# Changes in paddy soils under transition to water-saving and diversified cropping systems

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## Abstract

Most rice (*Oryza sativa* L.) is produced on soils with a prolonged period of submergence. Soil submergence has helped sustain the productivity of continuous rice production systems. It helps maintain soil organic matter (SOM), favors input of N through biological nitrogen fixation, and enhances availability of soil P to rice. Rice will increasingly be produced within political and economic environments of less supply of irrigation water and more income opportunities from alternative crops. This will lead to changes in water management, rice cultivation practices, and cropping patterns resulting in reduced soil submergence and increased duration of soil aeration. Soil aeration alters soil biogeochemical processes, which can lead to loss of SOM, reduced supply of plant-available N and P, and reduced zinc and iron availability on high-pH soils. Soil aeration favors the formation of nitrate, which can be lost via denitrification upon soil submergence for rice cultivation. Soil drying and wetting favor increased emission of nitrous oxide and reduced emission of methane. The productivity of paddy soils, which has been sustained with ample water resources, must in the future be sustained with management interventions that more effectively use water and provide enhanced crop diversification and income generation.

## Key Words

Paddy soils, rice, water savings, crop diversification, soil organic matter, nitrogen.

## Introduction

"Paddy soils" denote soils in irrigated and rainfed lowland rice production systems with a prolonged period of submergence. About 90% of the global area of paddy soils is located in Asia. Soil submergence leads to unique biogeochemical processes, which influence ecosystem sustainability and ecosystem services such as carbon storage, nutrient cycling, and nutrient supply to crops. Soil submergence does not occur in the production of other major food crops, and the management of natural resources differs between landscapes dominated by lowland rice and other agricultural land-uses.

Rice produced on submerged soil is a major beneficiary of freshwater resources. An estimated 24% to 30% of the world's developed freshwater resources are used for the irrigation of rice (Bouman *et al.* 2006). Much of the world's rice is produced in countries with rapidly growing economies. With economic growth comes competing demand for use of water by industries and households rather than agriculture. Groundwater has become an important source for irrigation, particularly in South Asia, but groundwater tables are falling in many areas. Thus, there are valid concerns regarding how the reduced availability and increased price of irrigation water will affect paddy soils and rice production.

Production systems on paddy soils include one, two, or three rice crops per year. Double and triple cropping of continuous monoculture rice account for about 40% of the global rice supply. Rice is also commonly grown in rotation with other crops on paddy soils. The rice–wheat (*Triticum aestivum* L.) cropping system is common in the subtropics of South Asia and China. The rice–maize (*Zea mays* L.) cropping system is gaining importance on paddy soils across tropical and subtropical Asia in response to the increasing demand of maize for feed and biofuel.

Rice will increasingly be produced within political, economic, and social environments of less supply of irrigation water and more income opportunities from crop diversification. This could result in changes in water management, cultivation practices, and cropping patterns leading to reduced soil submergence and increased duration of soil aeration. A change from soil submergence to greater soil aeration, while increasing the efficiency of water use, can significantly affect the biogeochemical processes influencing carbon storage, nutrient cycling and supply to crops, greenhouse gas emissions, and rice productivity. In this paper, we review changes in paddy soils arising from both growing rice with less water and switching to more diversified cropping systems.

## Effect of growing rice with less water

Continuous rice cropping with up to three crops per year was made possible with short-duration, high-yielding rice cultivars and irrigation. Rice in Asia is traditionally established on paddy soil by transplanting, but as labor costs increase there has been a move to direct wet seeding of germinated seed. Land preparation for both transplanted and wet-seeded rice typically consists of soaking the soil followed by plowing and harrowing of saturated soil. The tillage of saturated soil — referred to as puddling — destroys soil structure, creates a soft muddy layer of 10–15 cm depth, and reduces subsequent downward movement and loss of water during rice cropping. Rice fields are typically kept submerged with 5 cm or more of water throughout the growing season until just prior to harvest. This submergence helps control weeds and increase the availability of a number of nutrients. The production of irrigated rice consequently requires considerable water because of the high water use for land preparation and the losses by seepage, percolation, and evaporation when soil is submerged (Bouman *et al.* 2006).

