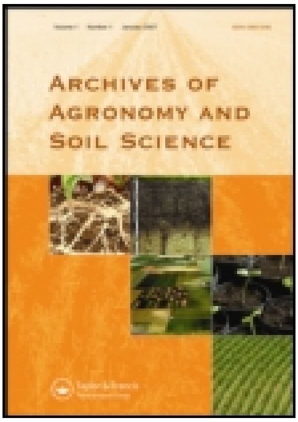

Archives of Agronomy and Soil Science
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gags20

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To cite this article: Kanwar Lal Sahrawat (2012): Soil fertility in flooded and non-flooded irrigated rice systems, Archives of Agronomy and Soil Science, 58:4, 423-436

To link to this article: http://dx.doi.org/10.1080/03650340.2010.522993

Archives of Agronomy and Soil Science
Vol. 58, No. 4, April 2012, 423–436

Soil fertility in flooded and non-flooded irrigated rice systems

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(*Received 19 March 2010; final version received 8 September 2010*)

The 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, water shortages are becoming 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 article therefore is to analyze the consequences of switching growing of rice from flooded to aerobic conditions on soil fertility and its 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 the lowland rice system. However, the fertility problems under aerobic rice are better addressed with the crop as a component of a cropping system because continuous growing of aerobic rice in sequence does not seem sustainable due to complex, site-specific chemical and biological constraints.

Keywords: aerobic rice; chemical and biological fertility; flooded soil, 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 Phillipines, determined during six seasons including both rainy and post-rainy seasons, varied from 1240 to 1889 mm in the flooded fields and from 790 to 1430 mm in aerobic fields (Bouman et al. 2005).

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ISSN 0365-0340 print/ISSN 1476-3567 online

http://dx.doi.org/10.1080/03650340.2010.522993
http://www.tandfonline.com

Actually, an 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 to explore 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).

To grow rice under non-flooded or aerobic conditions, there is 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 for integrated nutrient and pest management to increase sustainable yields by the adapted rice cultivars. However, rice yield under aerobic conditions is influenced by complex site-specific nutrient disorders as well as by ecological constraints (Sahrawat 2009). In addition, appropriate soil, water and nutrient management practices are needed to alleviate these constraints at the farm level. Soil, water and nutrient management practices need to be integrated with the use of adopted rice varieties as a technology package to achieve high and stable productivity in aerobic-rice-based production systems (Atlin et al. 2006; Hiradate et al. 2007; Peng et al. 2008; Xue et al. 2008; Sahrawat 2009).

Indeed, aerobic rice is seen as an emerging option to produce rice with less water than that used by flooded rice (Tuong et al. 2005; Xue et al. 2008; Kato et al. 2009). The aerobic rice system uses cultivars that maintain high productivity under aerobic, non-submerged or non-saturated soil conditions (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 current water shortage situation in growing rice (Bouman et al. 2007) also presents an opportunity to review and critically analyze the effects of a change from a flooded to an aerobic rice system on soil fertility management. Therefore, the main objective of this article is to provide a setting for soil fertility-related problems that constrain the aerobic rice system compared with flooded rice system with emphasis on soil fertility management and maintenance. Future research in this important area should focus on diagnosing and managing site-specific nutrient disorders and pest and diseases for the adoption and adaptation of aerobic rice systems by rice growers, especially in 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 associated with and that follow from flooding of the soil. However, upland rice is also grown in well-drained soils. Lowland rice is perhaps the only food crop that thrives in submerged soils in monsoon Asia and other regions prone to seasonal or prolonged flooding (Kamoshita 2007). The adaptation of lowland rice to flooded conditions is due to the presence of aerenchyma or pore spaces 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 convergence and 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 (Ponnamperuma 1975; De Datta 1981; Rao AN et al. 2007; Mahajan et al. 2009).

