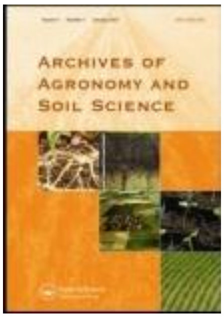

Soil fertility in flooded and non-flooded irrigated rice systems

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Soil fertility in flooded and non-flooded irrigated rice systems

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Abstract

Lowland rice system in Asia makes a major contribution to the global rice supply and is often cited as an example of a sustainable system in which two or three crops of rice are grown in sequence under submerged conditions. However, reports indicate that water shortage may become critical in some regions for lowland rice cultivation; and there is high potential in exploring rice cultivation under moisture regimes that save water and also increase productivity. The objective of this paper is to analyze the consequences of switching the growing of rice from flooded to non-flooded conditions on soil fertility management. Fertility advantages of submerged rice include amelioration of chemical fertility, preferential accumulation of organic matter and improved availability of major, secondary and selected micronutrients, which contribute to the long-term maintenance of soil fertility and sustainability of lowland rice system. On the other hand, the fertility problems in aerobic rice have to be dealt through diversification of the production systems. Continuous growing of aerobic rice on a plot might not be sustainable due to chemical and biological constraints.

Keywords: aerobic rice; chemical and biological fertility; nutrient availability; paddy rice; soil health; sustainability

Introduction

Lowland rice or paddy systems in Asia make a major contribution to the global rice supply (Cassman and Pingali 1995). The lowland rice system is often cited as an example of a sustainable system (De Datta 1981; Kyuma 2004). Growing of rice in submerged soils is an integral component of the traditional, age-old technology in monsoon Asia (Kyuma 2004). This method of rice cultivation involves land preparation by cultivating the land in the flooded or saturated state (termed puddling), followed by transplanting rice seedlings into the puddled paddies, and growing of rice in submerged soils until two to three weeks prior to the harvest of the crop.

Over 70% of Asia's rice is produced in irrigated lowland fields with high irrigation requirements to maintain a layer of standing water on the soil surface during most of the growing season (Bouman and Tuong 2001).**The water requirement of flooded rice in the Philippines determined during six seasons including both rainy and post-rainy seasons, varied from 1240 to 1889 mm in the flooded fields and 790-1430 mm in aerobic fields (Bouman et al. 2005). Actually,** irrigation water shortage being experienced in some regions of Asia, is threatening the traditional system of lowland rice cultivation (Bouman et al. 2007). **Hence, there is a need for exploring alternate water management practices that save water and at the same time enhance water productivity. Water productivity here is defined as the weight of economic yield or grains produced per unit of water input including rainfall plus irrigation (Bouman et al. 2005).**

For growing rice under non-flooded conditions, there is a need to develop a strategy that includes the development of rice cultivars that are adapted to aerobic conditions. **Also, management practices need to be developed in an integrated nutrient and pest management approach so that adapted rice cultivars sustain high yields. It is however, realized that rice yields under aerobic conditions are influenced by complex site-specific and ecological constraints and they need to be considered while developing management practices to go with adopted rice cultivars.**

Indeed, aerobic rice is seen as an emerging option to produce rice with less water than the submerged rice system (Tuong et al. 2005; Xue et al. 2008; Kato et al. 2009). The aerobic rice uses cultivars that maintain high productivity under aerobic non-submerged or non-saturated soils (Atlin et al. 2006; Peng et al. 2006; Kato et al. 2009). There is an overlap in the definitions of traditional upland rice and aerobic rice (Bouman et al. 2007). **Generally, rice grown on fertile uplands using high-yielding cultivars with adequate water supply can be regarded as aerobic rice and**

non-irrigated or rain-fed rice with lower productivity expectations is regarded as upland rice (Kato et al. 2009).

The present water shortage situation for growing rice (Bouman et al. 2007) indeed presents an opportunity to review and critically analyze the effects on soil fertility of non-flooded rice systems relative to those that accrue in flooded or submerged rice systems. Therefore, the main objective of this paper is to provide a setting for nutrient disorder-related problems that constrain aerobic rice as compared to flooded rice system with emphasis on soil fertility maintenance. Future research in this important area should focus in diagnosing and managing nutrient disorders and pest and diseases for the adoption and adaptation of aerobic or non-flooded rice systems by rice growers especially in the regions facing critical irrigation water shortages.

