30%) specified</td>
</tr>
<tr>
<td>Plinthic</td>
<td>Plinthite</td>
<td>minimum thickness (15 cm) specified</td>
</tr>
<tr>
<td>Salic</td>
<td>-</td>
<td>new</td>
</tr>
<tr>
<td>Spodic</td>
<td>Spodic B</td>
<td>new upper limit 10 cm; colour requirements added; oxalate extractable Al + Fe value introduced; ODOE value added</td>
</tr>
<tr>
<td>Sulfidic</td>
<td>Sulfidic materials</td>
<td>minimum thickness (15 cm) specified</td>
</tr>
<tr>
<td>Sulfuric</td>
<td>Sulfuric</td>
<td>similar</td>
</tr>
<tr>
<td>Umbric</td>
<td>Umbric A</td>
<td>P₂O₅ requirement deleted</td>
</tr>
<tr>
<td>Vertic</td>
<td>-</td>
<td>new</td>
</tr>
</tbody>
</table>
Table 1. Continued.

B. Main differences in diagnostic properties and materials.

<table>
<thead>
<tr>
<th>Diagnostic property/material</th>
<th>Approximate equivalent Revised Legend</th>
<th>Differences / comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrupt textural change</td>
<td>Abrupt textural change</td>
<td>new depth range (7.5 cm) for occurring change</td>
</tr>
<tr>
<td>Albeluvic tonguing</td>
<td>tonguing</td>
<td>type of tonguing specified</td>
</tr>
<tr>
<td>Alic properties</td>
<td></td>
<td>new</td>
</tr>
<tr>
<td>Anthropogenic soil material</td>
<td></td>
<td>new</td>
</tr>
<tr>
<td>Calcaric properties</td>
<td>Calcareous</td>
<td>similar</td>
</tr>
<tr>
<td>Fluvic soil material</td>
<td>Fluvic properties</td>
<td>similar</td>
</tr>
<tr>
<td>Geric properties</td>
<td>Geric properties</td>
<td>extractable aluminium instead of extractable acidity</td>
</tr>
<tr>
<td>Gleyic properties</td>
<td>Gleyic properties</td>
<td>'gleyic colour pattern' (50 or 100%) instead of 95% neutral, blue or green colours</td>
</tr>
<tr>
<td>Gypsreric properties</td>
<td>Gypserferous</td>
<td>similar</td>
</tr>
<tr>
<td>Lixic properties</td>
<td></td>
<td>new</td>
</tr>
<tr>
<td>Organic soil material</td>
<td>Organic soil materials</td>
<td>content in mineral material deleted; minimum amount of organic matter fixed similar</td>
</tr>
<tr>
<td>Soft powdery lime</td>
<td>Soft powdery lime</td>
<td>'stagnic colour pattern' (50 or 100%) defined in hue, value and chroma instead of chroma alone</td>
</tr>
<tr>
<td>Stagnic properties</td>
<td>Stagnic properties</td>
<td>new</td>
</tr>
<tr>
<td>Tephric soil material</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The following diagnostic horizons and properties defined in the Revised Legend have not been adopted: fimmic A horizon, andic properties, calcareous, calcic, continuous hard rock, ferralic properties, ferric properties, gypserferous, interfingered, nitic properties, permafrost, plinthite, slickensides, smeary consistence, strongly humic, sulfidic materials, tonguing, vertic properties and weatherable minerals.

Proposed modifications compared to FAO's definitions of diagnostic horizons and properties. Of the 16 diagnostic horizons defined in FAO's revised legend only the fimmic A horizon has not been retained. It covers a too wide range of man-made surface layers and is replaced in the WRB proposals by the irragric, hortic, plaggen and terric horizons. In the WRB's histic horizon the minimum depth requirement is reduced to 10 cm. This is the result of another use that is made of its definition. In the Revised Legend the histic H horizon is used at second level to identify histic soil units; in the WRB it is used also at the highest level to define Histosols. It was agreed that Histosols over continuous hard rock should have
a minimum thickness of 10 cm in order to avoid very thin organic layers over rock being classified as Histosols. Consequently, the minimum depth requirement for the histic horizon has been set at 10 cm. The maximum thickness requirement has been dropped for obvious reasons. The $P_2O_5$ content requirement for FAO’s mollic and umbric A horizons has been deleted from the WRB definition of mollic and umbric horizons. This requirement cannot be considered diagnostic anymore since thick, man-made horizons in, for instance, China also have low amounts of phosphate and other criteria have to be found to separate mollic and umbric horizons from anthric horizons.

The definition of the ochric horizon is similar to the ochric A horizon as is the one for the albic horizon compared to the albic E horizon.

The argic horizon definition differs from that of the argic B horizon in that the percentage clay skins on both horizontal and vertical ped faces and in pores has been increased from 1 to 10 percent. It can be argued that no 1:1 relationship exists between percentage clay skins observed in the field and the amount visible in thin sections. In fact, Khalifa and Buol (6) found that the $B_{21}$ of a Cecil soil had continuous clay skins on ped surfaces and in pores. Oriented clay, however, occupied 5 to 10 percent of the thin section area. Thus the ratio of clay skins recorded in the field on ped surfaces and in pores to clay skins observed in thin sections would be between 10 and 20 to 1. Based upon such observations, the requirement for clay skins visible in the field is set on 10 percent.

Guidelines to recognize a lithological discontinuity, if not clear from the field (data), are added to the description of the argic horizon. It can be identified by the percentage of coarse sand, fine sand and silt, calculated on a clay-free basis (international particle size distribution or using the additional groupings of the USDA system or other), or by changes in the content of gravel and coarser fractions. A relative change of at least 20 percent in any of the major particle size fractions is regarded to be diagnostic for a lithological discontinuity. However, it should only be taken into account if it is located in the section of the solum where the clay increase occurs and if there is evidence that the overlying layer was coarser textured.

The adjustments made in the description of the argic horizon also apply to the natric horizon. The definition of FAO’s cambic B horizon has been slightly amended by deleting the requirement ‘...and has at least 8% clay’. This requirement forces some soils, that have a well-developed structural-B horizon and silt loam or silt textures but a low clay content, as they are, for instance, found in fluvio-glacial deposits of the nordic countries, into the Regosols rather than in the Cambisols. As there is also no need anymore for this requirement to separate Cambisols from Arenosols (defined in the WRB as soils having a loamy sand or coarser texture) it has not been taken up in the definition of the WRB cambic horizon.

Major alterations have been made in the definition of the spodic horizon. It has been brought much in line with the recent modifications in the Soil Taxonomy (8) regarding the definition of spodic materials. Colour requirements were added, a limit of 0.5 or more in percentage oxalate extractable aluminium plus half that of iron is used, and a value for the optical density of oxalate extract (ODOE) of 0.25 or more is introduced. Moreover, the upper limit of spodic horizons has been set on 10 cm depth.

The silt-clay ratio of 0.2 or less has been deleted for the time being from the definition of the ferralic horizon. This criterion was felt to be too strict. Other values have been proposed (silt-clay ratio of 0.7 or less; fine silt-clay ratio of 0.5 or less) but a final decision depends on further research and consensus.

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Other amendments proposed are a new diagnostic thickness for the calcic horizon (20 cm), a minimum content of 15% gypsum for the gypsic horizon. Petrocalcic and petrogypsic horizons are not used as these are incorporated in the concept of hypercalcic and hypergypsic horizons, which includes both cemented layers and continuous calcic or gypsic horizons with 50 or 60% calcium carbonate or gypsum, respectively. The definitions of the sulfuric horizon is more or less similar to the one of the Revised Legend. Slight changes are proposed in the descriptions of abrupt textural change and geric properties. They concern a different depth in which the abrupt change in texture must occur and another way of calculating the effective cation exchange capacity, respectively.

Newly proposed diagnostic horizons, properties and materials. In addition to the "traditional" diagnostic horizons described previously, 14 new ones are proposed. Some are adopted from FAO’s diagnostic properties, others are newly formulated. Together they bring the total of diagnostic horizons recognized in the WRB to 30.

The andic horizon is a soil horizon at least 30 cm thick in which the mineralogy is dominated by short-range-order minerals. Three subtypes of andic horizons are distinguished: (a) an andic horizon consisting of only slightly altered pyroclastic material which is rich in volcanic glass and other primary minerals (vitr-andic); (b) one characterized by the dominant presence of secondary para- or cryptocrystalline clay minerals such as allophane, imogolite and hisingerite (sil-andic); and (c) an andic horizon in which aluminium complexed by organic acids prevail (alu-andic).

The anthric horizon comprises a variety of surface horizons at least 50 cm thick, that result from long-continued cultivation. The characteristics and properties present depend very much on the soil management practices used. Four different types are distinguished: the hortic, irragric, plaggen and terric horizons. Together they form the fimmic A horizon of the Revised Legend. The hortic horizon is a dark coloured and thoroughly mixed horizon resulting from deep cultivation, intensive fertilisation and/or long-term application of human and animal wastes and other organic residues. The irragric horizon shows evidence, either historical or from field observation, of surface raising through long-continued irrigation with sediment-rich waters, resulting in a light coloured, uniformly structured surface layer. The plaggen horizon is a brownish or blackish coloured, uniformly textured (usually sand or loamy sand) surface horizon resulting from additions of sods or soddy materials mixed with farmyard manure. The terric horizon is a thoroughly mixed, but texturally variable horizon with a colour related to the source material or the underlying substrate resulting from additions of earthy manures, compost or mud. It may contain stones and free lime.

The cryic horizon is the soil layer above the permafrost that becomes saturated with water during the thawing period, but lacks gleyic or stagnic properties. A duripan represents a soil layer cemented by silica. The eluvic horizon is a horizon at least 5 cm thick at or near to the soil surface which shows a concentration of sand and silt fractions high in resistant minerals, resulting from a loss of clay, iron or aluminium or some combination of them, either as solutes or in suspension by lateral or vertical throughflow or by biological activity. A ferric horizon is a horizon at least 15 cm thick showing many coarse reddish coloured mottles and/or discrete nodules. The folic horizon represents the dry counterpart of the histic horizon, being saturated for less than one month in most years. A fragipan is a loamy (uncommonly a sandy) subsurface horizon at least 25 cm thick which generally has a high bulk density relative to the overlying
horizons and a low content in organic matter (< 0.5% org. C). It is hard or very hard and seemingly cemented when dry and weakly to moderately brittle when moist.

New is the use of a sequence of horizons as diagnostic criterion. The **hydragric horizon sequence** consists of related surface and subsurface horizons with a combined thickness of at least 50 cm, that show evidence of alteration through wet-cultivation practices. It comprises a puddled layer, a plough pan and a illuvial subsurface horizon. This sequence is characteristic for soils that have been used for long-term paddy rice cultivation.

A **nitic horizon** is a subsurface horizon having as its main feature a moderately to strongly developed straight-edged-blocky (nutty or polyhedral) structure with many shiny pedfaces, which cannot or can only partially be attributed to clay illuviation. To be diagnostic the nitic horizon has a minimum thickness of 30 cm, with diffuse to gradual transitions to horizons immediately above and below. A **petroplinthic horizon** is a continuous layer of indurated material, in which iron is an important cement and organic matter is absent, or present only in traces. The morphology of the horizon can be nodular, platy, polygonal, vesicular or reticulate. Petroferric horizons contain a high amount of iron (normally 30 percent or more Fe₂O₃), especially in the upper part. A **plinthic horizon** is a subsurface horizon at least 15 cm thick with 25 percent or more of an iron-rich, humus-poor mixture of clay containing quartz and other diluents, which changes irreversibly to a hardpan (petroplinthic horizon) or to irregular aggregates on exposure to repeated wetting and drying. A **salic horizon** is a surface or shallow subsurface horizon at least 15 cm thick, containing secondary enrichment of readily soluble salts, i.e. salts more soluble than gypsum. A **sulfidic horizon** is a waterlogged subsurface horizon at least 15 cm thick containing sulfur, mostly in the form of sulfides, and only moderate amounts of calcium carbonate. Finally, a **vertic horizon** is a subsurface horizon 25 cm or more thick, that as a result of shrinking and swelling has either slickensides close enough to intersect, or wedge-shaped or parallelepiped structural aggregates. It contains throughout 30% or more clay.

Newly defined diagnostic properties and materials are alic and lixic properties, and anthropogenic and tephric soil material. Gleyic and stagnic properties have been reformulated, tonguing and interfingering has been renamed albeluvic properties, while slight changes are proposed in FAO's abrupt textural change and geric properties.

The term **alic properties** is used to define soil material that has a CEC of 24 cmol(+)kg clay or more, a KCl extractable Al content of 12 cmol(+)/kg clay, and an aluminium saturation of 60 percent or more. **Lixic properties** apply to an increase in clay content in absence of evidence of illuviation with requirements similar to that of the argic horizon showing evidence of clay illuviation. Introduced in the description of the **gleyic and stagnic properties** is the occurrence of 'gleyic' and 'stagnic colour patterns'. The terms apply to the specific distribution pattern of Fe/Mn (hydr)oxides that is caused by saturation with groundwater or stagnating surface water. A gleyic colour pattern has 'oximorphic' features on the outside of structural elements, along root channels and pores, or as a gradient upwards in the soil, while a stagnic colour pattern shows these features in the centre of peds or as a gradient downwards.

**Anthropogenic soil material** applies to unconsolidated mineral or organic material (land fills, mine soil, urban fill, garbage dumps, dredgings, etc.) resulting from anthrogeomorphic processes. **Tephric soil material** consists either of tephra (unconsolidated, non or only slightly altered primary pyroclastic products of volcanic eruptions) or tephric deposits (material derived for more than 60 percent from tephra).
**Linkages.** Spatial and temporal linkages form an important element in the description of the WRB soil units. These linkages refer to vertical and lateral successions of soil horizons, associations of soils related to the position in the landscape, and the evolution of soil horizons and soils over time. Placing the soils in their geographical context facilitates separation of soil groups at a high level of generalization, and thus it is instrumental in the creation of appropriate soil classes. Good examples of such linkages can be found in the descriptions of the Histosols, Calcisols and Nitisols.

**DISCUSSION**

**Problems encountered.** A basic philosophy in the WRB is that the final soil groups must show coherence in geographical distribution and pedogenetic character, and that soils must be characterized by their morphological expression rather than by analytical data. In a number of proposed major soil groups this has led in some cases to divisions and in others to amalgamation. For example, FAO’s Leptosols comprise "soils limited in depth by ... a continuous cemented layer within 30 cm of the surface", i.e. petrocalcic, petrogypsic, petroferric layers or duripans. As these in the WRB are considered as pedogenetic layers these soils should be classed with their respective groups. In case of shallow soils over petrocalcic or petrogypsic horizons, these soils are grouped with the Calcisols and Gypsisols. However, problems rise with the proper placement of soils over a petroferric layer or a duripan, both of which are considered as phases in FAO’s revised legend. It is been proposed to group the soils with a petroplinthic horizon together with the soils having a plinthis horizon, as these are genetically related (see Sesquisols). It must be emphasized, however, that shallow soils over a petroplinthic horizon may occupy distinctly different positions in the landscape than those containing a plinthic layer. While the latter usually occur in depressions, the former are frequently encountered in elevated positions, e.g. as 'cuirasses' in Western Africa, which form caps on hill tops. Moreover, it has to be noted that not all soils that contain a layer cemented by iron are the result of hardening of plinthite. For these soils, as for the soils with duripans no proper place has been found yet and proposals for proper placement are welcomed. Leptosols also comprise soils with a very high content in coarse fragments. This combination left the Leptosol group an odd group of either shallow soils or relatively deep soils, with as a common characteristic a low amount of available moisture. It has been proposed to group the coarse fragmented soils with the Regosols. This, however, may purify the Leptosols, but it pollutes the Regosols, which then would entail medium and fine textured soils plus coarse fragmented soils, as the sandy soils are grouped together in Arenosols. Therefore, for the time being, coarse fragmented soils are retained in the Leptosols. A major concern is how to treat man-influenced soils that do not qualify as Anthrosols. In the major soil groups of Podzols and Umbrisols especially, soils occur in which the surface layer has been modified by fertilization and liming to such an extent that the original characteristic of low base saturation has disappeared. If left to nature, the low base saturation will return in time. It is a common principle that short term management effects should not influence soil grouping and therefore, such soils which have an 'artificial' mollic horizon should be kept with the Podzols and Umbrisols. However, this would result in e.g. Mollis Umbriisol, a *contradictio in terminus*. It was felt that these soils should better be grouped with the Cambisols, to keep the
Podzols and Umbrisols pure. The question remains if such man-influenced modifications are to be reflected at the second level or a third level.

Some interfaces between certain soils seem to be difficult to establish, especially on the basis of field criteria. FAO's separation of Luvisols, Alisols, Acrisols and Lixisols may be very useful, however, the split is based entirely on analytical data and differences between the soils are difficult to detect in the field. At one stage it was proposed to group Luvisols together with Alisols and Acrisols together with Lixisols. Although it would have been possible to separate these two groups in the field probably on the basis of structural development, the result would be that one of the better soils in Africa (Lixisols) would be together with one of the worst (Acrisols), and that the fertile Luvisols of the loess belt in western Europe would be classed together with the extremely acid and infertile Alisols of the foothills in the Andes or on Kalimantan, thus ignoring the WRB principle of relationships in soil geographical distribution.

It was therefore decided to retain the separation made in the revised FAO legend, to define the difference between Luvisols and Alisols on the basis of aluminium saturation, and at the same time to search for morphological and associated criteria that would enable the four soils to be distinguished in the field.

Similar problems exist between Andosols and Podzols, especially between those Andosols that are dominated by alumino-organic complexes and Podzols lacking an albic horizon. Here, also there are no sound field differentiating criteria which could be established apart from circumstantial evidence derived from the geography of the area, and the difference between the two still needs support from the results of analytical tests.

No consensus has yet been reached on the problem concerning the priority of ferralic horizons and argic horizons with low activity clays. A general rule could be that all horizons with a CEC of 16 cmol(+) kg clay qualify for ferralic, provided all other requirements are also met. This, however, results in grouping with the Ferralsols soils known in southern Africa as 'Sandvelt soils', which are characterized by sandy loam topsoils that become very hard when dry, over a sandy clay or clayey subsoil. These soils, many of which now qualify for Acrisol and Lixisol, pose entirely different problems and require complete different management than Ferralsols. Therefore grouping these soils together seems inappropriate and some rule needs to be established to ensure separation.