Also, the forms and availability of nutrients are related to moisture supply and the flooded condition improves both availability (favorable soil pH) and accessibility (nutrient 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 (Ponnamperuma 1984). In general, soil chemical properties are improved following submergence of the soil (Ponnamperuma 1984; Narteh and Sahrawat 1999). Lowland rice ecosystems provide a congenial environment for biological nitrogen fixation by a range of aerobic (in the flood water and aerated soil surface), facultative anaerobes and anaerobic bacteria (in the reduced soil system) (Ponnamperuma 1972, 1984; Sahrawat 1998, 2004b; Kyuma 2004; Koegel-Knabner et al. 2010).

The most important effect of submerging a soil under water is to cut the supply of oxygen. As a result, entrapped oxygen is quickly exhausted and the soil becomes devoid of free oxygen. The lack of free oxygen causes soil reduction and this is accompanied by a series of physical, chemical and biological processes that profoundly influence the quality of the soil as medium for growing rice or any other wetland crop (e.g. see Ponnamperuma 1972, 1984; Kyuma 2004; Koegel-Knabner et al. 2010).

Submerging an aerobic soil in water decreases its redox potential, which stabilizes at a range of +200 to −300 mV depending on the soil, particularly on the content and quality of organic matter and the presence and contents of reducible nutrient elements such as nitrate N (NO_3^-), manganic manganese (Mn^{4+}), sulfate (SO_4^{2-}) and especially ferric iron (Fe^{3+}) (Table 1). However, the redox potential of the surface water and the first few millimeters 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; Koegel-Knabner et al. 2010).

The soil redox potential (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 2). 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 or active iron (Sahrawat 2004a; Koegel-Knabner et al. 2010).

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

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

Note: [a]Adapted from Patrick and Reddy (1978).

Table 2. Range of redox potentials in which the main oxidized components in submerged soils become unstable[a].

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

Note: [a]Adapted from Patrick and Reddy (1978).

Fertility advantages of flooded rice system

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

Under submerged or flooded conditions, the pH of soils is generally stabilized in the neutral range (6.5–7.5) (Ponnamperuma 1972). Following submergence, the pH of alkaline soils decreases because under prevailing anaerobic conditions 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) as shown in Equation (1):

$$Fe_2O_3 + \tfrac{1}{2}CH_2O + 4H^+ \rightarrow 2Fe^{2+} + 5/2H_2O + \tfrac{1}{2}CO_2. \tag{1}$$

In these redox reactions, ferric iron (from amorphous ferric hydroxides) serves as an electron acceptor and organic matter (CH_2O) as the electron donor. This reaction results in the consumption of acidity and increase in the soil pH (Ponnamperuma 1984).

A decrease in the pH of alkali or calcareous soils is a result of the accumulation of carbon dioxide in flooded soil, which neutralizes alkalinity (Ponnamperuma 1972; Narteh and Sahrawat 1999). Moreover, the 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 neutralize alkalinity in the soil–flood water system (see Equations 2 and 3). Moreover, the submerged soil system provides an ideal environment for the reaction between carbon dioxide (carbonic acid) and alkalinity.

$$CO_2 + H_2O \rightarrow H_2CO_3 \tag{2}$$

$$H_2CO_3 \rightarrow H^+ + HCO_3^- \tag{3}$$

Thus, iron reduction and carbon dioxide concentration in the submerged reduced soil system play key roles 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 the submerging of soils benefits the lowland rice crop through the better availability of nutrients such as ammonium, phosphorus (P), potassium (K) and other exchangeable cations, which are mobilized in soil solution (Ponnamperuma 1984; Narteh and Sahrawat 1999).

Aluminum (Al) toxicity and other acid soil-related nutrient problems prevalent in upland soils (for review see Sahrawat 2009) are minimized or alleviated by soil flooding (Ponnamperuma 1972; Narteh and Sahrawat 1999). A summary of results gleaned from various literature sources on the influence of flooding on nutrient availability, is provided in Table 3.

Equally importantly, growing 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 growing a lowland rice crop keeps the salt-affected soils productive, even during the reclamation phase. During the reclamation of salt-affected soils, growing 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 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

Table 3. Changes in soil organic matter, availability of plant nutrients and other factors affecting plant growth under submerged and aerobic rice systems[a].

	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

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

the soil surface facilitates the leaching of salts (Gupta and Abrol 1990; Rao DLN and Pathak 1996; Qadir et al. 2007).