Basic principles of fertility in rice soils

Rice is a sub-aquatic plant, well adapted to flooded soils, and thus is able to derive the benefits following flooding of the soil. However, upland rice is also grown in well-drained soils. **Lowland rice is perhaps** the only food crop, which thrives in submerged soils in monsoon Asia and other regions prone to seasonal or prolonged flooding (Kamoshita 2007). The adaptation of the lowland rice to flooded conditions is due to the presence of aerenchyma or pore space in the rice plant that conduit air from leaves to roots (Reddy and De Laune 2008).

Submerged soils benefit the rice crop by providing a more conducive environment for nutrient availability and uptake as a result of the adjustment of soil pH in the neutral range (Ponnamperuma 1972, 1984). The presence of free water on the soil eliminates water stress and minimizes weed competition to the

rice crop growth (Ponnamperuma 1975; DeDatta 1981; Rao et al. 2007). Also, the forms and availability of nutrients are related to moisture supply and flooded condition improves both availability (favorable soil pH) and the accessibility (nutrients delivery to rice plant roots improved both by mass flow and diffusion mechanisms) (Ponnamperuma 1975, 1984). Moreover, soil physical properties related to structure, which are important under arable or drained conditions, are not as important, as long as the soil is submerged under water (Ponnaperuma 1984). In general, soil chemical properties are improved following submergence of the soil (Ponnamperuma 1984; Narteh and Sahrawat 1999). Paddy soils also provide a congenial environment for biological nitrogen fixation by a range of aerobic, facultative anaerobes and anaerobic bacteria (Ponnamperuma 1972; Sahrawat 1998; Kyuma 2004; Sahrawat 2004 b).

The most important effect of submerging a soil under water is to cut the supply of oxygen. As a result, the entrapped oxygen is quickly exhausted and the soil becomes devoid of free oxygen. The lack of free oxygen or anaerobiosis causes soil reduction and sets in motion a series of physical, chemical, and biological processes that profoundly influence the quality of a soil as medium for growing rice or any other wetland crop (e.g., see Ponnamperuma 1972, 1984; Kyuma 2004). Submerging an aerobic soil in the water decreases its redox potential, which drops and stabilizes at a fairly stable range of + 200 mV to – 300 mV depending on the soil, especially on the content of organic matter and reducible nutrient elements—nitrate N (NO_3^-), manganic manganese (Mn^{4+}), sulfate (SO_4^{2-}) and ferric iron (Fe^{3+}), especially iron (Table 2). However, the redox potential of the surface water and first few mm of top soil in contact with the surface water remains relatively oxidized in the redox potential range of + 300 to + 500 mV (Gambrell and Patrick 1978; Patrick and Reddy 1978; Fiedler et al. 2007).

The Eh controls the stability of various oxidized components [oxygen, nitrate, manganese (Mn IV), ferric (Fe III) iron, sulfate (SO_4^{2-}), and carbon dioxide (CO_2)] in submerged soils and sediments (Patrick and Reddy 1978; Fiedler et al. 2007, Table 3). Soil reduction is influenced by the quality of the decomposable organic matter (OM) and the capacity of reduction is controlled by the quantity of easily reducible iron or active iron (Sahrawat 2004 a).

Fertility advantages of flooded rice system

Convergence of pH in the neutral range and the implications for nutrient availability

Under submerged condition, the pH of soils is generally stabilized in the neutral range (6.5-7.5). Following submergence, the pH of alkaline soils decrease because under prevailing anaerobic condition ferric iron is used as an electron acceptor for oxidizing organic matter and during this process acidity is consumed (Ponnamperuma 1972; Narteh and Sahrawat 1999):

$$Fe_2O_3 + \frac{1}{2} CH_2O + 4 H^+ = 2 Fe^{2+} + 5/2 H_2O + \frac{1}{2} CO_2 \qquad (1)$$

In these redox reactions, ferric iron (from amorphous ferric hydroxides) serves as an electron acceptor and OM (CH_2O) as the electron donor. This reaction results in the consumption of acidity and raising the soil pH.

