Quantified soil dynamics and spatial fragmentation within the shifting agricultural landscape in southern Cameroon

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Abstract
This research used scientific modeling tools to produce quantitative information on the effects of shifting agriculture on soil and spatial pattern of landscape dynamics in the area. An analysis of farming system led to the development of a conceptual model of the spatio-temporal dynamics of shifting agriculture, including transition matrices of rotational cycles. The study of soil variability showed that 30-35% of the total variance of some topsoil (0-20 cm) properties was due to the influence land use practices. A robust quantitative multi-criteria method was then developed that selected five soil properties (pH, calcium, available phosphorus, bulk density and organic carbon) that are the most sensitive to these agricultural practices. Empirical models of linear/quadratic fractional rational functions were successfully fitted to time series soil variables to derive quantitative measures on temporal changes in soil with land use. Multi-spectral satellite imagery was able to map with 80% accuracy the extension front of shifting agricultural landscape and the most dynamic land cover types (crop fields, young fallows), which shift every season and every year. Data and methods produced are useful for soil quality assessment and spatio-temporal dynamic simulation in order to guide decision-making for sustainable land-use planning and forest resources management.

Key words
Shifting agriculture; Farming systems analysis; Soil dynamics; Landscape fragmentation; Rain forest; Southern Cameroon.

Introduction
In the tropical rain forest zone of Southern Cameroon, the spatial pattern of the shifting agricultural land use system is a landscape mosaic system (Forman 1995), which is defined here as a spatial and temporal heterogeneity of aggregated elements of distinct boundaries, where various fallow types, various food crop fields, various perennial plantation types, undisturbed forest, and settlement areas are repeated in similar form over the landscape. This leads to a dynamic process acting in soil and on the spatial pattern of land use/Land cover (LULC) within the mosaic system. Beside the small-scale farmers' agriculture, the sustainable use and management of the national forests has become a challenge at national as well as international levels (ITTO 1990). In such a context of multifunctional use of the space, better land management practices that can ensure efficient use of energy and nutrient capital from soil-vegetation complex, and minimize land use conflicts should be promoted. However, this can only be effective if based on thorough knowledge on integrative indicators of the current status of the agricultural production capacity of land and their changes over time. This is what motivated the research reported in this paper which main objective was to provide quantitative information, developed through modelling processes, on short and long-term effects of shifting agriculture on soil and the landscape dynamic in space.

The research design and methods
The study area is located between 2º47' - 3º14' N and 10º24' - 10º51' E. It belongs to the mid-altitude dense moist evergreen Biafran forest of Cameroon (Gartlan 1989). Two rainy seasons account for 1600-2000 mm of annual rainfall. Most soils are Ferralsols and Acrisols (FAO-ISRIC 2006). The area is sparsely populated. Selective industrial logging and extensive shifting agriculture are the most important land use activities.
In four representative villages of the area, a synchronic approach for data collection was combined with diachronic monitoring of plots during the two-year cropping period and after five subsequent years. LULC treatments (10 in total) were chosen based on actual agricultural production cycles (Figure 1) described in Yemefack (2005, Chapter 2). Samples were taken with 3-4 replications in each village. In selected LULC patches, composite soil samples were collected, at three depths (0-10, 10-20, and 30-50 cm). Soil samples were analysed in the IRAD laboratory for pH, organic matter, available phosphorus, exchangeable bases, exchange acidity and particle size distribution, using procedures described in Van Reeuwijk (1993). Surface areas of 293 crop fields opened within three years by 35 households were measured. 33 plots were monitored from the first year of cropping to seven years.

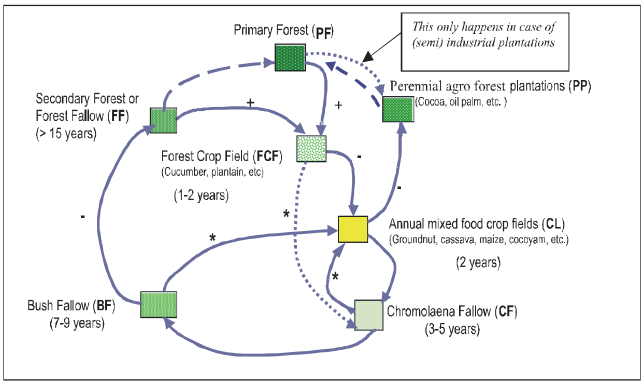


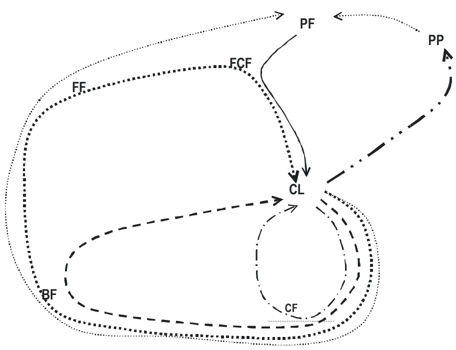
Figure 1. Observed transitions between land uses. Adapted from Yemefack (2005, Chapter 2)
Key:( ) Common transitions; ( ) Infrequent transitions; ( ) PF recovery after definite abandonment; (+) patches can split (fragmentation); (-) patches can merge with others of the same type (consolidation); (*) patches can merge with those of other types.