Standardization regarding depths used in describing and defining soil units, including the issue of the control section still needs to be addressed. As far as possible, standard depths of 10, 20, 25, 30, 40, 50, 75, 100, 125 and 200 cm have been used, unless there is an overriding argument not to do so. As a result it is proposed to change the 18 cm depth value, which relates to the old imperial measure of 7 inch, in the mixing requirement for mollic and umbric horizons into 20 cm. Overriding arguments could be different depth values used in national classification systems from which a description has been taken. This is done to ensure compliance with one of the main WRB objectives, namely to serve as an internationally acceptable framework for delineating soil resources to which these classifications can be attached and related.

Finally some concern has been expressed about the number of major soil groups and soil units proposed. Twenty-nine MSG's have been identified and the number of soil units per major soil group varies between 5 and 14. This may result in a final number of soil units between 250 and 300, which is a drastic increase compared to the 153 units of the present revised FAO legend. Care ought to be taken to exclude minor units the extent of which is very limited, as these can easily be accommodated at a lower level of classification.
Correlation with existing classification systems. The WRB, having taken the framework of the revised FAO legend as guide, obviously bears many similarities to it. The nomenclature has been adopted and, where necessary, adapted using the set rules. Its concepts of diagnostic horizons and properties, supplemented by diagnostic soil materials, have been taken up. The FAO legend of 1974 (3) in itself has been build on knowledge and experience of many soil scientists from all over the world and, as such, reflects a consensus of a number of classification systems. Separation of, for instance, Greyzems, Chernozems and Kastanozems is related to the older Russian classification of Grey Forest soils, Chernozems and Chestnut soils. Similarly, Cambisols coincide largely with the German Braunerde and French Sols bruns, while Ferralsols closely follow the US Oxisols and Brazilian Latosols.

Many of the definitions in both the original and revised FAO legends were adopted from the US Soil Taxonomy (7, 8). These definitions are in most cases summarized and simplified, in accordance with the requirements of the legend.

The World Reference Base for Soil Resources also continues to build on existing classification systems. The Anthrosols as proposed contains many elements from the recently published Chinese Soil Taxonomic Classification System (2), the description and definition of Andosols is closely related to that of the Andisols in the Référentiel Pédologique Français (RPF) (1), as do the Podzols with the RPF Podzosols, but to a lesser extent than the Andosols. On the other hand some of the proposals for Solonchaks, Gleysols, Ferralsols, Stagnosols, Alisols, Umbrisols and Regosols result from new ideas not yet reflected in published classification systems. Definitions of diagnostic horizons, properties and materials derived from existing classification systems, not used in the revised FAO legend, but which are proposed for the WRB, concern some anthric horizons (2), the hydragric horizon sequence (2) and tephric soil material (5).

Follow-up. The present first draft of the World Reference Base for Soil Resources needs to undergo a period of testing and refining. Only such an exercise will show the strengths and weaknesses of the WRB. Particular emphasis should be placed on determining sound field criteria, especially in the problem areas outlined above. Limits between the major soil groups and soil units must be checked for usefulness and pragmatism. Gaps are to be identified and removed. "Floating" soils, i.e. soils that are either difficult to classify or that are unsatisfactorily classified, need to be re-assessed and, consequently, the proposed WRB classes may have to be altered. Work needs to continue on defining the second level ('soil units') and the development of the third and possible fourth level of classification.

The final result may become a well described and defined World Reference Base for Soil Resources that is internationally acceptable by the soils community and that also can serve different applications in related fields such as agriculture, geology and ecology. Funds permitting, it should be supplemented by a publication on "Benchmark soils of the world", in which all WRB soil units are briefly described and defined, their potential and problems highlighted and illustrated by a typifying pedon with relevant analytical data.

ACKNOWLEDGEMENTS

The first draft of the World Reference Base for Soil Resources as presented here is the result of a long process of consultations, proposals, modifications and consensus reaching. Over the years many scientists have participated in its formulation. The text of this publication is mainly
Based on the following contributions: Histosols - Driessen (Netherlands) and Okruszko (Poland); Anthrosols - Gong Zi-tong (China) and Kosse (USA); Leptosols - Bridges (UK); Cryosols - Konyushkov, Naumov and Sokolov (Russia); Vertisols - Seghal (India); Fluvisols - Creutzberg (Netherlands); Solonchaks - Loyer (France), Gleysols - Blume (Germany) and Zaidelman (Russia); Andosols - Quantin (France); Podzols - McKague (Canada) and Righi (France); Sesquisols - Sombroek (FAO); Ferralsols - Esvaran (USA) and Klamt (Brazil); Planosols - Brinkman (FAO); Solonetz - Tursina (Russia); Chernozems, Kastanozems, Phaeozems - Bronger (Germany), Rozanov and Sotnikov (Russia); Gypsisols - Boyadgiev (Bulgaria) and Ilaawi (Syria); Calcisols - Ruellan (France); Glossisols - Langohr (Belgium) and Targulian (Russia); Stagnosols - Blume (Germany) and Zaidelman (Russia); Nitisols - Muchena (Kenya) and Sombroek (FAO); Alisols - Delvaux (Belgium) and Herbillon (France); Acrisols - Schargel (Venezuela); Luvisols - Deckers and Dudal (Belgium); Lixisols - Schargel (Venezuela); Umbrisols - Hollis (UK) and Nemecek (Czechia); Cambisols - Laker (RSA); Arenosols - Laker (RSA) and Remmelzwaal (Netherlands); Regosols - Arnold (USA).

During the process of compiling and editing of the draft WRB valuable comments were given by Nachtergaele (FAO) on the texts of the major soil groups, descriptions and definitions of diagnostic horizons, properties and materials, and the key to the major soil groups.

Finally, the assistance of FAO to provide funds for the initial editing of papers and for printing the text of the first draft World Reference Base for Soil Resources, as well as ISRIC’s contribution to ensure manpower and logistic support for the final preparation of this publication, is gratefully acknowledged.

Literature Cited.

Guidelines for Distinguishing Soil Subunits


Abstract

The standardized definitions and subdivisions of soil subunits, or third-level units, for the Revised Legend of the Soil Map of the World and the World Reference Base are meant to provide a more detailed basis for the classification of individual soil profiles and a framework for construction of legends of soil maps at scales more detailed than the original 1:5 million scale Soil Map of the World. General principles for distinguishing soil subunits, their definitions and priority sequence are provided for 20 major soil groups. Diagnostic desert surface horizons are discussed in more detail.

Introduction

The third level of the Revised Legend of the Soil Map of the World (1) is meant to provide (i) a more detailed basis for the classification of individual soil profiles and (ii) a framework for the construction of legends of soil maps at scales more detailed than the original 1:5 million scale Soil Map of the World. Scales of 1:1 million to 1:250 000 are considered appropriate for use of the third level, which may be applied on a global, regional or national basis.

An advantage of a standardized subdivision at the third level of the Revised Legend is that it will facilitate and enhance soil correlation and technology transfer between countries and regions. It should, in addition, serve useful purposes (for example, Land Evaluation) and should not be considered as an end in itself but rather contribute to the better understanding of the soil resource.

Because of the increasingly close relation between the development of the successive revisions of the Legend of the Soil Map of the World and WRB, the World Reference Base for Soil Resources, the guidelines for distinguishing third-level units may be, and should be, very similar. Particularly for WRB, systematic guidelines for third-level classification would avoid the proliferation of second-level units.

At this stage it is not possible to provide a comprehensive list of subunit names for the Revised Legend. Reviewing the uses which have been made of third-level names in soil survey (i.e. in Botswana, Kenya, Zambia, Bangladesh, Mozambique and in the EEC) and reclassifying a number of typifying pedons of 20 major soil groups, a provisional list of names and definition has been established.

Most of these names and definitions appear to be applicable, directly or with minor modifications, to the corresponding reference soils of the WRB. It is for this reason that the
principles followed, and the examples for the major soil groups available so far, are presented here for consideration and discussion.

General Principles for Distinguishing Soil Subunits

In order to keep the system simple and easy to use, criteria to differentiate soil subunits are selected that closely relate to the diagnostic criteria defined at the first and second levels.

The new criteria introduced relate to additional soil properties which are thought to be relevant at the third level. The use of phases as differentiating criteria of soil subunits should, in principle, be avoided. A few of them, however, have been proposed and have been included in the provisional list of names.

General Rules. The general rules to be followed when differentiating soil subunits are:

1. Soil subunits should be mappable at a scale of 1:1 million to 1:250 000.

2. The diagnostic criteria applied at the third level are derived from the already established higher-level diagnostic horizons, properties and other defined characteristics. They may, in addition, include new elements as well as criteria used for phase definitions at higher levels.

3. Subunits may be defined, and named, on the basis of the presence of diagnostic horizons. Weaker or incomplete occurrences of similar features are not considered as differentiae at the third level.

4. Differentiating criteria related to climate, parent material, vegetation, time of development or to physiographic features such as slope, geomorphology or erosion are not considered. The same applies to criteria derived from soil-water relationships such as depth of watertable or drainage. Substratum layers and thickness and morphology of solum or individual soil horizons are not considered as diagnostic criteria for the differentiation of soil subunits.

5. There is one set of diagnostic criteria for the definition of the soil subunits. The subunit name contains in its definition the diagnostic criterion for the soil subunit and functions at the same time as the third level connotative. Each soil subunit name is, as far as possible, given one unique meaning which should be applicable to all major soil groupings in which it occurs.

6. A single soil subunit name should be used to define third-level units. If additional names are needed for further characterization, these should be listed after the soil major grouping names, in brackets. For instance: Acri-Geric Ferralsol (Abruptic and Xanthic).

7. Definitions of soil subunits should not overlap or conflict with other soil subunits or with higher-category units definitions.
8. Definitions, including subordinate criteria, should be standardized as much as possible, especially with regard to quantities and depth of occurrence.

9. Soil subunit names should not be repetitive, contradictory or irrelevant in relation to soil unit connotatives.

10. Priority rules for the use of soil subunit names are to be followed as far as feasible. Priority rules should, as far as possible, be applicable to all major soil groupings of the system.

Priority Rules. At this stage, there is no intention to establish specific and comprehensive priority rules governing the use of soil subunit names which are applicable to all major soil groupings. However, in the interest of international correlation purposes and third-level compatibility, it is important some specific rules have been formulated for the system and for selected major soil groupings.

The first rule is that the priority sequence of third-level soil subunits should follow as much as possible the same sequence as used in the key for the second-level soil units. Any further subdivision should also follow this principle. The second rule is that priority be given to properties and characteristics occurring in the topsoil rather than in the subsoil.

Taking these considerations into account, it is recommended to apply the general priority sequence presented in Table 1. Specific priority sequences for Vertisols, Arenosols, Ferralsols, Calcisols, Nitisols, Alisols, Acrisols, Luvisols, Lixisols, Fluvisols, Gleysols, Histosols, Planosols, Plinthisols, Gypsisols, Cambisols, Solonchaks, Solonetzi, Regosols and Leptosols are given in Table 2.

Table 1. General Priority List of Soil Subunit Names

<table>
<thead>
<tr>
<th>01</th>
<th>Geli-</th>
<th>Humi-</th>
<th>Petrosali-</th>
<th>50</th>
<th>Glossi-</th>
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<tbody>
<tr>
<td></td>
<td>Orthothioni-</td>
<td>Hist-</td>
<td>Petroferri-</td>
<td></td>
<td>Ferri-</td>
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<td></td>
<td>Takyri-</td>
<td>Fibrihisti-</td>
<td>Petri-</td>
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<td>Calci-</td>
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<td></td>
<td>Yermi-</td>
<td>Terrihisti-</td>
<td>Duri-</td>
<td></td>
<td>Calcar-</td>
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<td>20</td>
<td>Nudiyermi-</td>
<td>Placi-</td>
<td></td>
<td>Pelli-</td>
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<tr>
<td></td>
<td>Aridi-</td>
<td>Umbri-</td>
<td>Fragi-</td>
<td></td>
<td>Grumi-</td>
</tr>
<tr>
<td></td>
<td>Plinthi-</td>
<td>Acri-</td>
<td>Gypsi-</td>
<td></td>
<td>Mazi-</td>
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<tr>
<td></td>
<td>Gleyi-</td>
<td>Lixi-</td>
<td>Sodi-</td>
<td></td>
<td>Rhodi-</td>
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<td></td>
<td>Stagni-</td>
<td>Ali-</td>
<td>Salii-</td>
<td></td>
<td>Chromi-</td>
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<tr>
<td>10</td>
<td>Anthraqui-</td>
<td>Luvi-</td>
<td>Alcali-</td>
<td>60</td>
<td>Eutri-</td>
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<tr>
<td></td>
<td>Fluvi-</td>
<td>Sili-</td>
<td>Veti-</td>
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<td>Bathi-</td>
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<td></td>
<td>Albi-</td>
<td>Verti-</td>
<td>Abrupti-</td>
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<td>Orthi-</td>
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<td></td>
<td>Areni-</td>
<td>Lithi-</td>
<td>Plani-</td>
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<td></td>
<td>Geri-</td>
<td>Rupti-</td>
<td>Lamelli-</td>
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<td></td>
<td>30</td>
<td>Mollihumi-</td>
<td>Petrogypsi-</td>
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<td></td>
<td>Umbrihumi-</td>
<td>Petrocalci-</td>
<td>Pachi-</td>
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<td></td>
<td></td>
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<td>Niti-</td>
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</table>
In most situations only a limited number of combinations will be possible, as most of the definitions are mutually exclusive. Where thought relevant the names in Table 1 can be further defined using prefixes, for example Epigleyic, Protothionic, etc. The following prefixes can be used:

- Hyper-
- Epi-
- Bathi-
- Proto-
- Hypo-
- Endo-
- Cumuli-
- Orthi-

**Definitions of Soil Subunit Names**

The definitions of diagnostic horizons and properties are those of the Revised Legend of the Soil Map of the World (1) unless stated otherwise. Definitions related to depth of occurrence (i.e. epi- and endo-) have been included in the following alphabetic list only when depth limits differ from the original epi- and endo- definitions.

- **Abrupti-** having an abrupt textural change.
- **Acri-** having a ferralic B horizon that meets the clay increase requirements of an argic B and has a base saturation (by NH\(_4\)OAc) of less than 50 percent in at least some part of the B horizon within 125 cm of the surface.
- **Albi-** having an albic E horizon lying at a depth of 50 cm or more.
- **Hyperalbi-** having an albic E horizon within 50 cm from the surface and the lower boundary at a depth of 100 cm or more from the surface.
- **Alcali-** having a \( \mathrm{pH} \ \mathrm{H}_2\mathrm{O} \) of 8.5 or more within 50 cm of the surface.
- **Ali-** having an argic B horizon which has a cation exchange capacity equal to or more than 24 cmol(+)kg\(^{-1}\) clay throughout, and a base saturation (by NH\(_4\)OAc) of less than 50 percent in at least some part of the B horizon.
- **Alumi-** having an Al saturation of 50 percent or more in at least some part of the B horizon between 50 and 125 cm of the surface.
- **Andi-** having andic properties to a depth of 35 cm or more from the surface.
- **Epiandi-** having andic properties in a layer with a thickness of 15 cm or more within 35 cm of the surface.
- **Endoandi-** having andic properties in one or more layers with a cumulative thickness of 35 cm or more within 100 cm of the surface.
- **Anthraqui-** having stagnic properties associated with surface waterlogging due to irrigation within 125 cm from the surface.
Areni- having a texture of loamy fine sand or coarser throughout the upper 50 cm of the soil.

Aridi- having aridic properties (see Appendix 2) without having a takyric or a yermic A horizon.

Bathi- starting between 125 and 200 cm from the surface.

Calcari- calcareous at least between 20 and 50 cm from the surface.

Calcic- having a calcic horizon or concentrations of soft powdery lime between 50 and 125 cm from the surface.

Hypercalcic- having a calcic horizon which has 40 percent or more calcium carbonate equivalent.

Orthocalcic- having a calcic horizon within 125 cm from the surface.

Hypocalcic- having concentrations of soft powdery lime within 125 cm from the surface.

Chromic- having a B horizon which in the major part has a hue of 7.5YR and a chroma of more than 4, or a hue redder than 7.5YR.

Cumulic- having a repetitive accumulation of 50 cm or more in the epipedon.

Duri- having a duripan or a horizon of accumulation of silica that is 15 cm thick or more and contains 20 percent or more silica by volume, within 125 cm of the surface.

Dystric- having a base saturation of less than 50 percent (by NH4OAc) in at least some part between 50 and 125 cm from the surface.

Hyperdystric- having a base saturation of less than 50 percent (by NH4OAc) in all parts between 20 and 125 cm from the surface, and less than 20 percent in at least some part within 125 cm from the surface.

Orthodystric- having a base saturation of less than 50 percent (by NH4OAc) in all parts between 20 and 125 cm from the surface.

Epidystric- having a base saturation of less than 50 percent (by NH4OAc) at least between 20 and 50 cm from the surface.

Endo- occurrence between 50 and 125 cm from the surface.

Epi- occurrence within 50 cm from the surface.
Eutri- having a base saturation of 50 percent or more (by NH4OAc) at least between 50 and 125 cm from the surface.

Hypereutri- having a base saturation of 80 percent or more (by NH4OAc) in all parts between 20 and 125 cm from the surface.

Orthieutri- having a base saturation of 50 percent or more (by NH4OAc) in all parts between 20 and 125 cm from the surface.

Ferrali- having ferralic properties within 125 cm from the surface.

Hyperferrali- having a cation exchange capacity (by NH4OAc) of less than 16 cmol(+)kg-1 clay in at least some subhorizons within 125 cm from the surface.

Ferri- showing ferric properties within 125 cm from the surface.

Hyperferri- having one or more layers with a total thickness of 25 cm or more consisting of 40 percent or more ferric nodules within 125 cm from the surface.

Fimi- having a fimic A horizon.

Fluvi- showing fluvic properties.

Fragi- having a fragipan within 125 cm from the surface.

Geli- having permafrost within 200 cm from the surface.

Geri- having geric properties in at least some horizon of the B horizon within 125 cm from the surface.