A decrease in pH of alkali or calcareous soils is the result of accumulation of carbon dioxide in flooded soil, which neutralizes alkalinity. Moreover, carbon dioxide produced is retained in the flooded soil due to restricted diffusion through standing water on the soil surface. This allows large quantities of carbon dioxide to accumulate and form mild acid, which helps in neutralizing alkalinity in the soilfloodwater system (see equations 2 and 3). Moreover, the submerged soil system provides an ideal environment for reaction between carbon dioxide (carbonic acid) and alkalinity.

$$CO_2 + H_2O = H_2CO_3 \qquad (2)$$

$$H_2CO_3 = H^+ + HCO_3^- \qquad (3)$$

Thus, iron reduction and carbon dioxide concentration in the submerged reduced soil system, play key role in controlling the pH of submerged soils. The above reactions require an optimum temperature (between 25 and 35°C) and the availability of easily decomposable organic matter, reducible iron and other electron acceptors such as sulfate and carbon dioxide (Ponnamperuma 1972; Sahrawat 2004a).

The convergence of soil pH in the neutral range following submerging of soils benefits the lowland rice crop through better availability of nutrients such as ammonium, phosphorus (P), potassium (K) and exchangeable cations, which are mobilized in soil solution. Aluminum (Al) toxicity and other acid soil-related nutrient problems prevalent in the upland soils (for review see Sahrawat 2009) are reduced or alleviated by soil submergence of flooding (Ponnamperuma 1972; Narteh and Sahrawat 1999). A summary of results, gleaned from various sources in the literature, on the influence of flooding on nutrient availability is provided in Table 1.

Equally importantly, the growing of wetland rice in submerged soil is recognized as a component of technology for the reclamation of salt-affected (saline, saline-alkali and alkali soils) soils (Gupta and Abrol 1990; van Asten 2003); because the growing of a lowland rice crop keeps the salt-affected soils productive even during the reclamation phase. During the reclamation of salt-affected soils, growing of a lowland rice crop allows ponding of water to facilitate the leaching of salts after the application of amendments such as gypsum and organic matter. The application of carbonaceous materials (e.g., rice straw from previous harvest and or compost) to salt-affected soils prior to submergence and growing of the lowland rice, can further catalyze the amelioration of these soils. Production of extra carbon dioxide helps to neutralize the alkalinity of alkali soils. In the case of saline soils, ponding of water on the soil surface facilitates the leaching of salts (Gupta and Abrol 1990; Rao and Pathak 1996; Qadir et al. 2007).

Organic matter accumulation

In addition to the favorable effects of soil submergence on fertility in general and N fertility in particular, lowland rice cultivation maintains or in some cases improves the OM status of paddy soils. A review of recent global literature showed that organic matter status of soils under continuous rice (two or three crops per year) is either maintained or even increased compared with soils under upland rice or in wetland rice-upland crop sequence where a general decline in soil organic matter has been reported (Witt et al. 2000; Sahrawat 2004 b; Pampolino et al. 2008; Cheng et al. 2009).

Witt et al. (2000) showed that the sequestration of organic C and total N in wetland soils was significant during two years of cropping under flooded condition. An experiment was conducted on a clay soil at the International Rice Research Institute in Los Baños, Laguna, Philippines where five successive croppings (1993-1995) involving rice-rice or maize-rice were grown. Surface (0-15 cm) soil samples were taken at the start of the experiment in 1993 (wet season) and again in 1995 after harvest of the fifth crop in the wet season. There was a net gain in soil organic C and total N under the rice-rice system and a net decline under the maize-rice system.

Replacement of dry season flooded rice crop by maize caused a reduction in C and N sequestration in the soil. The results demonstrated the capacity of continuous irrigated lowland rice system to sequester C and N during relatively short time periods (Table 4) and were in accord with those reported by other researchers on the long-term benefits of flooding on soil OM accumulation (Zhang and He 2004; Shrestha et al. 2006; Pampolino et al. 2008; Cheng et al. 2009 ; Nayak et al. 2009).