Investigating landscape spatial fragmentation, two questions guided our research: (i) Can Landsat-7 ETM+ imagery be used to map various LULC of the area? (ii) At which level of aggregation could this landscape structure be characterized in terms of composition and spatial configuration? In two sample sub-areas (Ebimimbang area on Acrisols and Mvie area on Ferralsols), the geographic coordinates of the centre of 158 LULC patches were recorded with a GPS six weeks before the image was taken on the 31 March 2003. Descriptive statistics, analysis of variance and means separations (Tukey's method), principal component analysis, cluster analysis, discriminant analysis, and geostatistical analysis were applied to different datasets designed purposely for each specific objective. Detailed descriptions of these analyses are giving in Yemefack (2005). The analyses were carried out with R environment (Ihaka and Gentleman 1996). Spatial analysis and remote sensing processing were done using ILWIS (ITC ILWIS Unit 2001).

Results and discussion

Dynamics of shifting agriculture

The analysis of farmers' field size distribution and the conceptual model of land use dynamic exposed the issue of rotational fallow systems, which tend to replace the ideal shifting cultivation in which short-term cropping alternates with secondary forest on a plot. This has shown (Figure 2) that 1/5 of food crop field plots were based on short rotational fallow cycles (RSFS), about 1/2 on long rotational fallow cycles (RLFS), 1/5 on very long fallow cycles (RVFS), and 1/10 on forest conversion (FCS). If the shorter fallow cycles are sustainable, this may require intensification: tighter integration into the market economy and some purchased inputs, with special attention to nutrient cycling and soil management.



Key:

Cycle	Area (%)	Household (%)	
CL-BF-CL (RSFS)	19	32	Food crop production cycles
CL-CF-BF-CL (RLFS)	52	52	Food crop production cycles
CL-CF-BF-FF-FCF-CL (RVFS)	17	11	Food crop production cycles
PF-FCF (FCS)	12	5	Food crop production cycles
PP cycle	3-25 (including elites' plantations)		
PF recovery	unknown		

Figure 2. Cycle proportions of shifting agricultural land use management in southern Cameroon. Adapted and modified from Yemefack (2005, Chapter 2).

In this study, 35 households cleared 95 ha in three years, of which 88% of the area cleared for crop fields came from fallow lands and only 12% from primary forest (Figure 2). However, with the involvement of elites in agricultural plantations, net deforestation is probably occurring, since their plantation plot sizes are far larger than those of small farmers. This brings the total proportion of PF in the cleared area to about 40% when including elite plantations.

Soil variability in the study area

For a better understanding of complex relations between soil properties, environmental factors and land use systems, sources of soil variability were evaluated at four scales: region, village, plot and laboratory (Yemefack *et al.* 2005). This four-scale study was able to explain for several variables, an encouraging 80% (for less sensitive soil variables) to 95% (most sensitive ones) of the overall soil variation; with 5 to 70% by regional factors, 3 to 35% by local factors, 1 to 10% by within-plot factors, and less than 5% by laboratory errors. Land use practices significantly ($p<0.05$) influenced topsoil variation at village level and accounted for 30-35% of topsoil (0-20 cm depth) variation. Thus, because regional factors of soil variability are more stable over time, our research should focus chiefly on processes and factors occurring at local-scale level under the influence of a dynamical land use system.

Soil dynamics under shifting agriculture

Soil behaviour in time was here quantified by the most sensitive soil properties to shifting agricultural practices and their mathematical model as a function of time.

Most sensitive soil properties: A multi-criteria quantitative selection procedure was developed (Yemefack *et al.* 2006b) and applied to a set of 13 soil variables collected within a chronosequence of shifting cultivation system. Five soil properties (pH, exchangeable Ca, available P, bulk density and organic carbon) were selected as the most affected by the practices. These can be used individually or in combination to assess the effect of this practice on soil condition. The five indicators could be easily interpreted in terms of their relation to land management practices and land use changes (Yemefack *et al.* 2006b).

Change in soil properties with time: The five most sensitive soil properties were used individually to model the behaviour of soil over time, the time being represented by a land use chronosequence (Yemefack *et al.* 2006c). Within the longest cycles of shifting cultivation (SC) and agroforest cocoa plantations (PP), each soil property changes as a function of time *t,* with $P(t) = P_0 + f(t)$

where $P(t)$ is the value of the soil property P at time t, P_0 is the value of soil property P at time $t=0$ (under the forest cover, PF), and $f(t)$ is the change function of time. Since our interest for this study was to model the change, not the absolute values, we converted each variable to a proportional deviation (*Pd*) from the reference sites PF. Pd values were plotted against time to determine the form of $f(t)$ and attempts were made to fit suitable functional forms, of which low-order fractional rational functions proved to be most appropriate. In this case, proper linear/quadratic fractional rational functions,