Gleyi- showing gleyic properties between 50 and 100 cm from the surface.

Epigleyi- showing gleyic properties between 50 cm from the surface.

Glossi- showing tonguing of an albic E horizon into an argic or natric B horizon.

Hypoglossi- showing interfingering of an albic E horizon into an argic or natric B horizon.

Grumi- used for Vertisols exclusively, indicating the presence of a surface layer with a thickness of 3 cm or more having a strong coarse, or finer, granular structure.

Gypsi- having a gypsic horizon within 125 cm from the surface.

Hypergypsi- having a gypsic horizon which has 40 percent or more gypsum.
Gypsiri- gypsiferous at least between 20 and 50 cm from the surface.

Histi- having a histic H horizon within 40 cm from the surface.

Fibrihisti- having a Histic H horizon within 40 cm from the surface, consisting of raw or weakly decomposed organic materials in which the fibre content dominates.

Terrihisti- having a histic H horizon within 40 cm from the surface, consisting of highly decomposed organic materials with only small amounts of visible plant fibres and a very dark grey to black colour.

Endohisti- having a buried histic H horizon within 100 cm from the surface.

Humi- having strongly humic properties.

Mollihumi- having strongly humic properties and a mollic A horizon.

Umbrihumi- having strongly humic properties and an umbric A horizon.

Hyper- excessive or strong expression of.

Hypo- slight or weak expression of.

Lamelli- having clay illuviation lamellae within 125 cm from the surface.

Lithi- having continuous hard rock within 50 cm from the surface.

Lixi- having a ferralic B horizon that meets the clay increase requirements of an argic B and has a base saturation (by NH₄OAc) of 50 percent or more throughout the B horizon to a depth of 125 cm.

Luvi- having an argic B horizon which has a cation exchange capacity equal to or more than 24 cmol(+)/kg-1 clay throughout, and a base saturation (by NH₄OAc) of 50 percent or more throughout the horizon to a depth of 125 cm.

Mazi- is used for Vertisols exclusively, indicating a massive structure and hard or very hard consistence in the upper 18 cm of the soil.

Molli- having a mollic A horizon.

Niti- having nitic properties in some subhorizon of the B horizon within 125 cm from the surface.

Nudiyermi- having a yermic horizon without a desert pavement.
Orthi- typical expression of (typical in the sense that there is no further or meaningful characterisation at this level).

Pachi- having an argic B horizon which has such a clay distribution that the clay percentage does not decrease by as much as 20 percent of the maximum within a depth of 150 cm from the soil surface.

Pelli- Vertisols only: having a moist value of 3.5 or less and a chroma of 1.5 or less in the upper 30 cm of the soil matrix.

Petri- strongly cemented or indurated within 125 cm from the surface.

Petrocalc- having a petrocalcic horizon within 125 cm from the surface.

Petroferr- having a petroferric (ironstone) layer within 125 cm from the surface.

Petrogypsi- having a petrogypsic horizon within 125 cm from the surface.

Petrosali- having a petrosalic horizon within 125 cm of the surface. The petrosalic horizon is a horizon cemented by salts more soluble than gypsum, which is 10 cm or more thick.

Placi- having a thin ironpan within 125 cm from the surface.

Plan- having a horizon abruptly overlying a slowly permeable horizon within 125 cm from the surface.

Plinhti- having 25 percent or more plinthite by volume in a horizon which is at least 15 cm thick within 125 cm from the surface.

Hypoplinthi- having plinthite within 125 cm from the surface, but with no horizon with more than 25 percent by volume, unless less than 15 cm thick.

Proto- indicates a precondition or an early development of certain properties (Protothionic).

Rhodi- having a B horizon which has a hue redder than 5YR (3.5YR or redder) in all parts (apart from minor transitional horizons to A and C horizons), and has a colour value moist of less than 3.5, and a colour value dry no more than one unit higher than one unit higher than the value moist.

Rupti- having a lithological discontinuity within 125 cm from the surface.

Sali- having salic properties within 30 cm from the surface.

Endosali- having salic properties within 100 cm from the surface.
Hyposali- having electric conductivity values of the saturation extract higher than 4 dS/m at 25°C in at least some subhorizon within 100 cm from the surface.

Silti- having 40 percent or more silt in some subhorizons within 125 cm from the surface.

Sodi- having sodic properties within 50 cm from the surface.

Endosodi- having sodic properties within 100 cm from the surface.

Hyposodi- has more than 6 percent saturation with exchangeable sodium in at least some subhorizon within 100 cm from the surface.

Spodi- having a spodic B horizon.

Stagni- having stagnic properties within 50 cm from the surface.

Endostagni- having stagnic properties between 50 and 100 cm from the surface.

Takyri- having a takyric A horizon.

Thioni- having a sulfuric horizon or sulfidic material within 125 cm from the surface.

Orthithioni- having a sulfuric horizon.

Protothioni- having sulfidic materials.

Toxi- having significant concentrations of toxic ions for plant growth other than aluminium, iron, sodium or calcium.

Veti- having a content of extractable bases plus extractable aluminium less than 6 cmol(+)kg- clay in at least some subhorizon of the B horizon within 125 cm from the surface.

Vermi- having 50 percent or more by volume of wormholes, wormcasts, and filled animal burrows in the upper 100 cm or down to rock or to a petroferric, petrocalcic or petrogypsic horizon, or to a duripan, whichever is shallower.

Verti- having vertic properties within 50 cm from the surface.

Xanthi- having a ferralic B horizon with a yellow to pale yellow colour (rubbed soil has hues of 7.5YR or yellower with a moist value of 4 or more and a moist chroma of 5 or more).

Yermi- having a yermic horizon including a desert pavement.
Explanatory Notes to the Use and Definition of a Number of Soil Subunit Names

Related to Diagnostic Horizons. Most of the diagnostic horizons can be considered for naming soil subunits with the following exceptions or clarifications.

**Natric and cambic horizons**

The use of the soil subunit name Natri- is not envisaged. The use of the soil subunit name Cambi- is in general not recommended, as this would be most irrelevant for the subdivision of Dystric, Eutric and Haplic soil units.

**Sulfuric horizon**

The use of the soil subunit name Sulfuri- is not recommended for the subdivision of Thionic soil units. Instead of Sulfuri-Thionic, Orthi-Thionic should be used.

**Calcic horizon**

Considering the present use at the second level, the soil subunit name Calci- is defined as follows:

- having a calcic horizon or concentrations of soft powdery lime within 125 cm from the surface.

Names such as epi-, hyper- and hypo- are used on their own at third level when the soil unit name is Calcic:

- **Epicalcic** within 50 cm from the surface.
- **Hypercalcic** having a calcic horizon which has 40 percent or more calcium carbonate equivalent.
- **Orthicalcic** having a calcic horizon.
- **Hypocalcic** having concentrations of soft powdery lime.

**Ferralic B horizon**

The name Ferrali- is not used at the third level to indicate the occurrence of a ferralic B horizon, as this would be confusing with the meaning of the diagnostic property and soil unit connotative ferralic. It is however used to separate soil subunits having ferralic properties within 125 cm.

**Argic B horizon**

The name Luvi- is used at the third level to indicate the occurrence of an argic B horizon, rather than Argi. This is similar to the use at the second level.

Related to Diagnostic Properties and Other First and Second Level Criteria. Most of the diagnostic criteria can be used without changing the definition or the corresponding connotative of the first and second level. However, the following annotations have to be made:

**Abrupt textural change**

The diagnostic property is only used at first and second level for Planosols, but the name Abrupti- can be used at third level for e.g. Ferralsols, Acrisols, Lixisols, Alisols, Solonetz or Luvisols with an abrupt textural change.
Andic properties
Previous definitions of third level connotatives such as ando- and vitri- and phases of volcanic admixtures vary strongly in detail of thickness and properties. The name Andi- should only be used to indicate the presence of material having andic properties.

A topsoil containing, within 30 cm from the surface, a layer having andic properties with a thickness of 10 cm or more, or, when mixed, estimated to originally have had such thickness, may be expressed in the classification using the name Epiandi-.

Dystric/Eutric
According to the rules for the definitions of soil subunit names, Dystri- and Eutri- have unique meanings, and should not be used to subdivide Dystric and Eutric soil units. The definitions as established for Dystri- and Eutri- at the third level correspond with the use of Dystric and Eutric at the second level but related to the B horizon control at the third level.

Fluvic properties
The soil subunit names Fluvi- may be significant for major soil groupings such as Gleysols and Cambisols to indicate the presence of fluvic properties at full definition. Thin surface mantles of new material (less than 50 cm thick) should not be recorded at the third level.

Rhodic
The diagnostic colour requirement related to Rhodic soil units is used for the soil subunit name Rhodi-, applying to B horizons which have a hue redder than 5YR (3.5YR or redder) in all parts, apart from minor transitional horizons, and have a colour value moist or less than 3.5, and a colour dry no more than one unit higher than the value moist (slightly modified definition).

Sodic properties
The soil subunit name Sodi- can be used indicated sodic properties within 50 cm from the surface.

Soft powdery lime
As mentioned above, it is recommended to indicate the presence of significant concentrations of soft powdery lime within 125 cm from the surface with the soil subunit name Hypocalci-, or Hypo- for Calcic units.

Sulfidic materials
The diagnostic property sulfidic materials is used together with the sulfuric diagnostic horizon to separate Thionic soil units. It is not recommended to use the name Sulfi- or sulfidi- to subdivide Thionic soil units. If a subdivision of Thionic soil units is required, it is suggested to use qualifier Proto- for soils with sulfidic materials only.

Tonguing and Interfingering
Soil subunit names Glossi- can be used to reflect the occurrence of the diagnostic property tonguing. Interfingering is indicated by the soil subunit name Hypoglossi-.
Related to Phases. The use of phases as diagnostic criteria at the third level is in general not recommended, with the exception of some phases which often show a clear relationship with the soil unit.

The following phases may be used at the third level. When used as soil subunit names, they should no longer be used as phases at that level. Some of the original depth limits have been standardized to 125 cm.

<table>
<thead>
<tr>
<th>Phase</th>
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<td>Sodic</td>
<td>Hyposodi-</td>
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</table>

Related to Depth or Intensity. The following names relate directly to the second level connotatives. They may, in addition, be used in connection with third-level soil subunit names. In such cases, the hyphen (-) is not used, but the two elements are written as one word, e.g. Orthicalci-.

- Bathi- starting between 125 and 200 cm from the surface.
- Cumuli- may be used to indicate repetitive accumulation in epiedons, having a thickness of 50 cm or more.
- Epi- indicates occurrence starting within 50 cm from the surface.
- Hyper- represents an excessive or strong expression of certain features.
- Hypo- represents a slight or weak expression of certain features.
- Orthi- represents the typical expression of the soil unit or soil subunit, or indicates that there is no further or meaningful characterization needs.
- Proto- indicates a pre-condition or an early development of certain properties.

Soil Subunit Names and Priority Rules for a Number of Major Soil Groupings

The priority rules for third-level subunit designation of 20 major soil groupings examined so far have been listed in Table 2. The priority sequence of soil subunit names has been established following the priority rules.

* Except for Podzols, Chernozems, Kastanozems, Greyzems, Phaeozems, Anthrosols, Andosols, Podzoluvisols.
It should be emphasized that the priority sequence for a given major soil grouping takes into account the possible third-level connotative combinations for all the soil units pertaining to that major soil grouping, but may not be applicable to every soil unit defined within the grouping as third-level definitions and general rules of the system preclude the occurrence of certain combinations.

**Diagnostic Desert Surface Horizons**

The names Aridi-, Yermi- and Takyri- are used. These are discussed in some detail below.

**Introduction.** The revision of the FAO/Unesco/ISRIC Legend of the Soil Map of the World (1) suppressed the use of climate in the definition of high-level taxa and replaced the aridic moisture regime with a yermic phase. There are no specific desert soil taxa at the first and second level in the legend.

Strong moisture deficit, extreme temperature and high winds are the main factors controlling soil formation in deserts. These factors, alone or in combination, are reflected in the composition, morphology and behaviour of desert soils. The shallow penetration of moisture in desert soils restricts current soil development to the upper horizons. Surface horizons are therefore the best markers of current soil formation in deserts.

Some desert soils are subject to rapid accumulation of aeolian or alluvial sediments. In this situation, sedimentation is faster than pedogenesis, therefore the topsoil remains a C horizon.

When sedimentation is slower than pedogenesis, specific desert genetic surface horizons form. These genetic horizons combine in different assemblages, according to the nature of the parent material, the type of desert environment and the age of the soil. Certain properties, which may be called "aridic properties", are however common to all desert soils.

**Aridic Properties**

*Organic carbon:* The organic carbon content is less than 0.6 percent if the texture is sandy loam or finer and less than 0.2 percent if coarser (weighted average of top 18 cm or down to the top of a B horizon, a cemented horizon or to the rock, whichever is shallower). The organic carbon content may be higher if the soil is periodically flooded, or if it has an electrical conductivity of the saturated paste extract of 4 dS/m or more somewhere within 125 cm below the surface.

*Aeolian features:* Soils having aridic properties show evidence of aeolian activity in one or more of the following forms:
- The sand fraction in some subhorizon or in inblown material filling the cracks contains a noticeable proportion of rounded or subangular sand particles showing a mat (dull) surface (use of 10X magnifier). These particles make up 10 percent or more of the medium and coarser quartz sand fraction.
- Wind-shaped rock fragments on the surface.
- Aeroturbation (e.g. crossbedding).
- Evidence of wind erosion or deposition or both.
Colour: Both broken and crushed samples have a Munsell colour value of 3 or more when moist and 4.5 or more when dry, and a chroma of 2 or more when moist.

Base saturation: Always more than 75 percent. Normally base saturated. The presence of acicular (needle-shaped) clay minerals (polygorskite and sepiolite) in soils is connotative of a desert climate but has not been reported in all desert soils. This is probably due to the fact that desert climate does not produce acicular clays, but only preserves them provided they exist in the parent material or in the dust that falls on the soil.

Yermic Horizon. Most desert stable surfaces are covered with a typical (desert) pavement. Pavements are surface accumulations of rock fragments called reg or serir in Arab countries, gobi in China, gibber in Australia. Pavements are usually embedded in a loamy vesicular crust covered with a thin aeolian sand (or loess) layer. The vesicular crust shows a polygonal network of desiccation cracks, often filled with inblown material, which extend into underlying horizons. The vesicular crust and the A horizons below have a weak to moderate platy structure.

Pavements have been considered as genetic horizons and the symbol D was proposed for them. The subscript v was used for vesicular crusts (A_v horizon). Therefore, a desert pavement is usually included in D/A_v/A sequence. It happens sometimes that the A horizon is so thin that the topsoil is reduced to a D/A_v sequence.

In very cold deserts (e.g. in Antarctica), coarse cryoclastic material dominates and there is little dust to be deflated and deposited by winds. In these conditions a dense pavement with varnish, ventifacts, aeolian sand layer and soluble minerals accumulations may occur directly on loose C horizons, without a vesicular crust and underlying A horizons. Then there is only a D surface horizon.

Mature pavements that are composed of resistant rock are varnished on their exposed surfaces, and if the dust that falls contains calcium carbonate, gypsum or more soluble salts, their embedded surfaces are coated with these soluble minerals which accumulate also in the underlying A horizons. We then have a D/A_v/A_ky sequence. Mature pavements usually include ventifacts (wind-shaped stones).

In areas where a shallow non-saline watertable occurs or in areas transition to semi-arid, a relatively dense bush vegetation often grows. This vegetation traps aeolian dust and makes it deposit on the topsoil. It also protects surface horizons form wind erosion. In these conditions, a thick fine-textured vesicular crust forms. It is underlain by a platy A horizon. Wide polygonal cracks from upon drying and give the soil a takyr-like morphology. We then have an A_ky/A topsoil sequence. Many solonetztes have this type of topsoil.

All the horizons assemblages described above are variants of what may be called the yermic surface horizon which may be defined as follows:

The yermic epidedon consists of mineral soil material. It is a surface horizon unless it underlies a deposit of largely unaltered new material less than 50 cm thick. It has aridic properties, as defined above, and:

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a pavement which is varnished or includes ventifacts, or both, or
- a pavement and a vesicular crust, or
- a vesicular crust above a platy A horizon, without a pavement.

Takyric Horizon. In depressions where surface water, rich in clay and silt suspensions and having a relatively low concentration of salts, is available and can accumulate and leach the upper soil horizons, a thick fine-textured crust forms. Periodic salt leaching causes the dispersion of the clay fraction and the formation of a compact crust which forms prominent polygonal cracks upon drying. Such crusts are extensive in central Asia, where they are called takyrs. Clay and silt often make up more than 80 percent of the crust material.

Takyric crusts form an inhospitable seedbed and the only meagre vegetation they support develops on blown sand accumulations. Though takyric horizons are closely associated with surface flooding, they can be considered genetic horizons because they have a structure (platy) and undergo periodic dispersion and leaching. The symbol T is proposed to designate the takyric horizon which is defined as follows:

The takyric horizon is a surface mineral horizon which forms in desert soils which are periodically flooded. It has aridic properties as defined above, a platy structure and has a crust which has all the following properties:
- it is thick enough so that it does not curl entirely upon drying;
- it has polygonal desiccation cracks extending at least into the upper 2 cm when the soil is dry;
- it has a sandy-clay-loam, clay-loam, silty-clay-loam or finer texture;
- its consistence is very hard when dry and very plastic and sticky when wet;
- the electrical conductivity of the saturated paste extract is less than 4 dS/m or less than that of the horizon immediately below.

Literature Cited

## Table 2. Priority Rules for Third-Level Names for 20 Major Soil Groups

<table>
<thead>
<tr>
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Contrasting Properties of Acri, Alic, Lixic and Luvic Soils

J. Deckers*, B. Delvaux** and R. Dudal*.

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In most systems of soil classification, a textural differentiation within a solum has been used as a diagnostic feature to separate soil units at a high level of generalization. Such 'textural B' horizons are generally attributed to an accumulation in the subsurface of layer-lattice silicate clays as a result of illuviation. Originally, this clay movement was considered to be a 'podzolic' process, however, by the 1930's, it was realized that a number of soils called 'podzolic' did develop under the influence of soil forming processes other than podzolisation (Baldwin, 1928).