Results reported from long-term experiments suggest that soil organic matter (SOM) levels under rice-wheat system in the Indo-Gangetic Plains have declined (Bhandari et al., 2002; Regmi, et al. 2002). On the other hand, prolonged submerged soil conditions stimulate SOM accumulation and C sequestration in wetland soils and sediments (Sahrawat 2004 b; Sahrawat et al. 2005; Pampolino et al. 2008; Nayak et al. 2009). In a long-term (32 years) study of SOM sequestration in the rice-wheat and maize-wheat systems in Punjab (India) showed that in both rice-wheat and maize-wheat cropping systems the application of farm yard manure or balanced fertilization resulted in higher C sequestration. However, the rice-wheat system (mean value of 260 kg C ha^{-1} $year^{-1}$ in 0-60 cm depth) had a greater capacity to sequester C as compared to the maize-wheat (mean value of 70 kg C ha^{-1} $year^{-1}$ in 0-60 cm depth) system because of greater C input through enhanced productivity (Kukal et al. 2009).

Nishimura et al. (2008) studied the effects of land use change from paddy cultivation to upland crop cultivation on soil C budget and found that the drainage of paddy fields for upland cultivation caused significant C loss from crop land soil. These results are in accord with those of earlier studies which showed that the drainage of paddy fields for upland crop cultivation causes loss of SOM due to enhanced decomposition of OM under aerobic condition (Mitsuchi 1974; Koizumi et al. 1993; Hu et al. 2004) The benefits of OM accumulation under long-term paddy rice cultivation were reversed by bringing the land under upland crop culture (Sahrawat 2004 b). Prolonged cultivation of lowland rice permits the accumulation of SOM. For a detailed discussion of OM accumulation in submerged soils and sediments, readers are referred to a review by Sahrawat (2004 b).

The decomposition of OM in aerobic soils is rapid in the presence of oxygen, which is the most efficient electron acceptor. On the other hand, in the absence of oxygen in flooded soils and sediments, decomposition of OM depends on the availability of alternate electron acceptors such as NO_3^-, SO_4^{2-} or Fe^{2-}. Since iron is present in high amounts in rice soils, the ferric-ferrous iron redox reaction plays a dominant role in the oxidation of OM and its mineralization in submerged soils and sediments (Sahrawat 2004a, 2010). Compared with arable soils, the decomposition of organic materials in submerged soils is slower, incomplete and inefficient, leading to net accumulation of OM (Sahrawat 2004 b; Reddy and De Laune 2008).

The deficiencies of nutrients such as N, phosphorus (P), and sulfur (S) affect the growth of bacteria, which in turn influence C fixation, storage, and release in wetland ecosystems. The formation of recalcitrant complexes stabilizes OM, making it less accessible for decomposition by microbial activity and hence its accumulation. In addition, the productions of compounds in submerged soils and sediments, which are toxic to microbial population, also retard soil OM decomposition (Sahrawat 2004b).

The most important factor responsible for net accumulation of OM in wetland soils and sediments is the high net primary productivity of these systems (Neue et al.

1997; Sahrawat 2004 b). In essence, slow decomposition of OM and higher net primary productivity of submerged rice soils lead to net accumulation of organic matter and N in submerged soils and sediments.

Plant nutrient availability

Pre-flooding of the soil for about four weeks prior to transplanting of the rice seedlings leads to the release of ammonium, P, K and other exchangeable ions in soil solution, which is good for growth of the rice plant (Ponnamperuma 1984; Sahrawat and Narteh 2002). This may allow the farmer to skip the basal application of N and reduce the application rates of P and K in some cases. The extent and release of ammonium and other cations and anions depends on soil chemical characteristics including pH, OM and texture (Ponnamperuma 1972; Narteh and Sahrawat 1999; Sahrawat 2010).

Flooding soil is a great pH neutralizer in problem soils. This is brought about by the neutralization of acidity in acid soils and alkalinity in alkaline soils following flooding, thereby generally influencing favorably, the release and the availability of plant nutrients. Soils with moderate to high content of inherent or added organic matter can help bring soil pH to a neutral range, favoring nutrient uptake by wetland rice. Submergence of soil improves the availability of ammonium-N, P, K, calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), and silicon (Si). Toxic concentrations of Al and Mn in soil solution are minimized with reduced solubility of these metals as a result of increased pH. On the other hand, the availability of S may be reduced due to sulfate reduction to sulfide in flooded soils. The supply of micronutrients such as copper (Cu) and molybdenum (Mo) is generally adequate. The availability of zinc (Zn) is reduced in submerged soils (Ponnamperuma 1972;

Sahrawat 1998; Narteh and Sahrawat, 1999). Also see Table 1 for the summary of results on nutrient availability under flooded vs. aerobic conditions.