Organic matter (OM) 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 the OM 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 2004b; 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 conditions. 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 a continuous irrigated lowland rice system to sequester C and N over relatively short periods (Table 4) and were in accordance 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 a rice–wheat system in the Indo-Gangetic Plains have declined (Bhandari et al. 2002; Regmi et al. 2002). By contrast, prolonged submerged soil conditions stimulate SOM accumulation and C sequestration in wetland soils and sediments (Sahrawat 2004b; Sahrawat et al. 2005; Pampolino et al. 2008; Nayak

Table 4. Estimated soil organic carbon 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[a].

Cropping system	Rice–Rice	Maize–Rice
Soil organic C (kg ha^{-1})		
1993 wet season	19130 (827)	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)

Note: [a]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 a uniform application of P (26 kg ha^{-1}) and K (50 kg ha^{-1}) each season. Zinc (10 kg ha^{-1}) was applied uniformly in the 1993 wet season. Values in parentheses are standard errors.

et al. 2009). In a long-term (32-year) study of SOM sequestration in the rice–wheat and maize–wheat systems in Punjab (India), in both rice–wheat and maize–wheat cropping systems the application of farmyard 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 than 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 a change in land use from paddy 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 accordance 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 conditions (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 2004b). Clearly, prolonged cultivation of lowland rice permits the accumulation of SOM in submerged soils and sediments (for review see Sahrawat 2004b).

The decomposition of OM in aerobic soils is rapid in the presence of oxygen, which is the most efficient electron acceptor. However, in the absence of oxygen in flooded soils and sediments, the decomposition of OM depends on the availability of alternate electron acceptors such as NO_3^-, SO_4^{2-} or Fe^{2+}. Because iron is present in large 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 a net accumulation of OM (Sahrawat 2004b; Reddy and De Laune 2008).

Deficiencies in 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; hence its accumulation. In addition, the production of compounds in submerged soils and sediments that are toxic to microbial populations, also retard soil OM decomposition (Sahrawat 2004b).

The most important factor responsible for the net accumulation of OM in wetland soils and sediments is the high net primary productivity of these systems (Neue et al. 1997; Sahrawat 2004b). In essence, the slow decomposition of OM and higher net primary productivity of the flooded 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 the growth of the rice plant (Sahrawat 1983; Ponnamperuma 1984; Sahrawat and Narteh 2002). This may allow farmers to skip the basal application of N, and in some cases, reduce the application rates of P and K. The extent and release of ammonium and other cations and anions depend on soil chemical characteristics including pH, OM and texture (Ponnamperuma 1972; Sahrawat 1983, 2010; Narteh and Sahrawat 1999).

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 availability of plant nutrients. Soils with a moderate to high content of inherent or added organic matter can help bring soil pH into a neutral range, favoring nutrient uptake by wetland rice. The 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 by the reduced solubility of these metals as a result of increased pH. By contrast, the availability of S may be reduced due to the reduction of sulfate 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 3 for a summary of results on nutrient availability under flooded vs. aerobic rice soil conditions.

There are other disadvantages associated with certain tropical soils in humid regions that adversely influence the growth and production of lowland rice crops. For example, reducing conditions following the flooding of iron-rich, acid soils lead to the accumulation of excessive concentrations of ferrous iron in soil solution. The accumulation of excessive amounts of ferrous iron in soil solution could cause iron toxicity to lowland rice (for detailed discussions see reviews by Becker and Asch 2005 and Sahrawat 2004c). Also, submerged soils with a high level of OM or with added 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 3) shows that soil fertility and other associated advantages under submerged conditions generally outweigh those in aerobic rice conditions. In the longer term, these fertility advantages or disadvantages have cumulative effects on soil quality for growing rice, which in turn impact the sustainability of the production systems (Greenland 1997; Kyuma 2004).

Aerobic rice and soil fertility

The water shortages being experienced in some regions of Asia warrant exploring the adoption of water management practices that save water for growing rice. In this context, aerobic rice is emerging as an alternate agronomic production system that uses less water than traditional flooded rice production systems (Tuong et al. 2005; Bouman et al. 2007). The aerobic rice production system uses rice varieties that respond well to reduced water input in non-saturated and non-puddled soils under irrigated conditions (Humphreys et al. 2005; Atlin et al. 2006).