The term 'lessivage' came into use to name the soil forming process by which fine clay, and the ferric iron bound to it, is translocated mechanically from the surface horizons into the subsurface (Aubert, 1938).

Morphological evidence of clay accumulation from percolating water was provided by local concentrations of clay in the form of oriented clay skins on structural ped surfaces and of clay fillings in channels and pores (Frei and Cline, 1949).

It has more recently been observed that a textural differentiation may develop, besides through illuviation, also by destruction of clay in the surface horizon, selective surface erosion of clay, biological activity, or by a combination of two or more of these different processes. The 'textural B' horizon was renamed an 'argillic horizon' (Soil Survey Staff, 1975) or an 'argie horizon' (FAO, 1988) with a clear definition expressed in terms of quantified morphological requirements.

The definition of the argillic horizon reflects the broader concept of textural differentiation which may result from different soil forming processes.

The importance of the argillic horizon to soil classification is related not only to the textural differentiation in the solum but to its accessory properties, such as water holding capacity, hydraulic conductivity and chemical characteristics.

Because the formation of an argillic horizon is relatively slow, its presence indicates a stability of the landsurface on which it has developed. It shows that a substantial amount of water has moved through the soil and that besides clay movement it has also caused the removal of soluble materials. Although the presence of an argillic horizon is evidence, that climate and vegetation have had their effect in the formation of the soil one cannot imply that the argillic horizon has been formed under present climatic conditions.

If an argillic horizon is rarely moistened in the present environment, as for instance in sub-humid steppes, or in semi-arid and arid environments, it probably indicates a soil of old age formed under previous more humid conditions. In this case, the diagnostic significance of the argillic horizon comes second to the occurrence of mollic surface horizons in steppic regions or to the appearance of calcic or gypsic enrichments under semi-arid or arid environments. Similarly in humid tropical conditions, very strong weathering, resulting in high contents of iron and aluminium oxides and hydroxides, takes precedence as a diagnostic feature over the eventual presence of an argillic horizon.
horizon. Hence the meaning of the argic horizon and its diagnostic significance have to be assessed in connection with other diagnostic features.

In the revised legend of the FAO/Unesco soil map of the world (FAO, 1988, Driessen and Dudal, 1991), there are four major soil groupings in which the presence of an argic horizon is the main diagnostic feature at the highest level of generalization: the Acrisols, the Alisols, the Lixisols and the Luvisols. All four these names have been newly coined on account of the confusion which had arisen from the inappropriate use of a widely ranging 'podzolic' nomenclature (Dudal, 1970). The Acrisols and Alisols are soils with a low base saturation (< 50% by IM NH4OAc at pH 7) in the argic horizon; Lixisols and Luvisols have a high base saturation (> 50% by IM NH4OAc at pH 7) in the argic horizon. This implies a low pH, a low content of plant nutrients and a hazard of Al saturation in Acrisols and Alisols. On the contrary, Lixisols and Luvisols are less acid, have a more favourable plant nutrient status and do not show Al in the exchange complex. The difference between Acrisols and Alisols is that the former are dominated by low activity clays (CEC < 24 cmol(+)/kg clay) in the argic horizon while the Alisols are characterized by high activity clays (CEC > 24 cmol(+)/kg clay). The same criteria apply to the distinction of Lixisols and Luvisols in which the argic horizon is characterized by low and high activity clays respectively. Table 1 sums up the criteria by which these four major soil groupings are distinguished.

### Table 1. CEC of the clay fraction in the argic horizon

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<th>Base Saturation</th>
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<td>&lt; 50%</td>
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<td>≥ 50%</td>
<td>Lixisols</td>
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Many Acrisols and Lixisols share with Ferralsols very low CEC values of the clay fraction (≤ 16 cmol(+)/kg clay).

On the occasion of the preparation of a World Reference Base for Soil Resources (WRB), which uses the FAO-Unesco Legend (FAO, 1988) as a point of departure, it was argued that base saturation and cation exchange capacity were not suitable criteria for the separation of major soil groupings on two accounts: base saturation is variable in time and can be influenced through fertilization and liming; cation exchange capacity is a qualification which can be determined through analysis only and therefore not usable at the field level. In order to simplify the classification, it was suggested at same stage to merge Alisols and Luvisols in a group characterized by high activity clays, and similarly to group Acrisols and Lixisols having low activity clays in the argic horizon. It soon appeared that these 'mergers' would be inappropriate as they would lump soils of entirely different origin, geographic distribution, management requirements and development potential. It was concluded therefore to maintain the original separation while recognizing the need for a further validation of the proposed criteria.

It is realized that base saturation can be changed by human interference. It should be noted, however, that the proposed values apply to the argic horizon which is a subsurface horizon reaching down into the lower parts of the solum and thus probably less sensitive to changes.

The 'activity' of clays is not only an indication of cation exchange capacity, it also reflects the stage of weathering of the mineral fraction of the solum, it is an indicator of physical properties, including consistence and water holding capacity. Both base saturation and clay activity have implications for soil management. Hence these criteria reflect a cluster of properties which relate to soil formation, morphology, management and distribution. These properties clearly justify the separation of these four major soil groupings even though they have not yet been sufficiently quantified to be used as additional diagnostic characteristics.
The following brief description of each of these four groups should clarify the rationale for their separation.

**Acrisols (from L. acris, very acid):**

The argic horizon of the Acrisols is dominated by 1:1 lattice low activity clays. The balance between the liberation of bases by weathering and their removal by leaching is negative: Acrisols are acid and sometimes subject to Al toxicity. Plant nutrients are concentrated in the organic matter of the surface layers. Soil structure in the surface horizon is weak and peds collapse readily under the impact of heavy rainshowers. Acrisols develop mainly on acidic parent materials, in undulating landscapes of subhumid tropics and subtropics. In the tropics, they are still largely forested or used under shifting cultivation. When continuously cropped they require careful management to protect them from erosion and to enhance their fertility. Acrisols occur extensively in the Amazon basin, the humid parts of W. Africa, South Eastern China and the South-Eastern part of the United States.

**Alisols (from L. aluminum):**

The argic horizon in Alisols has moderate to high CEC which reflects the presence of high activity clays. Alisols have experienced prolonged weathering through which most weatherable primary minerals have disappeared (Delvaux and Herbillon, 1993). As a result, most of the base reserve 'TRB' (Total Reserve in Bases, Herbillon, 1989) is associated with the clay minerals. The current weathering of secondary 2:1 clay minerals releases large amounts of Aluminum giving rise to strongly acid conditions ($\text{pH}_{\text{KCl}} < 4.0$) and high Al saturation of the exchange complex (> 60% by ECEC). Some Alisols derived from basic rocks may have high contents in both exchangeable Mg and KCl extractable Al. These weathered soils contain low levels of plant nutrients (except for Mg, in some cases) and free Al is present in toxic quantities. Alisols are usually well drained soils with weakly developed structures in surface horizons and subsurface horizons that have angular blocky or prismatic structures. Clay content is medium to high and cracks develop upon drying. They are usually reddish in colour and have a low silt/clay ratio. They are usually derived from or associated with basic rocks. Forested Alisols accumulate organic matter in topsoils and B horizon. The major constraint in managing Alisols is Al toxicity at shallow depth. Cultivated Alisols are used for cash crops such as oil palm, rubber, tea, sugar cane; their productivity is very low in subsistence agriculture. These soils may become very productive after heavy fertilization and liming. Alisols occur mainly in the humid tropics and subtropics in the central part of South America, the Caribbean area, the Southeastern States of the USA, Africa, India and Southeast Asia.

**Lixisols (from L. lix, lye, lixiviation, washing out):**

The argic horizon is dominated by 1:1 lattice low activity clays. Their base saturation is medium to high which seems to be in contradiction with the strong weathering which these soils reflect. Lixisols occur extensively in a latitudinal belt which has undergone marked climatic changes during Pleistocene. Their development is to be ascribed to climatic conditions more humid than present, with a subsequent resaturation by dust and ongoing liberation of bases. In spite of the high base saturation, the total amount of plant nutrients remains low on account of the low cation exchange capacity. Soil structure of the surface horizons is weak. Surface crusts develop frequently during the dry season. Soil depth is often limited by a stoneline.

Lixisols develop on acidic parent materials in undulating landscapes of the subhumid tropics with a marked seasonal rainfall distribution. Lixisols are used for extensive grazing or for subsistence agriculture. They occur extensively in West and South-east Africa, in Eastern Brazil and on the Indian subcontinent.
Luvisols (from L. luere, to wash):

The argic horizon in Luvisols has a moderate to high cation exchange capacity which reflects the presence of high activity clays. Luvisols are moderately weathered soils and have high mineral reserves. A base saturation above 50% reflects a fair content of plant nutrients, and a favourable pH. A typical Luvisol has the following horizon sequence: a dark brown crumbly topsoil, a yellowish brown, weakly structured eluvial horizon, a dark-yellow brown or red sub-angular blocky argic B horizon below which the yellowish silty loamy parent material occurs. When the land is under cultivation, the upper horizons may erode so that the argic horizon comes close to the surface. Horizon depth and morphology change with soil texture of the parent material. The E horizon is thicker when the texture gets coarser. The B horizon usually occurs as a single layer, with a subangular blocky structure in silty loamy material. In coarse textured parent material, the argic B horizon occurs as lamellae, parallel to the surface, with a compact massive structure. Luvisols are generally fertile soils, which are grown to small grains, sugar beet, forage and fruit orchards in the temperate climates. Slopy land is either under meadow or under forest. The only problems with Luvisols are soil erosion and structure degradation under ploughing with heavy machinery when they are too wet. In Mediterranean areas, the Chromic, Calcic and Vertic Luvisols are commonly planted to cereals and to grapes. The greater part of the Luvisols occur in humid to sub-humid regions of Central and Western Europe, the USA, the Mediterranean region, China, South-America and Southern Australia.

Discussion

Cation exchange capacity and base saturation separate Acrisols, Alisols, Lixisols and Luvisols in the FAO/UNESCO legend (FAO, 1988). These criteria are likely indicators of a broad set of properties and of a geographic distribution which require a distinction at the highest level of a soil classification. However using only base saturation in the argic horizon is unsatisfactory to separate Alisols and Luvisols, at least from a genetic point of view. Most loess-derived Luvisols in Western Europe are cultivated and thus base saturated; many of their forested counterparts are strongly acid in the major part of the B horizon, and would presently key out as Alisols. Luvisols are moderately weathered soils while Alisols have experienced prolonged weathering. Criteria related to soil weathering stage could therefore be valid to clarify the border Luvisol/Alisol. Such criteria could include the particle size localization of TRB and/or the silt/clay ratio: in the Alisols, TRB is mostly associated with the clay fraction and silt/clay ratio is below 0.6. Such criteria would allow for the presence of Luvisols with a base saturation below 50% in the argic horizon.

Conclusion

Contrasting properties of Acric, Alic, Lixic and Luvic soils justify their distinction at the highest level. These major soil groupings differ in their environments, geographic distribution, management requirements and development potential. A pragmatic approach to making this separation is advocated for the present in the expectation that the further study of these soils will allow for a comprehensive and more user-friendly definition.

References


Abstract. WRB recommend that sandy as well as finer textured soils with gleyic properties within 50 cm the surface should normally be classified as Gleysols, included those with fluvic properties or plinthite. But those with an andic, an anthric, an argic, a thick (> 30 cm) histic, a natric, a salic, a spodic or a vertic horizon should be classified as gleyic subunits of other mayor soil units together with those with gleyic properties between 50 and 100 cm soil depth.

Soils with stagnic properties within 50 cm from the surface should be classified as Stagnosols, if they have no other diagnostic horizons or properties other than an histic, mollic, umbric or ochric horizon, an albic or argic horizon, or a cambic, plinthic, ferric or vertic horizon. Those with an eluvic horizon and planic properties within 125 cm, and lacking a natric or a spodic B should be classified as Planosols. Those having a natric horizon, or an argic horizon showing an irregular upper boundary resulting from albeluvic tonguing into the argic horizon should be classified as stagnic subunits of Solonetz or Glossisols respectively. Those with stagnic properties between 50 and 100 cm soil depth should be classified as stagnic third level units.

Arguments for recommended changings are given as well as more precisely definition of gleyic and stagnic properties.

Introduction.

Since more than 20 years differences between soils with gleyic properties and with stagnic properties have been discussed (Schlichting 1973, Moormann and Wetering 1985, Blume 1988). WRB now recommend to widen the unit of Gleysols in the legend of the FAO-Unesco Soil map of the world, and to install with the Stagnosols a second unit with stagnic properties beside the Planosols.

Soils with gleyic properties are permanently wet and reduced in the subsoil, and periodically to permanently wet in the topsoil. The upper part of the soil is therefore either mottled (in case of temporary aeration) or has reduction colours. These redoximorphic features are formed under the influence of poorly to well drained groundwater. This in contrast to soils with stagnic properties, which also have redoximorphic features but have another hydrology and morphology. Stagnic soils normally have a dense subsoil with low permeability but are not permanently wet in top and/or subsoil, where as gleyic soils can have high permeability.
Gleyic soils are found in valleys or depressions under almost all climate conditions, while stagnic soils are usually found in plateau positions or on gentle slopes under semihumid to perhumid climatic conditions. There are also pronounced differences in the ecology and utilization between these two soil groups with redoximorphic features (Schlichting and Schwertmann 1973, Banta 1985).

Typical gleyic soils are classified as Gleys or Groundwatergleys in many European soil classifications (Austria, France, Germany, Switzerland, UK). But in the German classification the periodically flooded soils of coastal regions are excluded as "Marschböden" from the normal Gley (and some Fluvisols). Typical stagnic soils are classified as Stagnogleys and/or Pseudogleys in many European soil classifications (Germany, United Kindom, Austria, France, Switzerland). In the Legend of the Soil Map of the World (FAO-Unesco, 1974) most of them belong to the Gleysols and some to the Planosols. In the revised Legend (FAO-Unesco-ISRIC, 1990) they partly belong to Plinthosols and Planosols, are soil units in the Solonetz, Phaeozems, Podzoluvisols, Alisols, Luvisols and Lixisols, and may occur as soil subunits in many other major soil groups. In the USDA Soil Taxonomy (Soil Survey Staff, 1992) the gleyic soils belong to soils with aquic conditions, together with the stagnic soils; nearly all Aquods and Aquepts and Aquolls are gleyic soils, while most Aqualfs and Aquults are stagnic soils.

Description and Definition of Gleyic and Stagnic Properties

Soils with gleyic properties are influenced by groundwater. The reductomorphic subsoil with white to black or blue to green color is wet all the time (unless drained), contains free Fe$^{2+}$ and/or has low to negative redoxpotentials. The topsoil may be oximorphic (reddish brown mottles, especially on aggregate surfaces) by alternating moist/wet conditions (Fig. 1). This depends on variations of the groundwater table, partly influenced by rain and evapotranspiration.

![Figure 1](image.png)

Figure 1: Typical soil with gleyic properties: G gleyic, o oximorphic, r reductomorphic; GWL groundwater table, mh mean high (together with capillary fringe), ml mean low
Soils with **stagnic properties** are soils in which rain water stagnates in the upper part of the soil on a slowly permeable layer. The lower permeability may generally be attributed to a change in bulk density or clay content between the soil layers, but may also be caused by an intake of interflow. As a result, stagnant soils show characteristic distribution pattern of the iron- and manganese oxides: the aggregate surfaces of the silty to clayey B horizon are bleached and depleted of Fe/Mn-oxides, while the centres of the aggregates are enriched showing brown to orange colours.

WRB recommend the following definitions of gleyic and stagnic properties:

Soils with gleyic or with stagnic properties are at least temporarily completely saturated with groundwater or with surface water, unless drained, for a period that allows reducing conditions to occur. In addition they have a gleyic or a stagnic colour pattern in more than 50 percent of the soil volume within 50 cm of the mineral soil surface, or they have a gleyic or a stagnic colour pattern in 100 percent of the soil volume below a plough layer within 50 cm of the surface.

**Groundwater** is subsurface water, devoid of oxygen, which fills all pores at least temporarily and at least a part of the soil within 50 cm of the surface.

**Surface water** is rainwater stagnating temporarily above a soil layer with low water permeability.

Reduced conditions are evident by one or more of the following:

- a value of \( rH \) of 19 or less (\( rH = \frac{Eh(mV)}{29} + 2pH \));
- the appearance of a solid blue colour on a freshly broken surface of a field-wet soil sample, after spraying it with a solution in water of 1% potassium ferric cyanide (\( K_3Fe(III)(CN)_6 \));
- the appearance of a strong red colour on a freshly broken surface of a field-wet soil sample after spraying it with a 0.2% 2,2'-dipyridyl solution in 10% acetic acid.

A gleyic colour pattern (or gleyic soil layer) results from a redox gradient, that differs in space between the groundwater and the capillary fringe causing an uneven distribution of Fe/Mn (hydr)oxides. In the lower part and/or in ped cores these oxides are either transformed into insoluble Fe/Mn(II) compounds or they are translocated, both processes leading to the absence of colours redder than 2.5Y (reductomorphic properties). Translocated Fe/Mn compounds can be concentrated in oxidized for (Fe(III), Mn(IV) on ped surfaces or in biopores, and towards the surface even in the matrix (oximorphic properties).
Oximorphic properties apply to soil materials in which reducing and oxidizing conditions alternate, as is the case in the capillary fringe and in the surface layer of soils with fluctuating groundwater levels. The oximorphic properties are evidenced by the presence of reddish brown (ferrihydrite) or bright yellowish brown (goethite) mottles. In acid sulfate soils bright yellow (jarosite) mottles occur as well. In loamy and clayey soils, the iron (hydr)oxides are concentrated on aggregate surfaces and walls of larger pores, like old root channels which in extreme cases can be entirely filled with such oxides, while the cores still show reductomorphic colours. This is especially so in the lower part of an oximorphic layer. Thus the distribution pattern of the Fe/Mn (hydr)oxides is "extrovertly" oriented towards the ped and soil surface from where the oxygen comes.