There are other disadvantages associated with certain tropical soils in the humid regions that adversely influence the growth and production of lowland rice crop. For example, reducing conditions following flooding of iron-rich, acid soils lead to accumulation of excessive concentrations of ferrous iron in soil solution. The accumulation of excessive amount of ferrous iron in soil solution could cause iron toxicity to lowland rice. For detailed discussion of the various aspects of the topic, the readers are referred to reviews by Becker and Asch (2005) and Sahrawat (2004c). Also, submerged soils with high amount of OM or with added as fresh crop and organic residues may lead to the production of organic acids and sulfide, which can be toxic to the rice plant (Kyuma 2004).

A summary of results on the comparative status of soil organic matter, availability of plant nutrients and other factors that influence rice plant growth and development under flooded and non-flooded conditions (Table 1) show that the fertility and other associated advantage under submerged conditions outweigh those in the aerobic rice conditions. In the longer these fertility advantages or disadvantages have a cumulative effect on soil quality for growing rice.

Aerobic rice and soil fertility

The soil reduction-driven moderation or amelioration in soil pH observed in submerged rice soils is not observed in aerobic soils. This is the major difference in the submerged and aerobic soils, which has an overwhelming influence on the general soil health and the availability of major and micro-nutrient elements in rice soils (Sahrawat 1998). The extreme soil pH acidic or alkaline in aerobic soils indeed causes complex nutrient imbalances in the root zone of plants because of high concentrations of nutrients such as Al, sodium (Na) and calcium (Foy 2002; Hiradate et al. 2007; Fageria and Baligar 2008; Sahrawat 2009). For example, Ponnamperuma (1975) reported that Fe and P deficiencies were prevalent in mineral soils with pH in the neutral range, while on strongly acid soils, P deficiencyand Mn toxicity were the likely toxicities to aerobic rice. The deficiencies of Fe and Zn to aerobic rice on the calcareous soils is well established (Ponnamperuma 1975;Yoshida 1981). The absence of free water on soil surface under aerobic rice soil conditions greatly influences weed control, and the availability and accessibility of nutrients by plant roots (Ponnamperuma 1975; Rao et al. 2007; Mahajan et al. 2009; Sahrawat 2009).

Soil water regime especially in high pH calcareous soils, greatly influences the availability of micronutrients such as Fe and Mn; and the rice crop grown under upland aerobic conditions frequently suffers from Fe and at times Mn deficiency (Ponnamperuma 1975; Yoshida 1981; Takkar et al. 1989; Takkar 1996; Fageria et al. 2002; Maruyama et al. 2005; Gao et al. 2006; Tao et al. 2007). On the other hand, in acid upland soils, the acid-soil-related infertility is a major constraint in the humid tropical regions. These soil infertility problems result from low pH, Al toxicity, P deficiency and low base saturation, and the interactions between various deficiencies and toxicities (Fageria and Baligar 2008; Sahrawat 2009).

Yield decline resulting from continuous cropping od non-flooded or aerobic rice is a constraint to the widespread adoption of the aerobic rice technology in Asia.

Shift in water regime from flooded to non-flooded conditions influence the availability N and requirement of the crop. For example, Belder et al. (2005) reported from a field study that the amount of N accounted for was higher under aerobic irrigated conditions than under flooded conditions. It was concluded that there is a need for optimizing the rate and timing of N application efficient N nutrition of the rice crop. Similar results were reported by Nie et al. (2009) from a pot culture study.

It was suggested that the form, rate and time of N application need to be optimized for satisfactory growth the rice crop. Also, fertilizer N source that acidified the soil was found to be more efficient in N nutrition of the rice plants (Nie et al. 2009). Further studies showed that soil acidification (by application of dilute sulfuric acid) followed by application of N improved both plant growth of rice plants grown in aerobic conditions in pots (Xiang et al. 2009). Nitrogen application was more effective than in increasing plant growth and N uptake than soil acidification. It was indicated that a reduction in soil N availability and plant N uptake following an increase in the soil pH probably contributed to the declines observed in the growth and yield of monocropped aerobic rice (Xiang et al. 2009).