There are several constraints to the growing of rice in aerobic soils. The major constraints that need attention include:

(1) Variable water stress caused by farmers' lack of capacity to precisely manage the water regime around the field capacity level in rice fields (Bouman et al. 2007).

(2) Weed infestation under aerobic rice-growing conditions is high in non-flooded and non-saturated soils; the absence of a layer of free water on the

soil surface stimulates weed growth and weeds fiercely compete with the rice plant for water and plant nutrients (Rao AN et al. 2007; Mahajan et al. 2009).

(3) Soil infertility-related nutrient disorder and imbalance are found in aerobic acidic and alkaline pH soils (Ponnamperuma 1975; Yoshida 1981; Sahrawat 2009).

(4) Developing rice cultivars for growth in aerobic soils that can match lowland rice varieties under flooded conditions in terms of yield remains a challenge.

These and several other factors that constrain and influence aerobic rice growth and yield along with the management practices to alleviate these constraints are discussed in this section.

Aerobic rice does not benefit from the electrochemical and chemical changes that occur in soils when the rice crop is grown under flooded conditions (Ponnamperuma 1984; Narteh and Sahrawat 1999). The first and the foremost disadvantage to aerobic rice is the lack of amelioration and convergence of soil pH in the neutral range (Ponnamperuma 1984), as opposed to that in the flooded rice soils where the soil pH is adjusted in the neutral range (Ponnamperuma 1972). In short, aerobic rice faces ambient soil pH conditions that vary widely from acidic to alkaline because the rice crop is grown on a range of diverse soils (Yoshida 1981; Sahrawat 1983). Whereas the availability of the most plant nutrients is optimum in soils with pH in the neutral range (flooded soil), the availability of plant nutrients varies in soils with a wide range in soil pH (aerobic soil) (Yoshida 1981;Ponnamperuma 1984; Sahrawat 1998). Salient comparative results from the literature on the availability of major, secondary and micro-nutrients under flooded and aerobic soil conditions are summarized in Table 3.

The major difference between aerobic and flooded rice soil conditions is the absence of oxygen in submerged soils. This not only affects the availability of plant nutrients (Table 3), but has an overwhelming overall influence on the soil as a growth medium for the rice crop (Ponnamperuma 1984). In practical terms, extreme acidic or alkaline pH in aerobic soils causes complex nutrient disorders and imbalances in the root zone of plants because of the high concentrations of nutrients such as Al, sodium (Na) and calcium (Ca) (Foy 2002; Hiradate et al. 2007; Fageria and Baligar 2008; Sahrawat 2009). These acidity- or alkalininty-related soil infertility problems are major fertility constraints to the growth of a rice crop in aerobic or non-flooded soils (Ponnamperuma 1975; Sahrawat 2009).

For example, Ponnamperuma (1975) reported that Fe and P deficiencies were prevalent in mineral soils with pH in the neutral range, whereas on strongly acid soils, P deficiency and Mn toxicity were the likely toxic to aerobic rice. Deficiencies in Fe and Zn to aerobic rice on calcareous soils is well established (Ponnamperuma 1975; Yoshida 1981).

Moreover, the soil water regime also directly influences the availability and accessibility of nutrients by plant roots and both these factors are less favorable under aerobic than flooded conditions (Ponnamperuma 1975; Rao AN et al. 2007; Mahajan et al. 2009; Sahrawat 2009). For example, in high pH aerobic calcareous soils, the availability of micronutrients such as Fe and Mn is a serious problem and rice crops grown under upland aerobic conditions frequently suffer 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). By contrast, in acid upland soils, acid soil-related infertility is a major constraint in humid tropical regions. These soil infertility problems result from low pH, Al toxicity, P deficiency and low base saturation, and the interactions between various nutrient deficiencies and toxicities (Fageria and Baligar 2008; Sahrawat 2009).