Reductomorphic properties apply to soil materials that are permanently wet as evidenced by a characteristic gleyic colour pattern (white to black: N1/ to N8/; bluish to greenish: 2.5Y, 5Y, 5G, 5B) in more than 95 percent of the soil matrix. In loamy and clayey materials blue-green dominates due to Fe (II, III) hydroxy salts ("green rust"), in materials rich in S it is black due to Fe sulfides carbonate-rich material is white due to calcite and/or siderite, while in sands colours are light gray to white, often impoverished in Fe and Mn. The upper part of a reductomorphic layer may show up to 5 percent rusty colours, mainly around channels of burrowing animals or plant roots.

A stagnic colour pattern (or stagnic soil layer) shows either mottling in such a way that the surfaces of the peds (or parts of the soil matrix if structure is absent) are lighter (by one value unit or more) and paler (by one chroma unit or more), and the interior of the peds (or parts of the soil matrix) are more red (by one hue unit or more) and brighter (one chroma unit or more) compared to the non-reductomorphic parts of the layer, or of its mixed average or an albic horizon with or without concretions above a mottled layer.

Soils with Gleyic Properties

WRB recommend that sandy as well as finer textured soils with gleyic properties within 50 cm of the surface should normally be classified as Gleysols, included those with fluvic properties or with plinthite. But those with an andic, an anthric, an argic, a thick (> 30 cm) histic, a matric, a salic, a spodic or a vertic horizon should be classified as gleyic subunits of other major soil units together with those with gleyic properties between 50 and 100 cm soil depth.

WRB recommend the following definition for Gleysols:

Gleysols are soils having gleyic properties within 50 cm of the surface. They have no diagnostic horizons other than a histic, mollic, umbric or ochric surface layer, a cambic horizon, or a
sulfidic, sulfuric, calcic, gypsic or plinthic horizon within 125 cm of the surface.

A subdivision of Gleysols at a second categoric level (soil units) is proposed the following way. They are arranged in key order:

Gleysols having a sulfidic or sulfuric horizon within 125 cm of the surface.

Thionic Gleysols

Other Gleysols having a plinthic horizon within 125 cm of the surface.

Plinthic Gleysols

Other Gleysols consisting of tephric soil materials to a depth of 50 cm or more from the surface.

Tephric Gleysols

Other Gleysols having salic properties.

Salic Gleysols

Other Gleysols having sodic properties within 50 cm of the surface.

Sodic Gleysols

Other Gleysols which are loamy sand or coarser throughout to a depth of a least 100 cm below the surface.

Arenic Gleysols

Other Gleysols having a histic horizon which is less than 40 cm thick.

Histic Gleysols

Other Gleysols having a mollic horizon.

Mollic Gleysols

Other Gleysols having an umbric horizon.

Umbric Gleysols

Other Gleysols showing stratification below a cambic horizon or having an organic carbon content that decreases irregularly with depth or that remains above 0.2 percent to a depth of 125 cm.

Fluvic Gleysols

Other Gleysols having a calcic horizon within 125 cm of the surface.

Calcic Gleysols

Other Gleysols having a ferric horizon within 125 cm of the surface.

Ferric Gleysols

Other Gleysols.
Haplic Gleysols

Soils with gleyic properties, and with an histic horizon thicker than 30 cm have to be classified as Histosols.

Soils with gleyic properties within 50 cm of the surface, and with an andic horizon should be classified as Gleyic Andosols.

Soils with gleyic properties within 100 cm of the surface, and an argic horizon have to be classified as Gleyic Acrisols, Gleyic Alisols, Gleyic Glossisols (former Gleyic Podzoluvisols), Gleyic Lixisols or Gleyic Luvisols respectively.

Soils with gleyic properties within 100 cm of the surface, and with a natric horizon have to be classified as Gleyic Solonetz.

Soils with gleyic properties within 100 cm of the surface, and with a spodic horizon have to be classified as Gleyic Spodosols.

Soils with gleyic properties within 100 cm of the surface, and with a salic horizon have to be classified as Gleyic Solonchaks.

Gleyic properties within 100 cm of the surface does mean: saturation with groundwater, unless drained, for a period that allows reducing conditions to occur, 30 cm below the surface of the mineral soil; and a gleyic colour pattern in more than 50 percent of the soil mass in a layer at least 50 cm thick within 100 cm of the mineral soil surface; or a gleyic colour pattern in 100 percent of the soil mass in a layer at least 20 cm thick within 100 cm of the mineral soil surface.

In opposite to soils with an argic, a natric, a salic, a spodic or a vertic horizon the Gleyic Arenosols, Gleyic Chernozems, Gleyic Phaeozems and Gleyic Cambisols have to be restricted to those, which show gleyic properties within 100 cm of the surface but at deeper levels than required for the Gleysols.

Soils with Stagnic Properties

WRB recommend that soils with stagnic properties within 50 cm of the surface should be classified as Stagnosols in principle. But those soils having an eluvic horizon and planic properties should be classified as Planosols. Those with a natric horizon should be classified as stagnic subunits of Solonetz. Those having an argic horizon, and showing an irregular upper boundary resulting from albeluvic tonguing into the argic horizon should be classified as subunits of Glossisols.

Therefore Stagnosols should be soils with stagnic properties within at least 50 cm of the surface, but having no diagnostic horizons other than a (thin) histic, mollic, umbric or ochric surface horizon, an albic horizon, or a(n) agric, cambic, plinthic, ferric or vertic horizon.
A subdivision of Stagnosols at a second categoric level (soil units) is proposed the following way. They are arranged in key order:

Stagnosols having permafrost within 200 cm of the surface, lacking cryic properties.

Other Stagnosols having a plinthic horizon within 125 cm of the surface.

Other Stagnosols having an albic horizon.

Other Stagnosols having an argic horizon and alic properties.

Other Stagnosols having an argic horizon.

Other Stagnosols having gleyic properties within 125 cm of the surface.

Other Stagnosols having a histic horizon.

Other Stagnosols having a mollic horizon.

Other Stagnosols having a vertic horizon with its upper boundary within 50 cm of the surface.

Other Stagnosols.

In oposite to Stagnosols, Planosols are soils with an eluvic horizon and planic properties within 125 cm of the surface; having an argic or vertic subsurface horizon but are lacking a natric or spodic horizon.

Planic properties refer to an abrupt textural change in association with stagnic properties above that boundary. An abrupt textural change requires a doubling of the clay content within 7.5 cm if the upper horizon has less than 20 percent clay, or a 20 percent (absolute) clay increase within 7.5 cm if it has 20 percent or more clay. In the latter case some part of the lower horizon should have at least twice the clay content of the upper horizon.

Soils with stagnic properties within 50 cm of the surface, and
with an argic horizon have to be classified as Stagnic Acrisols, Stagnic Alisols, Stagnic Glossisols, Stagnic Lixisols and Stagnic Luvisols respectively.

Soils with stagnic properties within 50 cm of the surface, and with a natric or a spodic horizon have to be classified as Stagnic Solonetz or Stagnic Podzol respectively.

This WRB recommendation does mean that most typical European secondary Pseudogleys with an argic B are Stagnosols (f.e. Luvic Stagnosols: Fig. 2a). But those with properties of Glossisols should be classified as Stagnic Glossisols. In cases where there is a bleached, light-coloured eluvial horizon abruptly overlying a dense, mottled subsoil with an extremely higher clay content, it is a Planosol (f.e. Fig 2 d). In addition stagnic soils without markable differences in clay content between top- and subsoil, and with rather monotonously mottling have to be classified as Stagnosols too. Those soils are dense sandy loams to silt loams without aggregation and nearly no coarse pores which are classified as Haftnässe-Pseudogleye in Germany on the one hand (f.e. Fig. 2c), and clayey soils with a pronounced prismatic structure, which are classified as Pelosol-Pseudogley in Germany on the other hand (f.e. Fig. 2b). Until now such soils were classified as Stagnic-dystric or Stagni-eutric Cambisols in most cases (FAO-Unesco 1990).

Figure 2: Typical soils with stagnic properties; a) Glossisols or Luvic Stagnosols; b) Haplic or Vertic Stagnosols; c) Haplic Stagnosols; d) Albic Stagnosols or Planosols; e) Histic Stagnosols or Planosols (IS = loamy sand, L = loam, T = clay, sU = sandy silt; horizon symbols after FAO-Unesco 1990; in addition a = prismatic structure, often slicken sides).

Soils with stagnic properties between 50 and 100 cm soil depth should be classified as stagnic third level units.
Literature Cited.


The ANDOSOLS

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ABSTRACT

This paper presents a new approach concerning the concepts and major units of Andosols, which has been elaborated for the World Reference Base for Soil Resources (W. R. B. 1994).

In introduction there is a review of meaning and use of the Andosol taxon in the world soil classifications. Then a new proposal is presented concerning the concepts of Andosol and Andic horizon, as well as three major subtypes, viz. Vitrandic, Silandic and Aluandic horizons. At second level eight major units are distinguished namely: Vitric, Hydralic, Pachyalic, Alic, Hydric, Pachic, Eutric and Silic-Andosols, according to the three subtypes of Andic horizon, as well as the major differentiations of constituents and properties among the Andosols.

After this proposal are reviewed the specific properties of Andosols, namely: morphology, physical and chemical properties, and mineralogy. Then some diagnostic criteria are given for field identification and at laboratory, as well as a flow chart to recognize the Vitrandic, Silandic and Aluandic horizons.

In addition this paper shows the linkages, namely the limits and relationships with other soil units, as Podzols, Histosols, Arenosols, Regosols, Fluvisols, Leptosols, Ferralsols and Cryosols, as well as the intergrades due to a superficial rejuvenation of former soils by pyroclastic deposits. It emphasizes also the spatial distribution of Andosol units according to climotoposequences, as well as their temporal evolution and linkage between former Andosols and latter deriving other soil units. Finally the problem of the Andosols-Podzols limit arises and some suggestions are made to solve this difficulty.

In conclusion concerning land use and management of Andosols are presented the potential fertility and the main constraints of plant growth for five of the major andosol units, viz Vitric, Eutric, Silic, Hydric and Alic, as well as their susceptibility to erosion.

INTRODUCTION

The aim of this paper concerning the Andosols is to present a new approach of the concepts and major Andosols Units, which has been elaborated for the World Reference Base for Soil Resources (W.R.B., 1994).

Andosols have first been recognized in Japan in 1947 (according to Simonson, 1978). In 1949 Thorp and Smith defined the Great Group of “Andosols”, which name finds its roots in Japanese: an = black and do = soil. The same root is used as formative element in Andept (Soil Survey Staff, 1960; 1975), Andosols (CPCS, 1967; FAO-Unesco, 1968), and later Andisols (ICOMAND, 1979; Soil Survey Staff, 1990; AFES, 1990). These soils have also been named after their original pyroclastic material, for instance “Volcanic Ash Soils” (FAO, 1964).

The group of Andosols is large and very variable, covering an area slightly over 100 million ha (FAO, 1991). They occur in a wide range of climates, landscapes, parent materials and may differ considerably in age. They are mainly derived from pyroclastic volcanic materials, but they have also been observed in humid temperate climates on old lava formations and volcanic tuffs, and in temperate and high altitude tropical regions even on other materials not of volcanic origin (loess, argilite, ferrallitic weathering products).

CONCEPT, DEFINITION and MAJOR UNITS.

1. Concept and processes of formation.

Andosols are characterized by the occurrence of a diagnostic andic horizon, i.e. a horizon dominated by paracrystalline, short-range-order minerals and/or relatively immobile humussesquioxide complexes. Such a horizon results from two different biochemical weathering processes,
viz. hydrolysis and complexation by organic acids:

a. Hydrolysis of volcanic glass is favoured by a well drained, slightly acid to moderately alkaline (pH water 5.5 to 8.5) environment that is also sufficiently warm and humid. The process rapidly produces paracrystalline minerals (allophane, imogolite, hisingerite, ferrihydrite), on which humic acids are adsorbed and stabilized. The near neutral or only moderately acid (pH water > 5) Andosols develop from recent pyroclastic materials (< 10,000 years old) and occur more frequently in tropical, subtropical and mediterranean climates than in temperate or cold climates where they may occur only on very recent basic ashes. The soils often show surface horizons rich in organic matter and a well differentiated mineralogy.

b. Complexation by organic acids takes place under acid conditions (pH water 3.5 to 5) and occurs in sufficiently humid and cold climates (T < 12°C). The chelates (humus-sesquioxide complexes) produced are dominantly saturated with aluminium and relatively immobile. The process gives rise to strongly acid Andosols with a pH (water) less than 4.5 in humidiferous surface horizons or less than 5 in non-humic or 'alic' (i.e. Al³⁺ > 2 cmol(+)/kg soil) subsurface horizons. It is favoured by acid materials (e.g. rhyolites) or by materials rich in aluminium (e.g. volcanic glass), although it also occurs on old tuffs and lava deposits, and even on non-volcanic materials (argilites). At low latitudes the process may take place in aluminium- and iron-rich weathering residues under perhumid and cold conditions (T < 12°C) in highlands and high mountain ranges (e.g. Andes). Organic matter is usually deeply distributed; non-humic subsurface horizons are rare and only little differentiated.

2. Definition and diagnostic horizons.

An andic horizon is a soil layer of which the mineral weathering products are mostly non-crystalline or paracrystalline (short range order) and associated with or complexed by humic acids. It must have a minimum content in Al₉+ + 1/2Fe₂ox (1) of 2 %, or at least 0.4 % if it contains more than 60 % of glass and other primary minerals. Three subtypes are distinguished, according to the degree or the type of weathering process:

- a. A vitrandic horizon (from L. vitrum, glass) is an andic horizon dominated by at least 60 % of glass and other primary minerals. It has only few weathering products, notably allophane, and contains a fair amount of organic matter (more than 0.6 % organic carbon). The bulk density is normally between 0.9 and 1.2 Mg/m³. The value Al₀x + 1/2 Fe₂ox (1) is between 0.4 and 2 %.

- b. A silandic horizon (from L. silicium) is characterized by the predominance of paracrystalline secondary aluminosilicates such as allophane, imogolite and hisingerite. Only a small amount of aluminium is complexed by the organic acids with respect to the aluminium of the allophane minerals. The pH is slightly or moderately acid (at least 4.5 in humidiferous surface horizon, or 5 in subsurface horizons) and bulk density is low, usually less than 0.9 Mg/m³. The value Al₀x + 1/2 Fe₂ox (1) is at least 2 %, Si₉ox (1) at least 0.6 %, Alpy/Al₀x (2) is less than 0.5.

- c. An aluandic horizon (from aluminium) is characterized by the predominance of aluminium complexed by organic acids over the aluminium of allophane minerals. The pH is acid to extremely acid (less than 4.5 in humidiferous surface horizon, or 5 in subsurface horizon). On the contrary of a silandic horizon, the value Si₉ox (1) is less than 0.6 %, Alpy/Al₀x at least 0.5 and exchangeable Al more than 2 cmol (+)/Kg.

(1) Al₀x, Fe₂ox and Si₉ox : acid oxlate extractable Al, Fe and Si
(2) Alpy : pyrophosphate extractable Al.

Thus, Andosols are soils having an andic horizon with its upper boundary within the first 30 cm of the mineral soil surface (excluding possible histic layers at the surface). Other diagnostic horizons may be present but these horizons must at the same time exhibit andic properties, at least within 50 cm of the surface.

Other diagnostic horizons or soil materials associated with Andosols or with pyroclastic products, are the histic, mollic, umbric, melanic, fulvic and cambic horizons, and tephric soil material. The histic, mollic, umbric and cambic horizons are described and defined in
connection with other major soil groups, viz. Histosols, Chernozems, Umbrisols and Cambisols respectively.

The melanic and fulvic horizons are horizons typical for Andosols. Tephric soil material constitutes fresh pyroclastic deposits. The term tephric soil material is used in connection with Leptosols, Fluvisols, Gleysols, Cryosols and Regosols, to indicate the presence of soil materials that either fulfill the requirements for an andic horizon, but in which the andic properties are subordinate to other soil properties, or do not meet the requirements because the soils are too young or too coarse textured.

3. Major Andosols units.

At second level the Andosol are differentiated on properties of the material, according to the three subtypes and other diagnostic properties, i.e.: a high content of volcanic glass, or of organic-acid complexed and exchangeable aluminium, or of allophanic minerals. At first are distinguished vitric, alic and silic andosols. Then according to a high content in water, or in exchangeable bases, or a deep organic matter rich horizon, are distinguished the hydric, eutric and pachic subgroups of Andosols. Thus eight major Andosols units are proposed:

- 3.1. Vitric Andosols: having a vitrandic horizon within at least the first 30 cm of the mineral soil surface, or having a texture coarser than silt loam on a weighted average for all horizons within 100 cm of the surface, or both.

- 3.2. Hydric Andosols: having both aluandic horizons and a water retention at 1500 KPa of undried sample of 100% (oven dried fine earth) throughout layers 35 cm or more thick within 100 cm of the mineral soil surface.

- 3.3. Pachylic Andosols: having both aluandic horizons and more than 6% organic carbon in the fine earth and a colour of umbric horizon throughout a layer 50 cm or more thick from the mineral soil surface.

- 3.4. Alic Andosols: other andosols having aluandic horizons to a depth of at least 50 cm of the mineral soil surface.

- 3.5. Hydric Andosols: having both silandic horizons and water retention at 1500 KPa of undried samples of 100% (oven dried fine earth) throughout layers 35 cm or more thick within 100 cm of the mineral soil surface.

- 3.6. Pachic Andosols: having both silandic horizon and more than 6% organic carbon in the fine earth and a colour of umbric horizon throughout a layer 50 cm or more thick from the mineral soil surface.

- 3.7. Eutric Andosols: having both silandic horizons and a molllic horizon 30 cm or more thick, or eutric properties (either a base saturation by NH4OAc more than 50%, or a sum of exchangeable bases more than 25 cmol (+) Kg in the fine earth) within 50 cm of the mineral soil surface.

- 3.8. Silic Andosols: other andosols having silandic horizon to a depth of at least 50 cm of the mineral soil surface.

Third level modifiers may indicate the presence of other diagnostic soil horizons (argic, calcic, cambic, duric, ferralic, fragic, fulvic, gypsic, histic, melanic, molllic and umbric horizon) or important additional soil properties (cryic, dystric, eutric, gelic, gleyic, leptic, perhydric, placic or stagnic).