### *Alternate wetting and drying of puddled soil*

The use of irrigation water for producing lowland rice on puddled paddy soils can potentially be reduced by lowering the depth of standing water and by allowing the soil surface to dry before the next application of irrigation water. The practice of withholding irrigation until several days after the disappearance of ponded water is referred to as alternate wetting and drying (AWD) (Bouman *et al.* 2007). Even without ponded water, rice roots can access the water in the subsurface soil, which remains saturated. The practice of "safe" AWD now promoted as a mature water-saving technology entails irrigation when water depth falls to a threshold depth below the soil surface. Safe AWD results in a savings of irrigation water, increased water productivity, and no decline in rice yield (Bouman *et al.* 2007).

AWD results in periodic soil aeration, but the extent and duration of soil drying when implemented at safe levels, which do not result in loss of rice yield, are unlikely to have much effect on soil organic matter (SOM) and plant availability of macronutrients in the soil. No adjustments in management practices for fertilizer N, P, and K are proposed with safe AWD. Nutrient best management practices based on the principles of site-specific nutrient management (SSNM) (Buresh 2010, IRRI 2010) are the same for rice grown with AWD and continuous soil submergence, provided AWD does not result in water stress leading to lower attainable yield. Broadcasting urea before irrigation could help ensure the movement of N into the soil, where it would be less prone to loss via ammonia volatilization (Buresh *et al.* 2008).

Sequential nitrification-denitrification is greater in soil with alternate wetting and drying than with continuous submergence (Buresh *et al.* 2008). AWD could consequently lead to a slightly greater loss of broadcast fertilizer N and soil N by nitrification-denitrification, but this loss is expected to decrease with increasing age of the rice crop due to increased competition of rice with microorganisms for ammonium before it can be nitrified and for nitrate before it can be denitrified (Buresh *et al.* 1993).

Erratic rainfall in rainfed rice ecosystems and periodic unavailability of irrigation water in irrigated rice ecosystems can prolong the duration of soil drying, resulting in soil water deficit, leading to a loss in rice yield. As a general principle, as soil drying becomes more prolonged and severe, the availability of soil P to rice tends to decrease and the availability of zinc in acid soils tends to increase (Dobermann and Fairhurst 2000). Fertilizer rates should be adjusted to the anticipated water-limited grain yield of rice (Haefele and Bouman 2009).

### *Prolonged soil aeration of nonpuddled soils*

Another approach to growing rice with reduced water use is to grow rice as an upland crop — like wheat or maize — on nonpuddled, nonsaturated soil without ponded water. When rainfall is insufficient to maintain soil water content above a threshold between field capacity and wilting point, irrigation water can be applied to bring soil water content in the root zone to field capacity. This practice of rice cultivation under conditions of relatively severe shortages of irrigation water is referred to as "aerobic rice" (Bouman *et al.* 2007). The paddy soil remains aerated (aerobic) throughout the rice-growing cycle.

Rice production on aerobic soils often uses conventional full tillage of aerated soil for seedbed preparation, initial weed control, and crop establishment by direct dry seeding of nongerminated seed (Bouman *et al.* 2007). Alternatively, resource-conserving technologies are developed to grow rice using reduced or zero tillage and establishment by drill seeding or transplanting (Ladha *et al.* 2009).

The submergence of rice soils helps maintain SOM, even with intensive rice cropping and removal of crop residues (Pampolino *et al.* 2008). This maintenance of SOM ensures that C remains sequestered in the soil. Soil submergence also promotes biological nitrogen fixation (BNF) (Buresh *et al.* 2008), and submerged soils can sustain an indigenous N supply (INS) for rice as evidenced by long-term stable yields in minus-N plots in long-term experiments. Paddy soils historically cultivated with rice monoculture using puddling and soil submergence can be susceptible to loss of built-up SOM and INS when converted to the production of aerobic rice. On the other hand, SOM in paddy soils historically tilled aerobically for the production of upland crops — such as wheat and maize — might have already stabilized at relatively lower levels than for soils without such aerobic tillage. Conversion to aerobic rice on such soils might consequently have relatively less risk of loss of SOM. Resource-conserving technologies for rice aim to prevent further loss of SOM and potentially slowly build up SOM.