Declines in yield resulting from continuous cropping in sequence of non-flooded or aerobic rice is a major constraint to the widespread adoption of aerobic rice technology in Asia. Shifts in the water regime from flooded to non-flooded or aerobic conditions influence the N availability and requirement of the crop. For example, Belder et al. (2005) reported from a field study that the amount of N unaccounted for was greater under aerobic irrigated conditions than under flooded conditions. It was concluded that there was a need to optimize the rate and timing of N application for efficient N nutrition of the rice crop. Similar results were reported by Nie et al. (2009) from a pot culture study.

It has been suggested that the form, rate and time of N application need to be optimized for satisfactory growth of the rice crop. Also, the 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 the application of dilute sulfuric acid) followed by the application of N improved both growth in rice plants under aerobic conditions in pots (Xiang et al. 2009). Nitrogen application was more effective 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 soil pH probably contributed to the decline in the growth and yield observed in monocropped aerobic rice (Xiang et al. 2009).

To achieve stability in the yield of aerobic rice at reasonable high level, the crop has to be a part of a diversified system to maintain soil quality and health and control pests and diseases, e.g. through the use of legumes in various cropping systems. Without diversification in the system, there is a potential threat to the sustainability of the system due to biological and soil chemical fertility constraints. For example, research has shown that although aerobic rice can yield 3–6 t ha^{-1} under tropical climatic conditions, the crop yield can suffer from immediate failure or a drastic decline (George et al. 2002; Atlin et al. 2006; Xie et al. 2008).

Several factors have been suggested as the causal agents, including 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).

Critical analysis of the results reported from diverse sites suggests that for aerobic rice on soils with pH values in the alkaline range, micronutrient imbalances, especially caused by deficiencies in Fe and Mn, seem to be 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 invades the rice plant roots (Coyne et al. 2004; Kreye et al. 2009). By contrast, soil submergence precludes the invasion of new roots by root knot nematode (e.g. see Coyne et al. 2004; Bridge et al. 2005). Moreover, under extended aerobic conditions during the growing 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 or flooded soils are well documented (De Datta 1981; Kyuma 2004). It is known that growing rice in a submerged state not only imparts stability to rice production by alleviating constraints such as water shortage and providing effective weed control (Ponnamperuma 1972, 1984; De Datta 1981; Mahajan et al. 2009), but the lowland rice system also forms 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 (Sahrawat 2004b; Koegel-Knabner et al. 2010). Wetlands also have a 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 (Sahrawat 2004b).

The literature on constraints to aerobic rice clearly highlights that the major constraints to sustaining high yields hinge on aspects related to the genetic potential of aerobic rice varieties to provide high yields, weed control, and the management of soil infertility problems caused by soil acidity- and alkalinity-related nutrient disorders and imbalances (Ponnamperuma 1975; Yoshida 1981; Mahajan et al. 2009; Sahrawat 2009). Equally importantly, aerobic rice faces variable water stress due to farmers' inability to precisely manage water at the field level (Bouman et al. 2007).

Although the potential yield of flooded lowland rice has increased substantially over the years, the maximum yield of aerobic rice has been reported to be 30–40% lower than that of flooded rice, and the reasons for the yield gap, whether inherent to the two systems or the result of using varieties with different yield potential, are unclear (Takai et al. 2006; Xue et al. 2008; Kato et al. 2009). The development of high-yielding aerobic rice varieties still is in its infancy, although efforts in this direction are being earnestly pursued (Takai et al. 2006; Peng et al. 2008; Kato et al. 2009).

Soil fertility-related constraints in aerobic rice are complex, varied, and site-specific in nature; and they range from overall depletion of soil organic matter and nitrogen to the availability of nutrients such as P in acid soils and micronutrients such as Mn and Fe in calcareous soils (Ponnamperuma 1975; De Datta 1981; Yoshida 1981; Sahrawat 2004b; Belder et al. 2005; Maruyama et al. 2005; Kreye et al. 2009; Nie et al. 2009; Xiang et al. 2009). To promote the spread of aerobic rice, site-specific solutions need to be found and made available to farmers.

An approach in which the adopted rice cultivars and water and nutrient management practices are integrated at the farm level seems more appropriate for sustainably enhancing the yield of aerobic rice-based production systems.

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