PROPERTIES, FIELD and LABORATORY TESTS

1. Morphology and biological properties.

The often thick, dark coloured and strongly humic surface horizons (5 to 20% organic matter, dry weight) are characteristic for Andosols. Humus is intimately mixed with the mineral part from which it cannot be distinguished. The organo-mineral complex is closely linked to the grains of the skeletal fraction. Some black and very humic horizons may have in moist condition a smeary consistency. This should not be confused with the thixotropy, which relates to a sudden change of the soil material from a semi-rigid state to a fluid state when pressure is applied, characteristic for a gel-state in moist condition. The fine earth fraction has an apparent loamy texture. The structure is generally fine and fluffy, and aggregated in very friable flakes.
The transition to an underlying brighter coloured horizon is often gradual; there is no eluvial horizon. This indicates that translocation of organo-mineral complexes is hardly taking place. The subsurface horizons, if present, still contain an important amount of humus (1 to 5% organic matter, dry weight), despite their more vivid colour. The texture of its fine earth fraction appears loamy, while structure seems massive or fine granular. The consistency in moist condition is friable, and non to slightly plastic and non sticky; in dry state it becomes very friable, even powdery. Thixotropy is exceptional and only observed in perhumid climates. The transition with the substratum can be abrupt in the case of hard volcanic materials (lavas, tuffs) or gradual in soft materials. Rooting in Andosols is dense and roots penetrate deep in the soil. Mesofaunal activity is intense.

Most Andosols are developed in recent pyroclastic deposits. However, some Andosols are derived from older volcanic products or even from non-volcanic substrata. Recent pyroclastic materials may be heterogenous because of superposition. In such cases horizonation does not only result from pedogenesis, it may also be linked to depositional differences. When there are age differences between the pyroclastic layers the entire soil may be polygenetic. The material near to the surface is the youngest and the least altered. In old volcanic products the complexity of the soil is less evident and it becomes only clear after a thorough study of the mineral composition.

2. Physical properties.

A number of physical properties are typical for Andosols, i.e. a low bulk density, a high microporosity, varying between 60 and 90 percent, a high water retention capacity in relation to the content in clay-sized (< 2μm) particles, a high irreversible dehydration value (Quantin, 1985), a good stability of the microaggregates, little dispersion of the colloidal fraction, high susceptibility to erosion and a high friability after drying out (powdery state, low density, floating aggregates).

The microaggregated structure of Andosols is responsible for the low to moderate bulk density which usually is less than 0.9 Mg/m³ (undried sample at 33 kPa). The microaggregates are oval-shaped organo-mineral complexes 1 to 10 μm in diameter, compounded into weak and very porous polyaggregates (Rosello, 1984; Lassausse, 1991). Macroscopic porosity is highly developed in the surface horizons, while there is only little macroporosity in the subsurface horizons.

3. Chemical properties.

Chemically, Andosols exhibit some unique properties. They have a pH dependant variable charge of the cation exchange capacity (CEC) of between 40 and 80 percent, measured on the increase in CEC between pH 4 and 9 (Quantin, 1982). The value is significant for the chemical composition of the allophane products and increases towards the aluminium pole (imogolite). Phosphate retention (Blakemore et al., 1981) is normally more than 85% of the phosphorus added to the solution, although in only slightly weathered Andosols it may be less. The pH in 1M NaF is 9.5 or more when measured within 2 minutes. The value varies between 9.5 and 11, dependant on the reactivity (richness in Al) and the quantity of allophane products, and the complexes of aluminium and organic acids. The pH NaF may be used as field test to diagnose possible Andosols. The presence of non- or paracrystalline minerals in Andosols is chemically characterized by an Al₉⁺/Fe₉⁺ value (1) of more than 2% in the fine earth fraction (ICOMAND, 1987). It applies to aluminium and iron derived from minerals such as allophane, imogolite, hisingerite and ferrihydrite, from hydroxides and from the aluminium and iron complexed by the organic acids. The ratio Alpy/Alox (2) is a measure to establish if aluminium is dominantly complexed by organic acids or mainly present in non- or paracrystalline form.

The amount of allophanic minerals is derived from the Si₀⁺ (1) value. It can be calculated using the formula of imogolite (SiO₂.Al₂O₃.2.5H₂O, Al/Si=2) for aluminium-rich allophanic minerals or if fibrous imogolite is present, or from the formula of halloysite (2SiO₂.Al₂O₃.2.5H₂O, Al/Si=1) for more silica-rich forms, notably spherical allophane.

(1) Al₉⁺, Si₀⁺ and Fe₉⁺: oxalate extractable aluminium and iron, respectively (method of Blakemore et al., 1981).
(2) Alpy: pyrophosphate extractable aluminium.
4. Mineralogy

4.1 In allophane-rich Andosols (silic)

The primary minerals consist of weatherable volcanic minerals: felspars, amphiboles, pyroxenes, olivine, micas, spinels, etc., which are only slightly altered, as well as abundant glass and glassy aggregates in various stages of weathering depending on the age of the soil.

The set of secondary minerals is dominated by paracrystalline minerals: aluminosilicates (allophane, imogolite), iron-silicates (hisingerite), iron-oxyhydroxides (aluminium- or silica-rich ferrithydrite) and silica (opale). The amount of secondary allophane and other aluminosilicates is more than 5 percent in the fine earth fraction. Also small amounts of crystalline minerals may occur: halloysite, smectites, zeolites, goethite, hematite, gibbsite, boehmite, etc., as well as siliceous phytolites (diatoms, etc.).

4.2. In acid Andosols (Alic)

The primary weatherable minerals in acid Andosols are often still present but the amount varies according to the age of the soils. There is little or no glass or glassy aggregates.

The amount of secondary allophane and other aluminosilicates is less than 5 percent in the fine earth fraction. However, non-crystalline products, especially organo-mineral complexes dominated by aluminium and to a lesser extent by iron, are abundant. The ratio Alpy/Alox is more than 0.5. Moreover, only a very small amount of the complexed aluminium is mobile and translocated to lower parts of the profile. This is what distinguishes an acid, aluminium-rich Andosol from a Podzol. The quantity of allophanic minerals may increase to the middle and lower parts of the soil.

The presence of clay minerals like halloysite (10 and 7 Å), illite, chlorite, vermiculite and aluminium bearing hydroxy-smectites, sometimes gibbsite, may be distinct in the middle and lower parts of the soil and decreases towards the surface. The neoformations of oxides are in paracrystalline from of aluminium-bearing ferrhydrite. Inherited minerals such as ilmenite, magnetite and hematite may be present.

5. Field identification

Andic horizons may be identified using the pH NaF field test developed by Fieldes and Perrott (1966). The test is based on a red colour reaction with phenolphthaleine in less than 2 minutes, resulting from an alcaline exchange reaction between NaF and aluminium present in the compounds. It indicates an abundant presence of allophanic products and/or organo-aluminium complexes. The test is indicative for most andic horizons, except for those very rich in organic matter. However, care should be taken because the same reaction occurs in spodic horizons and in certain acid clayey soils, which are rich in aluminium interlayered clay minerals.

The vitr-andic horizon can be identified in the field with relative ease. It is a surface horizon which, however, may be buried under some tens of centimeters thick recent pyroclastic deposits. It has a fair amount of organic matter and a low clay content (less than 10 percent). The sand and silt fractions are still dominated by unaltered volcanic glass and other primary minerals. No other horizons are usually associated with the vitr-andic horizon except for buried horizons.

The sil-andic horizon is found both as surface and as subsurface horizon. As surface horizon it is humic, containing a high amount of organic matter and is very dark coloured (Munsell value and chroma, moist is 3 or less). The pH (H$_2$O) is 4.5 or more if humic or 5.0 or more if non-humic as is the case in subsurface sil-andic horizons. These pH characteristics can be used to discriminate sil-andic from alu-andic horizons in the field, which are otherwise fairly similar. The macrostructure of humic sil-andic horizons is fluffy.

The alu-andic horizon also occurs as surface and as subsurface horizon. As humic surface layer it usually has Munsell values and chromas of 2 or less, a fluffy macrostructure and a smeary consistence. The pH (H$_2$O) of a humic alu-andic horizon is less than 4.5, that of a non-humic one less than 5.0. The dominant property of the alu-andic horizon is the high content of aluminium complexed by organic acids. In contrast to the spodic horizon which also contains complexes of
sesquioxides and organic substances, the alunino-organic complexes in the alu-andic horizons are hardly mobile.

The differentiating criteria which may be used in the field to separate the three types of andic horizons are shown in the following flow chart.

6. Laboratory tests.

The presence and amount of non-crystalline or paracrystalline minerals is the main feature in andic horizons. This can be chemically assessed by the $\text{Al}_{\text{ox}} + \frac{1}{2} \text{Fe}_{\text{ox}}$ value in the fine earth fraction in which $\text{Al}_{\text{ox}}$ and $\text{Fe}_{\text{ox}}$ are acid oxalate extractable aluminium and iron, respectively (method of Blakemore et al., 1981). Other criteria used to diagnose andic horizons and their properties are the bulk density of the soil at field capacity (no prior drying), the phosphate retention capacity, oxalate extractable silica, the ratio of pyrophosphate extractable aluminium over oxalate extractable aluminium ($\text{Al}_{\text{py}}/\text{Al}_{\text{ox}}$), the pH and the amount of aluminium extractable in 1M KCl($\text{Al}^{3+}$). Characteristic analytical values for the three types of andic horizons are given in:

Table 1. Characteristic physical and chemical values for andic horizons. (differentiating values are printed in bold)

<table>
<thead>
<tr>
<th></th>
<th>Vitr-andic</th>
<th>Sil-andic</th>
<th>Alu-andic</th>
</tr>
</thead>
<tbody>
<tr>
<td>% volcanic glass and other primary minerals</td>
<td>&gt;60</td>
<td>&lt;60</td>
<td>&lt;60</td>
</tr>
<tr>
<td>$% \text{Al}<em>{\text{ox}} + \frac{1}{2} \text{Fe}</em>{\text{ox}}$ (1)</td>
<td>0.4-2</td>
<td>&gt;2</td>
<td>&gt;2</td>
</tr>
<tr>
<td>$\text{Si}_{\text{ox}}$ (1)</td>
<td>n.a.</td>
<td>$\geq 0.6$</td>
<td>&lt;0.6</td>
</tr>
<tr>
<td>$\text{Al}<em>{\text{py}}/\text{Al}</em>{\text{ox}}$ (2)</td>
<td>n.a.</td>
<td>&lt;0.5</td>
<td>$\geq 0.5$</td>
</tr>
<tr>
<td>pH $\text{H}_{2}\text{O}$</td>
<td>n.a.</td>
<td>$\geq 4.5$ if org.C$&gt;5%$</td>
<td>$&lt;4.5$ if org.C$&gt;5%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\geq 5.0$ if org.C$&lt;5%$</td>
<td>$&lt;5.0$ if org.C$&lt;5%$</td>
</tr>
<tr>
<td>Organic C %</td>
<td>&gt;0.6</td>
<td>&gt;0.6</td>
<td>&gt;0.6</td>
</tr>
<tr>
<td>Phosphate retention %</td>
<td>&lt;85</td>
<td>&gt;85</td>
<td>&gt;85</td>
</tr>
<tr>
<td>Water retention at 1500kPa</td>
<td>&lt;25%</td>
<td>&gt;25 %</td>
<td>&gt;25 %</td>
</tr>
<tr>
<td>Bulk density Mg/m$^3$</td>
<td>0.9-1.2</td>
<td>&lt;0.9</td>
<td>&lt;0.9</td>
</tr>
<tr>
<td>Exchangeable aluminium (cmol(+)/kg fine earth)</td>
<td>n.a.</td>
<td>&lt;2</td>
<td>&gt;2</td>
</tr>
</tbody>
</table>

(2) Alpy : pyrophosphate extractable aluminium.
Many andic horizons are rich in organic matter. To separate these horizons from histic horizons the upper limit in organic matter content is 25 percent organic carbon, while histic horizons with an organic carbon content between 12 and 25 percent are not permitted to have properties associated with andic horizons.

An andic horizon does not meet the illuviation criteria for Al and Fe associated with humic acids diagnostic for the spodic horizon. The ratio $\frac{Al_{te} + Fe_{te}}{Al_{ox} + Fe_{ox}}$ in which $Al_{te}$ and $Fe_{te}$ represent tetraborate extractable aluminium and iron according to the Jeanroy (1983) method and $Al_{ox}$ and $Fe_{ox}$ stand for acid oxalate extractable aluminium and iron, may be used to distinguish an alu-andic horizon from a spodic horizon.

**LINKAGES**

1. **Limits and relationships with other soils**

   Andosols, being a group of soils occurring worldwide in a large variety of environmental conditions, have linkages with almost all other major soil groups. They are distinguished from them by the presence of an andic horizon within 30 cm of the surface. However, some soils show similar properties as Andosols (Histosols, Podzols), or consist of pyroclastic materials not yet sufficiently altered to have the andic characteristics (Fluvisols, Regosols, Arenosols, Gleysols) or meet all requirements for an andic horizon except thickness.

   Podzols show properties in the spodic horizon which are close to the andic characteristics, notably an $Al_{ox} + \frac{1}{2}Fe_{ox}$ value of more than 2 percent fine earth, a microaggregated structure, and the presence of paracrystalline clay minerals and iron oxyhydroxides. Moreover, certain Podzols, especially the "umbric" and "ferric" (with a placic horizon) ones do not have an eluvial horizon between the humus horizon and the spodic horizon. They are therefore very similar to Alic Andosols which are, like Podzols, very acid and marked by the process of complexation by organic acids.

   Awaiting better criteria, a soil is regarded as an Alic Andisol when the andic horizon and acid properties (pH<4.5) are well established in the humiferous horizon and when the presence of a spodic horizon is not clear. On the contrary, it is a Podzol if not all characteristics of an andic horizon are present in the humiferous horizon and the properties of a spodic horizon below this humiferous layer are well expressed. Under these circumstances it is difficult to imagine an andic intergrade of the Podzols or a spodic one in the Andosols, apart from the case of rejuvenation by pyroclastic deposits on the surface (see below).

   Many Andosols have very humiferous surface horizons, sometimes with an organic matter content well over 20 percent. Histosols therefore are separated from Andosols by lacking an andic horizon over a depth of at most 30 cm. An andic (or tephric) intergrade in the Histosols is possible for a value of $Al_{ox} + \frac{1}{2}Fe_{ox}$ between 0.4 and 2 % in the fine earth fraction.

   Arenosols, Regosols, Gleysols and Fluvisols are distinguished from Andosols by having an $Al_{ox} + \frac{1}{2}Fe_{ox}$ value of less than 0.4 percent in the fine earth fraction. If there is more than 60 percent pyroclastic material present but $Al_{ox} + \frac{1}{2}Fe_{ox} < 0.4$, tephric intergrades are recognized in the Regosols, Gleysols and Fluvisols.

   The limit between Leptosols and Andosols is determined by the depth. An andic horizon must be at least 30 cm thick while Leptosols are 30 cm or less thick over hard and compact rock. A tephric intergrade is recognized in the Leptosols for those soils that have 60 percent or more pyroclastic material over hard rock within 30 cm, or if the $Al_{ox} + \frac{1}{2}Fe_{ox}$ value in the fine earth fraction of Leptosols is more than 0.4 percent.

   Similarly, other soils are separated from Andosols by lacking an andic horizon with an upper boundary within 30 cm of the surface. Andic intergrades are possible in the Cambisols or Umbrisols by accepting either a value for $Al_{ox} + \frac{1}{2}Fe_{ox}$ between 0.4 and 2 % in the fine earth fraction of the entire soil to a depth of 100 cm or a value of $Al_{ox} + \frac{1}{2}Fe_{ox} > 2$ % in the fine earth fraction of the humus horizon to a depth of at most 30 cm from the surface (rejuvenated Cambisols by pyroclastic deposits on the surface).

   An andic intergrade may be possible in the Ferralsols by accepting a value for $Al_{ox} + \frac{1}{2}Fe_{ox}$ between 0.4 and 2 % in the fine earth fraction. However, if the first three requirements for a
ferralic horizon are met in a mineral horizon of an Andosol in a thickness of at least 30 cm, viz. a cation exchange capacity and an effective cation exchange capacity less 16 and 12 cmol(+)/kg clay resp., and less than 10 percent weatherable minerals in the 50 - 200 μm, a ferralic intergrade in the Andosols may be considered. These are soils classified as "Soils ferralitiques andiques" (CPCS, 1967) or andic subgroups of the Oxisols (Soil Survey Staff, 1992).

Cryosols must be distinguished from Andosols by having an Alox + 1/2 Feox value less than 0.4 % in fine earth. A tephric intergrade in possible if there is more than 60 % of pyroclasts. An andic intergrade may be considered for value of Alox + 1/2 Feox between 0.4 and 2 %. If more than 2 %, a cryic intergrade should be considered at the third level of classification.

Soils rejuvenated by pyroclastic products and having properties characteristic for the andic horizon which are expressed, however, over a depth of less than 30 cm but more than 10 cm thickness may be considered as andic intergrades or tephric intergrades if the andic properties are not met.

2. Spatial and temporal linkages

The distribution and differentiation of Andosols is dependant on four major factors: volcanic formations, mountainous relief, climatic regimes and time of formation.

Andosols are strongly related to volcanic formations, especially those with recent pyroclastic material. They occur less commonly on old and/or compact volcanic material (lavas, tuffs, ignimbrites). Exceptionally they are encountered on non-volcanic materials (argillites, loess, etc.).

Andosols are most frequent and widespread in regions with humid and perhumid climates, from the tropics to the arctic. They are less common in climates with a long dry season and rare in arid climates.

A spatial differentiation of Andosols can be observed on mountainous volcanic topography according to climate and climotoposequences. This is mainly caused by zonation of the rainfall and sometimes also of the temperature, as a function of the relief and windward or leeward position of the slopes. This differentiation is always encountered in the tropical and subtropical regions where one may observe successively from the windward side over the top towards the leeward side a sequence of dystric, perhydric and eutric Andosols. It often occurs in the mediterranean and temperate regions as well.

Andosols are also spatially differentiated according to temperature regimes related to latitude and elevation. Two air temperature levels seem to be important. The first one is found between 10 and 12°C. Above this level most Andosols are allophane-dominated. Below it Alic Andosols are dominant, especially on older or more acid materials. A second level is found at 0°C, where the temperature regime becomes 'pergelic', permafrost occurs, and where Andic Cryosols prevail.