Thus, the issues relating to the sustainability of the aerobic rice, the crop need to be a part of the diversified system to maintain soil quality and health and control pests and diseases, e.g., through the use of legumes in the cropping systems. Without diversification of the system, there is a potential threat to the sustainability of the system due to biological and soil chemical fertility constraints. For example, research showed that although aerobic rice can yield 3-6 t ha^{-1} under tropical climatic conditions, the crop can suffer from immediate yield failure or a drastic yield decline. Several factors have been suggested as the causal agents, which vary from the involvement of chemicals, nutrient imbalance and biological agents especially nematodes and root pathogens (Ventura and Watanabe 1978; George et al. 2002; Fageria and Baligar 2003; Coyne et al. 2004; Atlin et al. 2006; Kreye et al. 2009; Sahrawat 2009).

A critical analysis of the results reported from diverse sites would suggest that under aerobic rice on soils with pH in the alkaline range, micronutrient imbalances especially caused by the deficiency of Fe and Mn seem the potential causal factors and need further research (Fageria et al. 2002). Under acidic conditions in aerobic soils, low base saturation leads to nutrient imbalance (Fageria and Baligar 2008; Sahrawat 2009). Another major constraint that influences the growth and yield of aerobic rice is the establishment of root knot nematode that invade the rice plant roots (Coyne et al. 2004; Kreye et al. 2009). On the other hand, soil submergence precludes the invasion of new roots of the rice plant by root knot nematode (e.g., see Coyne et al. 2004; Bridge et al. 2005). Moreover, under extended aerobic condition during the season, these problems related to micronutrient imbalance and root knot nematode invasion may occur and need to be addressed to help the rice growers cope with the problems associated with water-shortage. There is an obvious need to diagnose the causal factors that lead to yield decline in aerobic rice and to develop suitable management options to alleviate or avoid such constraints (Fageria and Baligar 2003; Kreye et al. 2009; Sahrawat 2009).

Perspectives

The benefits of growing rice in submerged soils are well documented and it is known that growing rice in submerged state not only imparts stability to rice production by alleviating water shortage, effective weed control (Ponnaperuma 1972, 1984; DeDatta 1981), but also form the basis of soil fertility and organic matter conservation and maintenance in the longer-term (Sahrawat 2004b; Pampolino et al. 2008). Soil erosion is not a problem in wetlands and indeed in some cases wetlands receive sediments from flowing water from the adjoining upland areas, which add to the organic matter and nutrient pools.

Lowland soils conserve soil fertility and organic matter by net gains through various physical, chemical, and biological (including biological nitrogen fixation) processes. Wetlands also have relatively large capacity to sequester and store organic matter. Carbon sequestration under soil submergence is the foundation of sustainable fertility maintenance in wetland rice soils and is also a strategy to reduce atmospheric carbon dioxide concentration and mitigate climate change.

Growing rice under non-flooded moisture regime likely would influence soil fertility and nutrient availability and this understandably has implications for the growth and productivity of aerobic rice. Such soil quality and fertility effects could range from overall depletion of soil organic matter and nitrogen to the availability of nutrients such as P on acid soils and micronutrients such as Mn and Fe on calcareous soils (Ponnamperuma 1975; DeDatta 1981; Sahrawat 1998). With the land use change from paddy to aerobic rice is likely to have a reverse influence on the fertility benefits derived from soil submergence. This has implications for the growth and yield of aerobic rice through the depletion of soil organic matter and nitrogen (Sahrawat 2004b; Belder et al. 2005; Nie et al. 2009; Xiang et al. 2009); and the availability of some nutrients especially micronutrients such as Mn and Fe on calcareous soils (Ponnamperuma 1975; Yoshida 1981; Maruyama et al. 2005). While the long-term fertility benefits of wetland rice are established, the information on those under the aerobic rice needs to be generated by long-term studies for a comparative evaluation of the long-term effects of growing aerobic rice on the dynamics of soil chemical and biological fertility.