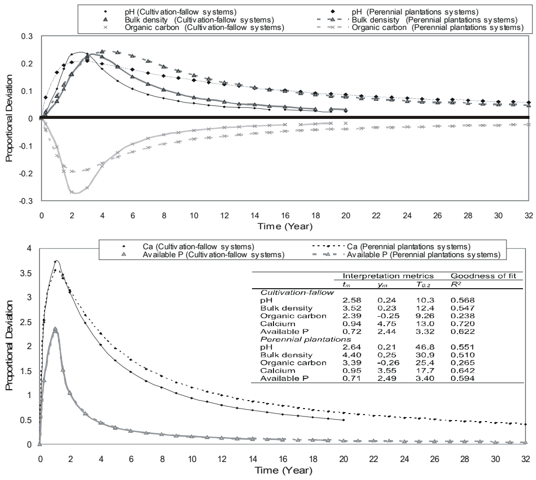
$$f(t) = \frac{a + bt}{1 + ct + dt^2}$$

showed a reasonable shape to model changing soil properties in response to events such as land clearing, burning, cropping, fallowing and PP. The fitted functions (Figure 3) were used to evaluate metrics describing soil behaviour over time: maximum proportional deviation from the base state (y_m), time to reach this maximum (t_m), and relaxation time towards the original value (t_p = time after t_m at which the curve reaches some predefined proportion of recovery).

The fitted function explained 50 to 80% of soil dynamics for the first four variables in the 0-20 cm layer on both Ferralsols and Acrisols but only 25% for organic carbon. These functions showed a very quick reaction to forest conversion for calcium, available P and organic carbon which maxima are reached at the end of the first year. Soil reaction and bulk density showed significant changes a bit later (2.5 to 3.5 years). The low contribution (only 25%) of organic carbon to the models could be explained by the strong fluctuations of data during the years.

Landscape spatial structure

Investigating statistical relationships between LULC types, Landsat-7 ETM^+ satellite imagery and landscape spatial fragmentation due to the conversion of tropical rain forest to shifting agriculture (Yemefack *et al.* 2006a), common statistical techniques applied to spectral point data and derived indices led to a suitable strategy for consolidating some of the current LULC types in the process of LULC aggregation for improving image classification. Thereafter, the application of the Maximum Likelihood Classifier (MLC) for supervised classification provided a LULC map (Figure 4) with the highest accuracy (81%) after consolidation of perennial LULC types into one mapping unit (bush fallow, forest fallow and cocoa plantations).



	Interpretation metrics			Goodness of fit
	t_m	y_m	$T_{0.2}$	R^2
Cultivation-fallow				
pH	2.58	0.24	10.3	0.568
Bulk density	3.52	0.23	12.4	0.547
Organic carbon	2.39	-0.25	9.26	0.238
Calcium	0.94	4.75	13.0	0.720
Available P	0.72	2.44	3.32	0.622
Perennial plantations				
pH	2.64	0.21	46.8	0.551
Bulk density	4.40	0.25	30.9	0.510
Organic carbon	3.39	-0.26	25.4	0.265
Calcium	0.95	3.55	17.7	0.642
Available P	0.71	2.49	3.40	0.594

Figure 3. Linear/quadratic fractional rational functions fitted to soil properties (0-10 cm) dynamics under two land use chronosequences (food cropping-fallow system and perennial plantation) as shown by proportional deviations from the reference under primary forest over time.

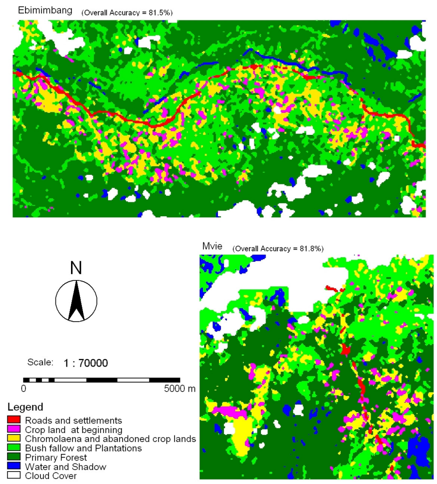


Figure 4. Spatial configuration of the two sub-areas based on the Maximum Likelihood supervised classification.

Concluding remarks

- The short rotational fallow cycle is increasingly being used due to the farmers' desire to replace cash income from cocoa with cash food crops. This may require intensification with special attention to nutrient cycling and soil management. This land use practice significantly influence topsoil variation and accounted for 30-35% of the total variance.
- Five soil properties (pH, exchangeable Ca, available P, bulk density and organic carbon) are the most affected by the shifting agricultural practices in topsoil. Interpretation metrics derived from their functions (linear/quadratic fractional rational functions) in time are useful figures for supporting decision in defining and timing any intervention action.
- From multispectral remote sensing, only crop fields and short fallow patches were most accurately classified by the maximum likelihood classifier with over 80% accuracy.
- Data and methods produced are useful for soil quality assessment and spatio-temporal dynamic simulation in order to guide decision-making for sustainable land-use planning and forest resources management.

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