As weathering of the pyroclastic products progresses, a transition of Vitric Andosols toward "silic" Andosols or acid "alic"Andosols occurs. These in turn develop into other groups of soils depending on the formation of new diagnostic horizons and properties. One may encounter the following sequences, depending on the various climatic regimes:

- tropical perhumid climates: Hydric Andosols -> Ferralsols/Acrisols
- tropical humid climates: Andosols ->Cambisols/Umbrisols -> Ferralsols/Acrisols.
- tropical climates with a dry season: Andosols -> Cambisols -> Lixisols/Vertisols.
- mediterranean climates: Andosols ->Cambisols -> Luvisols/Calcisols.
- tropical or temperate semiarid climates: Vitric Andosols -> Calcisols/Gypsisols/Solonetz/(Solonchaks).
- cold (<12-10°C to 0°C) temperate climates: Andosols -> Cambisols/Umbrisols/Lixisols or Alic Andosols -> Podzols.

3. Problem of the Andosol - Podzol interface

A diagnostic requirement for the spodic horizon is 'two times or more Alox + 1/2 Feox than an overlying umbric, ochric or albic horizon.' Many Andosols with a sil-andic or alu-andic horizon
show an $\text{Al}_{\text{ox}} + \frac{1}{2} \text{Fe}_{\text{ox}}$ value that meets this requirement. However, this does not necessarily indicate that it concerns here a Podzol.

The increase may be of depositional origin - pyroclastic materials are often younger and more silica-rich near to the surface - or may be due to very slow translocation of the stable and saturated aluminium-humic acids complexes deep into the soil, or both. Especially Alic Andosols contain these complexes and the process of translocation at a slow rate does not lead to the development of an eluvial horizon in these soils.

It is therefore necessary define or more selectively characterize the spodic horizon with respect to its limit to the andic horizon. This may be by limiting the ratio of $\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}}$ between the humiferous surface horizon and the spodic horizon, or a rate of increase of this amount related to the depth of the soil. One may also look for a reagent that is more discriminating towards the Al and Fe chelates, above all the iron which seems to dominate in the more mobile complexes which characterize the podzols. For the Alic Andosols sodium tetraborate may be suitable (Jeanroy, 1983). The ratio $\text{Al}_{\text{te}} + \text{Fe}_{\text{te}}/\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}}$ may be used, in which $\text{Al}_{\text{te}}$ and $\text{Fe}_{\text{te}}$ represent the tetraborate extractable aluminium and iron. Values of 0.5 or more are then indicative for the spodic horizon of Podzols (see also Lassausse, 1991).

This, however, poses a double problem. First, we do not have sufficient data on sodium tetraborate extracts of Podzols and Alic Andosols to establish a proper limit. Secondly, how can one distinguish in the field between a Podzol and an Alic Andosol without the evidence of an eluvial horizon from which simultaneously C, Al and Fe has eluviated. The second problem has been discussed during the 9th International Soil Classification Workshop in Japan, 1987. According to Arnold (1988) it is necessary to associate an albic horizon with an underlying spodic horizon to classify a soil as Podzol and to exclude an Andisol.

The problem may be solved in the laboratory by establishing a sound ratio characterizing the illuvial nature diagnostic for a spodic horizon and to exclude such andic criteria as $\text{P} > 85$ percent and variable CEC > 40 percent from the characteristics of humiferous horizons in Podzols. What remains is to specify more precise field criteria.

**LAND USE and MANAGEMENT**

1. **Potential fertility**

The volcanic ash soil, namely the Andosols, are often considered to be very fertile, because of their recent age and high content in weatherable glasses and primary minerals, as well as their large stock of nitrogen, phosphorus and sulphur included in organic matter. However some of the andosols have a rather poor fertility, owing to their hard phosphorus retention, or their acidity and aluminium toxicity, as well a slow turnover of organic matter, or some "anoxy" (oxygen deficiency) in some very hydrated subsurface horizons.

1.1. *The Vitric Andosols* are very young soils having properties of volcanic sand mixed with a little of humus. They are very rich in weatherable glasses and primary minerals, have a fairly sufficient content in exchangeable bases and available phosphorus (due to a low amount in allophane) and they are slightly acid. But they have some physical and chemical constraints, viz. shallow depth, large macroporosity, fast drainage, low water retention capacity and low cation exchange capacity. Thus they have initially a fairly good potential fertility, but they are susceptible to a fast impoverishment in some elements, namely in mineral nitrogen, sometimes in exchangeable potassium and available phosphorus.

1.2. *The Eutric Andosols* are constituted of a rather siliceous allophane which has a high cation exchange capacity with a fairly moderate rate of variable charges and presents a moderate phosphorus retention capacity. In addition they are slightly acid, rich in exchangeable bases and available nitrogen, and have a large stock of weatherable glasses and primary minerals. Their water retention capacity is fairly sufficient, though the drainage is fast. A large porosity accessible to air allows a dense and deep rooting. Indeed these soils are among the most fertile in the world and are favourable to an intensive cropping. However they are very friable and easily erodible, or eventually able to cause a hydric stress in the case of a long dry season.
1.3. *The Silic Andosols* have allophane rather more aluminous than soils of the Eutric Subgroup. Thus they have a fairly high rate of variable charges (in C.E.C.), as well as a high phosphorus retention capacity. However they keep a large content in weatherable glasses and primary minerals and can have a fairly sufficient amount of exchangeable cations and a moderately low base saturation ratio. Thus they offer a "mesotrophic" medium for plant growth. In addition they have good physical properties, above all a large water retention capacity and a fairly good drainage, which allow a dense and deep rooting. But almost always they present a deficiency in easily available phosphorus and nitrogen, as well as sometimes in sulphur and potassium, which are restrictive for intensive cultivation. However after an expensive phosphorus fertilization the crop potentiality may be high.

1.4. *The Hydric Andosols* contain aluminium rich allophane which has a very variable charge cation exchange capacity and a very large phosphorus retention capacity, as well as a high irreversible dehydration value. Though moderately acid and containing weatherable glasses and primary minerals, their base saturation ratio (in NH₄OA₃,pH₇) is very low (< 10 %). The availability of nitrogen, phosphorus and sulfur is restricted, in despite of a great stock of these elements in the abundant organic matter. Thus these soils give an "oligotrophic" medium for plant growth. In addition the excessive humidity of climate and soil, as well as some "anoxia" (oxygen deficiency) in subsurface horizons are severe constraints to plant growth and for an intensive cultivation. After deep ploughing and air drying these soils become very friable and erodible.

1.5. *The Alic Andosols* are acid and very rich in aluminium complexed by organic acids and exchangeable aluminium. They have a very low content in exchangeable bases and a very low base saturation ratio. The older soils contain few weatherable minerals and reserves in bases. Phosphorus is strongly retrained both in the stable organic matter and by the aluminium complexed by organic acids. Thus these soils give an "oligotrophic" medium for plant growth. In addition the subsurface horizons present a chemical barrier to root development, as well (in hydric subgroup) some "anoxia" (oxygen deficiency). The climate related to these soils in usually unfavourable (too cold or too wet) for good crops. Thus the potential fertility of the Alic Andosols is very low.

2. Management, erodibility and conservation

The Andosols at their natural state and under their original vegetal cover have a sufficiently porous and stable structure to permit a good rain water infiltration and to restrain erosion risks. However a well managed cultivation must avoid to deeply modify the physical properties of Andosols, especially by a deep tillage which is producing a too drastic soil dehydratation. After that the soil becomes very friable and lose a large part of its water retention capacity, transforming itself in an loose sandy loam of low bulk density which is easily erodible. Under a wet and especially perhumid climate in the case of Hydric Andosols, the soil submitted to mechanical constraints may attain quickly its fluidal limit. They have a low carring capability for heavy machinery. In addition an andic material being no plastic does not permit a goog ploughing. Thus it is suitable to use methods which will modify at the least possible the original physical properties.

The Vitric and Eutric Andosols do not give great problems of mineral fertilization. But in despite of their usually high content in weatherable primary minerals, almost all other Andosols give serious problems owing to their high phosphorus retention capacity under not or slowly available forms. Thus we have to saturate the phosphorus retention capacity with phosphate fertilizers, or to reduce it, before obtaining easily available phosphorus for plant growth. In the case of Silic Andosols the minimum level of phosphorus saturation is rather moderate, from 1000 to 2000 ppm of P₂O₅, or at most 3000 ppm. Beyond this limit their potential fertility becomes fairly high.

But the Hydric Andosols give serious problems to get intensive crop, owing to their very high level of phosphorus retention (at least 4000-ppm of P₂O₅), as well as physical constraint to root development in very hydrated subsurface horizons due to some "anoxia" (oxygen deficiency). It is suitable to avoid a hard soil degradation by deep tillage. The management of these soils needs very appropriate methods and land uses.
Finally the Alic Andosols give the most difficulties, owing to their very high phosphorus retention capacity as well as their acidity and aluminium toxicity, and eventually some "anoxia" in the subsurface horizons. Their land use capability seems to be very limited.

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Arenosols: Concept, Classification and Economic Value

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Introduction. The name of Arenosols is derived from the Latin word "arena", which means "sand".

Arenosols, or sandy soils with slight to moderate profile development, are recognized as a separate grouping in universal, regional and local soil classification systems, mostly at a medium to high hierarchical level.

In the 1938 USDA classification most Arenosols would probably have been included under "Azonal soils: 3. Sands (dry)". In the 1949 revision of this system they were included under Regosols (Soil Survey Staff, 1960). In the USDA Soil Taxonomy (Soil Survey Staff, 1975) sandy soils without marked profile development, including shifting sands, are classified as Entisols, suborder Psamments.

The first edition of the Legend of the Soil Map of the World (FAO, 1974) defined Arenosols as coarse-textured soils consisting of albic material or showing characteristics of argillic, cambic or oxic horizons, but not qualifying as these diagnostic horizons because their textural requirements are not met. Shifting sands, sandy soils with no or weak profile differentiation and sandy soils with an aridic moisture regime were generally excluded from Arenosols and classified as Regosols, Yermosols, etc. In the 1974 FAO concept Arenosols were required to have distinct soil development and were considered the coarse-textured counterparts of Cambisols, Luvisols and Ferralsols.

In the Revised Legend of the Soil Map of the World (FAO, 1988) revised textural and depth criteria were given for Arenosols and additional subdivisions were defined. The above-mentioned diagnostic characteristics were no longer a prerequisite, and weakly developed sandy soils were also included. However, large groups of sandy soils were still not included in the Arenosol concept because of insufficient profile development. Amongst these exclusions are shifting sands and sandy fluvic soils.

Other names for Arenosols, as defined by FAO-Unesco (1988), in other soil classification systems include the following: Psamments (USDA Soil Taxonomy); Sols mineraux bruts (France); Siliceous, earthy and calcareous sands and various podzolic soils (Australian handbook); Red and yellow sands (Brazil); Regosols (Canada, USSR and Zimbabwe); Soils of the Fernwood form and deep phases of the coarse-textured series (those with less than 15% clay) of the Hutton and Clovelly forms (1977 South African system); Deep phases of soils belonging to the Namib, Fernwood, Hutton and Clovelly forms as well as sandy soils with Neocarbonate B horizons (1991 South African system); Raw sands (Britain and Germany). See FitzPatrick (1980), MacVicar et al. (1977), Soil Classification Working Group (1991) and Nyamapfene (1991).
Arenosols are widely distributed and form one of the most extensive major soil groups in the world. According to Driessen and Dudal (1991) Arenosols (1988 FAO concept) cover about 400 million hectares. The recently published World Soil Resources report (FAO, 1991) estimates its coverage at 900 million hectares or 7 per cent of the land surface of the earth. If other sand areas such as shifting sands and active dunes are also included, the coverage is about 10 per cent.

Although most Arenosols are found in arid and semi-arid zones, they are typical azonal soils and occur in the widest possible range of climates, from very arid to very humid and from cold to hot.

Arenosols occur predominantly on aeolian sands, either dunes or flats, but have also formed on marine, littoral and lacustrine sands of beach ridges, lagoons, deltas, lakes, etc. In addition Arenosols are found on natural levees and other sandy fluvial deposits as well as coarse-grained weathering rock, mainly sandstone, quartzite, granite, etc.

There is no limitation as to the age or period in which soil formation took place. Arenosols occur on very old surfaces as well as on very recent surface forms, and may be associated with any type of vegetation.

The vast expanse of deep aeolian sand which covers the largest part of the central African plateau between the equator and 30° southern latitude is the largest sand body on earth. It is popularly known as Kalahari sand and is bordered by the Congo river in the north and the Orange river in the south. Other major areas of Arenosols are found in the Sahel region of Africa, various regions in the Sahara desert, central and western Australia, the deserts of the Middle East and China. Sandy coastal plains and coastal dune areas are of smaller geographic extent, but ecologically very important.

Concept and definition of Arenosols as developed and proposed by the WRB working group. Fundamental to the concept of Arenosols is the sandy nature of these soils, which dominates their characteristics and properties. There is no restriction as to the minimum degree of soil development that is required. The boundaries of Arenosols with other major soil groups are determined by the maximum degree of soil development which is permitted. The main consideration in determining the maximum degree of soil development allowed in Arenosols should be that the inherent properties and characteristics of the original sandy soil are in essence still present.

The texture of Arenosols is loamy sand and coarser. Loamy or clayey topsoils are not permitted. Sub-horizons within 100 cm of the soil surface are not permitted to contain more than 35% of rock fragments or other coarse materials. The texture requirement must be met either to a depth of 100 cm from the surface or to a lithic or petroferric contact, whichever is shallower. Thus, provision is made for the inclusion of moderately shallow to moderately deep soils, which satisfy the texture requirement, which have developed from parent materials such as granite, quartzite, sandstone, etc. This is in line with the Psamments of the USDA Soil Taxonomy. Soils with lithic or petroferric contacts within 30 cm or less from the surface are not included.

Ochric, umbric, mollic and albic horizons are permitted in Arenosols. Gypsic, petrogypsic, calcic
and petrocalcic horizons, duripans and salic properties are permitted in Arenosols, provided that their upper boundaries are not within 30 cm from the soil surface.

Sandy soils with fluvic properties are included with Arenosols. This is in contrast to the 1974 and 1988 FAO-Unesco classifications in which Arenosols were not permitted to have fluvic properties. Fluvic sandy soils were classified under Fluvisols. The diagnostic requirements for fluvic properties are based on organic carbon levels and stratification. For sandy sediments these criteria are less relevant. Organic substances are generally not deposited together with coarse grains. The non-sandy stratifications are very thin and similar stratifications, in the form of cross-bedding, are also found in aeolian sands. Fluvic sandy materials, especially in drier environments, strongly resemble Arenosols. Fluvic properties are also permitted in the Psamments of the USDA Soil Taxonomy.

Dropping of a minimum degree of soil development as prerequisite allows shifting sands to be classified as Arenosols.

According to the 1974 and 1988 FAO-Unesco classification Arenosols are permitted to have gleyic properties. Gleyic properties reflect conditions of prolonged, even permanent, wetness in a soil. This is a very extreme condition, which overrides sandy texture as dominant feature in the soil. At the April 1993 meeting of the WRB working group Laker (1993) proposed that the Gleyic Arenosols of the FAO-Unesco classification should be removed from Arenosols and classified as Arenic Gleysols. Hollis (1993) pointed out that such change would solve certain classification problems with British soils. Dudal (1993) indicated that the reason for not including sandy soils with fluvic properties under Arenosols in the 1974 and 1988 FAO-Unesco classifications was because such soils are invariably associated with wetness. The latter is not the case, substantial areas of fluvic sandy soils without prolonged wetness being found in dry environments. Dudal's argument does, however, underline a fundamental objection to inclusion of sandy soils which are subject to prolonged wetness under Arenosols. Gleyic properties are also not permitted in the Psamments of the USDA Soil Taxonomy. Soils with gleyic properties are, therefore, not included under the WRB concept of Arenosols.

There was some doubt as to whether a mollic horizon could in fact develop in an Arenosol, i.e. whether inclusion of a mollic horizon in the list of horizons permitted in Arenosols was a hypothetical concept or representing a reality. Hollis (1993) indicated that dark coloured, relatively organic-rich topsoils that qualify as mollic in all criteria except thickness are found in sandy materials in Britain. When such soils are cultivated, their topsoils are deepened and qualify as mollic horizons. Hollis (1993) indicated that his preference would be to recognize such soils as Arenosols, thus supporting the proposal of Remmelzwaal (1993) to make provision for mollic horizons in Arenosols.

Umbric horizons are found in sandy materials in both tropical areas, such as the "sandveld" of Zambia (Spaargaren, 1993), and temperate regions, such as Britain (Hollis, 1993). The question which was unresolved at the time of the writing of this paper was whether these should be classified as Umbric Arenosols or Arenic Umbrisols. We meanwhile include them with the Arenosols.
Extensive areas of sandy soils with duripans are found in arid regions, e.g. in Australia, South Africa (Ellis, 1988) and the Middle East (Kadry, 1975). In the FAO system of 1974, and its 1988 revision, duripans are used as phase criteria. True duripans, the reddish brown hard material which is cemented by silica so that it does not slake in water or acid (Soil Survey Staff, 1990), is a very specific pedogenetic material just as petrocalcic and petrogypsic horizons. It should, therefore, be used at the same hierarchical level as these horizons in classification, especially in Arenosols - where it is such a prominent feature.

There is a group of extremely important sandy soils, especially from a crop production viewpoint, for which no provision is apparently made in universal soil classification systems at the moment. These are the high chroma red and yellow aeolian sands which have a horizon at the bottom which is characterized by high chroma mottles and/or iron-manganese concretions in a matrix which has at least in some parts grey colours. This indicates the presence of a fluctuating water table in the bottom part of the profile. The latter is caused by a restricting clay layer below it. The enhanced water storage capacity of these soils gives them a much higher production potential than deep Arenosols, especially in marginal rainfall areas. These soils are extensive in the marginal rainfall areas of the western part of the maize quadrangle of the South African Highveld. Extensive areas of such soils are apparently also found in Australia. The chromic sand layer, which is the largest part of the profile, is subject to severe wind action. These are the sandy series of the so-called Bainsvlei and Avalon soil forms of the 1977 South African soil classification system (MacVicar et al., 1977). The degree of pedogenesis in the bottom part of these profiles probably exceeds the permissible level for Arenosols and they will probably have to be accommodated elsewhere in the classification system.