To enhance rice productivity under non-flooded conditions, the role of cultivars that are adapted to aerobic soil is of critical importance, but there is genetic limit in the adaptation of the rice cultivars. The overall role of production (crop rotations or intercropping) systems and nutrient and water management assume greater importance in the sustainability of the system as a whole. The critical limits for deficiency and toxicity of nutrients vary in flooded and non-flooded rice ecology and there is need for research in this important area for optimizing nutrient management strategy in aerobic rice (Nie et al. 2009). Equally importantly, there is need to generate information on the long-term effects of growing aerobic rice on chemical and biological fertility of soils as such information will help in developing management strategies for a sustainable aerobic rice production system.

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Table1. Changes in soil organic matter, availability of plant nutrients and other factors affecting plant growth under submerged and aerobic rice systems[1]

	Submerged rice	Aerobic rice
pH	Converges to neutral range	Ambient pH
Organic matter	Favors accumulation of C and N but reduction products can be toxic	Decomposition is rapid and the accumulation relatively slow
C:N ratio	Wider C:N ratio due to OC accumulation	Varies with soil and organic matter management
NH_4-N	Production and accumulation favored	Oxidized to nitrate, which is liable to loss by leaching and denitrification
P	Improved P availability	Not applicable
K	Improved K availability	Not applicable
S	Reduced S availability likely due to sulfide formation	Normal availability due to sulfate
Fe	Improved Fe availability in alkali and calcareous soils, but Fe toxicity may occur in acidic soils high in reducible Fe	Iron deficiency is a serious problem in calcareous and high pH soils
Mn	Reduced solubility	Depends on pH, toxicity in acid soils
Cu, Zn and Mo	Improved availability of Cu and Mo but not of Zn	Depends on soil pH
Al	Not a problem except perhaps in acid sulfate soils	Serious problem on acidic soils
Reduction products	Sulfide and organic acids produced can be toxic	Not a problem
Root knot nematodes	Relatively less of a problem	Serious problem
Sustainability	Stability provided	Stability under question

[1] Gleaned from various sources in literature (for details see Ponnamperuma 1972, 1975,1984; DeDatta 1981; Yoshida 1981; Bridge et al. 2005; Becker, Asch 2004; Coyne et al. 2004; Fageria et al. 2003; Kreye et al. 2009; Sahrawat 1998, 2004a,b,c,2009,2010; Sahrawat et al. 2005).

Table2. The range of oxidation-reduction potential found in rice soils ranging from well drained to waterlogged conditions[1]

Soil water condition	Redox potential (mV)
Aerated or well-drained	+ 700 to + 500
Moderately reduced	+ 400 to + 200
Reduced	+ 100 to – 100
Highly reduced	- 100 to – 300

[1] Adapted from Patrick and Reddy (1978).

Table3. The range of redox potentials in which the main oxidized components in submerged soils become unstable[1]

Reaction	Redox potential (mV)
$O_2 – H_2O$	+ 380 to + 320
$NO_3^- – N_2$, $Mn^{4+} – Mn^{2+}$	+ 280 to + 220
$Fe^{3+} – Fe^{2+}$	+ 180 to + 150
$SO_4^{2-} – S^{2-}$	- 120 to – 180
$CO_2 – CH_4$	- 200 to – 280

[1] Adapted from Patrick and Reddy (1978).

Table 4. Estimated soil organic6carbon and total soil nitrogen balance for the rice-upland crop rotation experiment after five consecutive crops in 1993-1995. The data presented are from treatments without any N fertilizer application[1].

Cropping system	Rice-Rice	Maize-Rice
Soil organic C, kg ha^{-1}		
1993 wet season	19130 (827)[2]	19222 (791)
1995 wet season	20973 (494)	19105 (403)
Change	+ 1843 (440)	- 216 (502)
Total soil N, kg ha^{-1}		
1993 wet season	1811 (47)	1771 (56)
1995 wet season	1863 (49)	1720 (29)
Change	+ 52 (30)	- 51 (32)

[1] Adapted from Witt et al. (2000). Five consecutive crops under two rotations were grown in wet and dry seasons under irrigated conditions. The crops received uniform application of P (26 kg ha^{-1}) and K (50 kg ha^{-1}) each season. Zinc (10 kg Zn ha^{-1}) was applied uniformly in 1993 wet season.

[2] Standard error.

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