As a general principle, fertilizer N, P, and K requirements for a given target yield could be higher for rice grown on aerobic soil than submerged soil. A higher need for fertilizer N can arise from lower INS due to lower BNF and possible lower net N mineralization in aerobic soil. A higher need for fertilizer P can arise from the reduced availability of soil P in aerobic soil. A higher need for fertilizer K can arise from reduced input of K with irrigation water due to water savings with aerobic rice. Soil aeration increases zinc availability on acid soils, but it can decrease zinc and iron availability on high-pH soils, leading to a need for iron and zinc fertilization for dry-seeded aerobic rice (Malik and Yadav 2008).

## Switching from continuous rice to diversified cropping systems

Even with water-saving technologies for rice cultivation, the water requirements for rice remain higher than for other cereal crops. Diminishing supplies of irrigation water and opportunities for income from non-rice crops can serve as drivers for diversification from the production of rice monoculture with soil submergence to a rotation of rice with other crops such as maize grown on well-drained aerobic soils.

Continuous rice with puddling and soil submergence sustains SOM and INS (Pampolino *et al.* 2008), but the conversion from continuous rice to a rice–upland crop rotation with conventional tillage of aerobic soil can lead to a loss of SOM. In a long-term experiment in the Philippines, the conversion from rice–rice to rice–maize led to a loss of SOM, which increased with aerobic soil tillage. Nitrogen balances were also more negative with rice–maize than with rice–rice (Buresh, unpublished). Resource-conserving technologies with reduced or zero tillage for establishment of the upland crop merit further investigation for sustaining SOM and INS built up during the historical cultivation of continuous rice with soil submergence.

Whereas ammonium is the stable form of inorganic N in submerged soils, nitrate accumulates in aerobic soils. The accumulated nitrate is prone to loss by leaching and denitrification with the formation of nitrous oxide when soil, after production of an upland crop, is submerged during land preparation for subsequent rice production (Buresh *et al.* 2008). This potentially greater loss of soil N combined with less input of N by BNF could result in reduced INS when continuous rice is converted to a rice–upland crop rotation.

## Environmental concerns

Soil submergence promotes the production of methane by anaerobic decomposition of SOM and added organic materials, whereas aeration of soil reduces methane emissions. Emissions of nitrous oxide, another greenhouse gas with a higher global warming potential than methane, are typically negligible or low during continuous soil submergence. Soil aeration increases the formation of nitrate and emissions of nitrous oxide.

Therefore, water-saving technologies for rice production, such as AWD and aerobic rice, and the inclusion of more upland crops in the cropping system can reduce emissions of one greenhouse gas (methane) while increasing the emissions of another more potent greenhouse gas (nitrous oxide). A greenhouse study suggested that continuous soil submergence has a lower risk of combined methane and nitrous oxide emissions than AWD when crop residues are not incorporated, but AWD has a comparable or lower risk than continuous soil submergence when crop residues are incorporated (Johnson-Beebout *et al*. 2009). Future research should identify combinations of water, residue, and crop management with the lowest global warming potential from combined methane and nitrous oxide emissions.

Weeds and nematodes are typically more serious constraints on aerobic soils than on submerged soils, potentially necessitating increased pesticide use. The accumulation and leaching of nitrate in aerobic soils could cause an increased nitrate contamination of the groundwater.

## Conclusions

Paddy soils in the future will increasingly be managed within environments of diminishing and erratic water supplies. Researchers are striving to develop crop, water, and residue management practices that help grow rice with less water and enable more diversified rice-based cropping systems. The developed management practices must simultaneously ensure the production of sufficient affordable rice and profitability for producers. Researchers will be increasingly challenged to document the effects of new management practices on C storage in soil, nutrient cycling, greenhouse gas emissions, and soil nutrient supplying capacity. When new management practices unavoidably lead to declines in indigenous nutrient supply from levels obtained for continuously submerged soils, existing recommendations for nutrient inputs must be appropriately tailored to meet emerging needs. Researchers should also aim to better understand critical threshold durations and frequencies of soil submergence for additional critical ecosystem services such as control of weeds, nematodes, and other pests.

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