Because Arenosols (a) key out very late in the classification system and (b) have linkages with a large number of other major soil groups, the concept and definition of Arenosols are very strongly dependent on how the concepts and definitions of a number of other major soil groups are developed.

Within the present framework of the WRB classification system the following definition is given for Arenosols:

Soils which are loamy sand or coarser to a depth of at least 100 cm from the surface or to a lithic, paralithic or petroferric contact or calcic, petrocalcic, gypsic or petrogypsic horizon or a duripan, whichever is shallower, provided that the upper boundaries of the mentioned contacts, horizons or duripan must be more than 30 cm from the soil surface; exclusive of materials showing andic properties to a depth of 35 cm or more from the soil surface or having salic properties within 30 cm from the soil surface; having less than 35 per cent of rock fragments or other coarse fragments within 100 cm from the soil surface; having no diagnostic horizons other than an ochric, umbric, mollic, albic, gypsic, petrogypsic, calcic or petrocalcic horizon or duripan.
Classification of Arenosols. The classification of the soil units at the second level reads as follows, as a key:

Arenosols showing fluvic properties

Other Arenosols having an albic horizon with a minimum thickness of 50 cm within 125 cm from the soil surface

Other Arenosols having a mollic horizon

Other Arenosols having an umbric horizon

Other Arenosols having a gypsic or petrogypsic horizon with an upper boundary between 30 and 125 cm from the soil surface

Other Arenosols having a calcic or petrocalcic horizon with an upper boundary between 30 and 125 cm from the soil surface

Other Arenosols having a duripan with an upper boundary between 30 and 125 cm from the soil surface

Other Arenosols in recent aeolian deposits not showing profile development

Other Arenosols which are calcareous at least between 20 and 50 cm from the surface

Other Arenosols having a clay increase of 3 per cent or more or showing lamellae of clay accumulation within 125 cm of the surface

Other Arenosols having ferralic properties (CEC < 4me/100 g soil) and showing colouring of the B horizon expressed by chromas of 5 and more and/or hues redder than 10YR
Other Arenosols showing colouring of the B horizon expressed by chromas of 5 and more and/or hues redder than 10YR

Cambic Arenosols

Haplic Arenosols

Notes:

1. * The term "Anthric" Arenosol, instead of "Mollic" Arenosol for Arenosols with mollic horizons was proposed by Hollis (1993) to indicate that mollic horizons in these soils result solely from human activities. He further motivates it as follows: "Such a subgroup in Arenosols would complement the proposed Anthric subgroups in Podzols and Umbrisols, both of which are only allowed to have Mollic horizons under special circumstances where they are the direct result of human activities."

2. Laker (1993) proposed that "Chromic Arenosols" be distinguished at the second level. In Southern Africa Arenosols with uniform bright red or yellow colours are well-known to generally have higher potential than other Arenosols. Although this suggestion has received some support, it has not been generally accepted and therefore this subgroup has not been distinguished here. This aspect will have to be considered seriously in future, however.

The Guidelines for Distinguishing Soil Subunits (FAO, 1990) provide rules for the differentiation of soil units at the third and lower levels. Various combinations can be made up to suit specific cases, according to these rules.

Two types of parameters which are of critical importance in the subdivision of Arenosols at lower levels are textural parameters (clay content and perhaps even more importantly sand grade) and the nature of the underlying material.

Economic value of Arenosols. There is a general tendency to write off all sandy soils as having very low potential because they are believed to be infertile and having low water storage capacities (e.g. FitzPatrick, 1980). This is an over-simplistic generalization which is far from the truth. The possibilities to use Arenosols for agriculture vary widely, as is outlined well by Driessen and Dudal (1991).

In arid areas Arenosols are predominantly used for extensive grazing. In the nomadic livestock farming areas of North Africa and the Middle East Arenosols are, according to Souirji (1993), in fact the mainstay of the farming enterprise. This is because vegetative growth reacts much faster in the sandy areas than in the areas with finer-textured or shallow soils. This is because the little rain that falls occasionally is much more effective on the sandy soils than on the other soils.
According to Driessen and Dudal (1991) dryland cropping on Arenosols is possible where the average annual rainfall is more than 300 mm. This limit seems a bit low. There is no doubt, however, that they can be cropped successfully under a rainfall of 400 to 500 mm per annum, where it is very difficult to achieve success on finer textured soils. The texture and depth of the soil and the nature of the underlying material are very important factors determining the success which can be achieved on Arenosols in semi-arid areas. Both the clay content and the sand grade play important roles in determining the plant-available water storage capacity of these soils. In the semi-arid western Highveld of South Africa it has been found that Arenosols with about 10% clay and dominated by fine sand the plant-available water storage capacity is about 125 mm per meter soil depth, which is considerable. This is until first wilt and not until dormancy or death. The coarse sandy counterparts of these soils store much less water. Recent unpublished research by a master’s student of the senior author (MCL) has shown that best results in this semi-arid region is in fact not obtained on the deep “bottomless” sands but where there is a “soft carbonate” horizon (Soil Classification Working Group, 1991) at about 600 to 700 mm depth in the profile. This horizon stores a lot of water which can be utilized by plant roots.

High yields of small grains, melons, pulses and fodder crops have been obtained on irrigated Arenosols (Driessen and Dudal, 1991). In the central irrigation schemes of South Africa small grains, vegetables, maize, groundnuts, lucerne, citrus, peaches, grapes and pecan nuts are amongst a wide variety of crops which are produced highly successfully under irrigation on fine sandy Arenosols with 8 to 10% clay.

Successful dryland or irrigated cropping of Arenosols in semi-arid to sub-humid areas require well-adapted management practices. The main problem on these soils is their extreme vulnerability to wind erosion, which needs to be combated - e.g. by means of wind breaks. In the marginal cropping areas a low risk approach is required under dryland conditions. This means aiming for relatively low yields, using low planting densities and low fertilizer inputs. The high infiltration capacities and hydraulic conductivities make surface and drip irrigation impracticable on most of them. Furthermore, the well-sorted, well-rounded fine sandy aeolian Arenosols (especially those with 8 to 15% clay) are extremely vulnerable to soil compaction, i.e. the development of "traffic pans", under intensive mechanized farming. This is aggravated under irrigation due to an increased tendency to cultivate soils while they are too wet. Zero tillage is not the answer because of the fairly high natural degree of compaction of these soils. It can be overcome by strategies such as the use of tined implements and controlled traffic.

A major advantage of the "chromic" Arenosols (the Kalahari sands, for example) is the fact that, although they are inherently infertile, soil fertility control on them is easy and inexpensive. The senior author (MCL) and a number of his post-graduate students have shown that top responses to light applications of P and Zn are obtained even on virgin soils with extremely low levels of these elements. Although the soils did not fix P and Zn into forms which were unavailable to plants, they did protect them against leaching - even under conditions of excessive flood irrigation. It was found that one, in fact, had to guard against over-fertilization with P. (These have been documented in a number of master’s dissertations which were all written in Afrikaans and consequently will not be referenced here.)

Driessen and Dudal (1991) points out that the Arenosols in the humid tropics should best be left
under their natural vegetation, especially the deeply weathered Albic Arenosols. Clearing of these soils "will inevitably produce infertile badlands without ecological or economic value" (Driessen and Dudal, 1991).

Cashew nuts provide a crop which can apparently profitably be grown on acid Albic Arenosols where water is limiting.

Conclusions. Arenosols cover large areas of the earth's surface. The concept and classification of Arenosols have not yet been fully developed due to its dependence on the development of the concepts of other major soil groups. Arenosols are of major economic importance, especially in semi-arid to sub-humid regions.

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Leptosols and Fluvisols
A contribution to the definition of Major Soil Groups and Soil Units for World Reference Base for Soil Resources.

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Abstract. This contribution deals with the proposals of the World Reference Base panel for the Leptosols and Fluvisols. These soils are respectively some of the most extensive and intensively used soils on the earth's surface and merit serious consideration in any form of soil classification. Some re-definition of both major soil groups is proposed which aims to eliminate any areas of doubt at the interface with soil units that have more highly developed profiles. The changes recommended have implications for several major soil groups because the Leptosols and Fluvisols have close relationships with many other major soils, as members of complexes and associations.

The most significant changes proposed are the exclusion from the Leptosols of soils with petrocalcic or petrogypsic horizons, and the relationship with soils having a thin cambic horizon has been more clearly defined. Soils with fluvic properties which also have a clear cambic horizon, may be accommodated in a new unit of Fluvic Cambisols. Where poor drainage is indicated by gleyic properties within 50 cm, the soils will be accommodated in the Fluvic Gleysols. Those soils with fluvic properties and a salic horizon will be included in Salic Fluvisols. In both Leptosols and Fluvisols these and other new categories at the unit level have been introduced.

Introduction. This paper contains a brief discussion of proposed changes to two major soil groups, Leptosols and Fluvisols. Both major soil groups are extensive, and in their different ways, important soils for agricultural productivity and the well-being of mankind. They have in common that both comprise immature soils which are weakly developed, forming either upon newly weathered or freshly deposited parent material. As both these weakly developed soil groups relate closely to all other soil groups into which these soils grade in their more mature phases, it is important that Fluvisols and Leptosols are unequivocably distinguished from more mature profiles. These soil groups are more widely distributed than one would expect from the study of small-scale maps, such as the 1:5 M FAO-Unesco Soil Map of the World, because their members form soil complexes with other soil groups.

Leptosols. The name Leptosols first appeared in the revised legend of the FAO-Unesco Soil Map of the World (1). The soils which now bear this name were previously known as Lithosols, Rankers, Rendzinas and in part Regosols. Altogether, it is estimated by FAO (2) that there are 1,655 M ha of these soils, concentrated in the mountainous, desert and boreal areas of the world, where they comprise 12 per cent of the World land area.

Although Leptosols are shallow, they are of great significance in the soil mantle as they represent, in many cases, young or weakly developed soils of the other soil units. In other cases, they may represent the eroded remnants of formerly deeper soils. So the maximum
development of these soils will often be prescribed by the minimum criteria necessary for acceptance into one of the other soil groups.

Young soils retain many of the features of the parent material, but as they mature, the amount of pedological organisation increases and the definition of the horizons within the soil profile becomes clear. In a reciprocal manner, the amount of recognisable geological structure and appearance decreases. For many parent materials, with a judicious choice of sites, it is possible to demonstrate a development sequence of soils from parent material to mature and even senile soils. However, with a combination of certain parent materials and a topographic position which favours erosion, the development of deep soil profiles is inhibited, and so the progress of soil development becomes arrested at a stage with a shallow profile lacking the criteria necessary to place the soil in any other groups.

Fluvisols. The concept of a group of soils developed from alluvial sediments has been a consistent feature of soil classification throughout the twentieth century. Their presence as a discrete grouping can be observed from earlier writings about soils right through to the present day. Fluvisols occur on all continents and in all climatic regimes. They are one of the most widespread soils and, as these soils occur in all the major river deltas, they are one of the most important soils used for the growth of food crops. Altogether, FAO (2) estimates there to be 355 M ha of alluvial soils, slightly less than 3 per cent of the World land area.

Three problems can be identified with the definition of the Fluvisols. The first is that mid-latitude pedologists have conceived of them as forming upon Holocene alluvia. In regions peripheral to the Quaternary glaciations, normally a clear distinction can be drawn between Holocene and earlier alluvial deposits. Elsewhere in the World, the distinction in the age of alluvial material is less easy to make.

Secondly, the variable nature of alluvial materials and environmental conditions permits a wide range of soil forming processes, and upon older alluvia, soil formation has taken place over a longer period producing profiles of greater maturity which intergrade to other soil units. Unfortunately, there are wide differences in the use made of the term alluvial soils. In its widest interpretation, all soils developed on alluvial sediments and any degree of profile development have been called alluvial soils.

Thirdly, it is implicit in the Legend of the Soil Map of the World (3) that colluvial soils should be included in the Fluvisols. Although partly moved by water, the main cause of their deeper profiles is the accumulation of material from upslope under the effect of gravity. In the opinion of the WRB panel, these colluvial soils should be placed in their respective soil units e.g. Regosols, Cambisols and other groups to which they are more closely related. It is anticipated that they would be distinguished from non-colluvial soils by the prefix colluvi- at the third level of classification.

Definitions

Leptosols. Leptosols (LP) were defined in the revised legend for the Soil Map of the World (1) as: "Soils which are limited in depth by continuous hard rock or highly calcareous materials (calcium carbonate equivalent of more than 40 per cent) or a continuous cemented layer within 30 cm of the surface, or having less than 20 per cent of fine earth over a depth
of 75 cm from the surface; diagnostic horizons may be present, in particular a mollie, umbric or ochric A horizon, a cambic B horizon, or a calcic or petrocalcic horizon, or a duripan or petroferric phase with an indurated layer within 30 cm of the surface”.

As a result of discussions held during the past two years, this definition has been modified by the omission of the reference to “a continuous cemented layer” and “a petrocalcic horizon” as it is clear that such horizons are the result of pedogenesis and therefore such soils do not fit the concept of Leptosols. Secondly, the reference to “a cambic B horizon” has been omitted because there was an illogical inclusion of a B horizon in the definition of an otherwise shallow soil.

The proposed definition is:-

Soils which are limited either in depth by continuous hard rock or are overlying highly calcareous materials, that have a calcium carbonate equivalent of more than 40 per cent, both within 30 cm of the surface, or having less than 10 per cent by weight of fine earth over a depth of 75 cm from the surface; having no diagnostic horizons other than a mollie, umbric, ochric or vertic horizon.

Fluvisols. The definition of Fluvisols (FL) in the FAO legend for the Soil Map of the World (3) was “Soils showing fluvic properties and having no diagnostic horizons other than an ochric, a mollie or an umbric A horizon, or a histic H horizon, or a sulfidic horizon, or sulfidic material within 125 cm of the surface, or salic properties”.

By definition, Fluvisols occur on materials deposited in sedimentary environments: fluvial, lacustrine, and marine conditions. These soils are developed in materials which show “fluvic properties”. Fluvic properties imply stratification of the parent material or which may be evident from an irregular distribution of organic carbon content of the profile.

Pedogenetic processes, such as homogenization caused by burrowing animals and rooting plants gradually destroys the original sedimentary layering and the soil begins to acquire the properties required for a cambic horizon. As the cambic horizon by definition must have its base at least 25 cm below the soil surface, it is necessary to restrict Fluvisols to those soils showing fluvic properties within 25 cm of the soil surface.

The definition proposed for Fluvisols is:

Soils showing fluvic properties within 25 cm of the surface and having no diagnostic horizons other than an ochric, a mollie, an umbric horizon, a histic, a salic, a sulfidic or a sulfidic horizon.

Changes

Changes to the Leptosol major group. The changes recommended by the WRB panel will result in the following modifications to the Leptosol units.

a) It is recommended that soils with a petrocalcic horizon at shallow depth are specifically excluded from the Leptosols and will now qualify as Petric Calcisols. Where a shallow soil has a mollie horizon over a highly calcareous parent material (>40 per cent) or if the soil contains calcareous fragments totalling more than 40 per cent, then the soil will be classified as a Rendzic Leptosol.
b) A shallow soil with a partly developed cambic horizon which is too thin (i.e. less than 15 cm), insufficiently deep (with its base less than 25 cm from the surface), or is coarser than a sandy loam, or lacks soil structure in over half of its volume will fall into the Leptosols.

c) A minimum depth of 10 cm is introduced for Histosols having a lithic or paralithic contact. This is done to avoid very thin organic soils being classified as Histosols. All these shallow soils will key out now as Lithic Leptosols. Further definition is left for a third-level of classification.

d) Soils showing cryic features and with or without permafrost within 200 cm of surface are placed in the new soil unit of Cryic Leptosols.

e) Anthropic Leptosols have been introduced to cater for shallow soils overlying materials from refuse dumps and mines, thinly covered by topsoil or imported soil material.

f) In volcanic areas, tephric materials may form shallow soils over older continuous hard rock. A unit of Tephric Leptosols is introduced for these soils.

g) Similarly, Leptosols with 90 per cent or more by weight of gravel or coarser fragments to a depth of 75 cm or to continuous hard rock qualify as Skeletic Leptosols.

h) Loamy sand or coarser (but not gravelly) shallow soils will be classified as Arenic Leptosols.

i) Mollic, Umbric and Dystric and Eutric Leptosols continue to be used as before.

Changes to the Fluvisol major group. Changes in the definition of the Fluvisols recommended by the WRB panel will result in the following modifications to the Fluvisol units:

a) Where soil formation disrupts the original stratification below 25 cm to create a cambic horizon, it now means that the soil is no longer a Fluvisol and becomes instead a Fluvic Cambisol.

b) Soils which have stratification below a cambic horizon and additionally have gleyic properties within 50 cm of the surface, now pass through the Fluvisols to become Fluvic Gleysols.

c) A soil with fluvic properties but which is limited by continuous hard rock or highly calcareous material within 30 cm, or which has > 90 per cent coarse fragments will key out before Fluvisols, and so will now become classified as appropriate Leptosols.

d) Fluvial soils with a salic horizon will be allocated to the unit of Salic Fluvisols as recommended by FAO-Unesco (1).

Conclusions. Within the WRB panel a case was put forward for abandoning the major soil group of Leptosols, but after consideration of the advantages and disadvantages, it was decided to retain it. There had been no such proposal for the Fluvisols, but it was agreed that the definition of both groupings of soils required some tightening. These proposals have been outlined in this contribution. Leptosols have limitations for their use; they are shallow and often on steeply sloping land where erosion is a strong possibility. The use of machinery is usually precluded because of the steep slopes on which they occur. Leptosols tend to be droughty soils which are best left to natural woodland or light grazing. Under strictly controlled conditions they can be terraced.
and cultivated either with or without irrigation as has successfully been done in many parts of the World.

Fluvisols are usually very productive soils including a wide range of dryland crops and paddy rice. Normally they are within the command area of irrigation. However, in dry climates they may be subject to salinization and in coastal regions acid sulphate conditions may arise when they are drained. Occasional flooding of Fluvisols renews nutrients, but it can also bring pollution and weed seeds which can detract from their inherent fertility.

**Literature cited**


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