RESEARCH, REVIEWS, PRACTICES, POLICY AND TECHNOLOGY

Soil Fertility Advantages of Submerged Rice Cropping Systems: A Review

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ABSTRACT. Wetland rice production systems in Asia are making a major contribution to the global rice supply. Wetland rice cultivation is often cited as an example of a sustainable cropping system. Wetland or paddy rice growing involves land preparation by cultivating in the flooded or saturated state (puddling), followed by transplanting of seedlings in soils under submerged condition and growing of the crop until two to three weeks before harvest. In other rice-based cropping systems, the land is either dry- or flood-fallowed during the period between two crops. Afterwards, two or three crops of rice are grown in submerged soil condition. However, shortage of freshwater is becoming critical for this traditional lowland rice cultivation. Obviously, there is high potential in exploring rice cultivation under moisture regimes that save water and

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Journal of Sustainable Agriculture, Vol. 31(3) 2007
Available online at http://jsa.haworthpress.com

doi:10.1300/J064v31n03_03

also increase productivity. Such a situation provides an opportunity to critically analyze the fertility benefits of submerged rice cropping systems that would help facilitate in making a practical and right choice for growing of rice in future. The objective of this paper is to highlight the underlying principles, which govern the fertility advantages to submerged rice cropping systems. The advantages of growing rice in submerged soils include a general amelioration of chemical fertility, preferential accumulation of organic matter and improved availability of major, secondary and selected micronutrients. These soil fertility advantages benefit the long-term maintenance of soil fertility and sustainability of wetland rice systems. The paper emphasizes the potential of growing wetland rice in monsoon Asia, specifically in poorly drained, waterlogging-prone areas where the water table is shallow (within 30 cm of the soil surface).
doi:10.1300/J064v31n03_03 *[Article copies available for a fee from The Haworth Document Delivery Service: 1-800-HAWORTH. E-mail address: <docdelivery@haworthpress.com> Website: <http://www.HaworthPress.com>*

KEYWORDS. Aerobic rice and sustainability, amelioration of chemical fertility, lowland rice sustainability, organic matter accumulation, poorly drained soils, soil submergence and nutrient availability

INTRODUCTION

Wetland rice production systems in Asia are making a major contribution to the global rice supply (Cassman and Pingali, 1995). The wetland rice system is often cited as an example of a sustainable system (De Datta, 1981; FAO, 1994; Greenland, 1997). Growing of rice in submerged soils is an integral component of traditional, age-old technology in monsoon Asia (Kyuma, 2004). This method of rice cultivation involves land preparation by cultivating the land in 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 harvest of rice crop.

However, water shortage experienced in some regions of Asia is threatening the traditional system of lowland rice cultivation. Hence, there is a need for exploring alternate water management practices that save water and at the same time, increase water productivity. Water productivity is generally defined as the weight of economic yield or grains produced per unit of water input (rainfall plus irrigation) (Bouman et al., 2005).

The present water shortage situation for growing rice indeed presents an opportunity to critically analyze the advantages of submerged rice systems in maintaining soil fertility for a sustainable rice production. Therefore, the objective of this paper is to highlight the underlying principles that govern fertility advantages in submerged rice systems. Additionally, recent research developments on comparative evaluation of rice production under submerged and alternate submerged and non-submerged water regimes are reviewed.

RICE PRODUCTION UNDER FLOODED VERSUS NON-FLOODED WATER REGIMES

Before discussing the soil fertility of submerged rice cropping systems, it is important to assess recent research development on comparative evaluation of rice production under submerged and alternate water management practices (drained or alternate submerged and non-submerged) that have the potential to save water. This discussion attempts to put into perspective the role of soil submergence on rice productivity, which is based on sustainable fertility maintenance.

In some regions of Asia, lowland irrigated rice cultivation is increasingly threatened by freshwater scarcity and as a result, alternate water management practices are being proposed, considered and evaluated for rice culture. The various water-saving practices proposed and evaluated include: growing of rice under water-saturated soil condition (no free water on the surface) or under alternate submerged (flooding) and non-submerged water regimes (Tabbal et al., 2002; Belder et al., 2004). Recently, a new radical approach proposed, to reduce water inputs in rice, was to grow rice under aerobic soil conditions (aerobic rice) like an irrigated upland crop, for example, maize or wheat crop. The aerobic rice crop was grown in unpuddled, unsaturated soil without ponded water (Yang et al., 2005; Bouman et al., 2005). The rice crop was irrigated to keep the soil water content in the root zone up to the field capacity. More detailed descriptions of water management practice for aerobic rice cultivation are available in papers by Yang et al. (2005) and Bouman et al. (2005).

This section discusses the results of recent research on the evaluation of effects of various alternate non-submerged water regimes compared to submerged water regime on the performance of wetland rice in the field, as judged by yield, water-use efficiency and water productivity.

An earlier study found that when lowland rice variety (IR 20) was grown in aerobic soil under furrow irrigation at the International Rice Research Institute (IRRI) farm in the Philippines, water savings were 55% compared with flooded conditions, but the rice yield drastically decreased from about 8 t ha^{-1} under submerged water regime to 3.4 t ha^{-1} under aerobic condition (De Datta et al., 1973).

Several subsequent studies from Asia and elsewhere, also reported a range in the reduction of rice yields when lowland rice varieties were grown in aerobic soils compared to under flooded soil conditions (Blackwell et al., 1985; McCauley, 1990; Bouman and Tuong, 2001; Yang et al., 2005). The decrease in rice yields varied depending on the adaptability of the rice varieties to aerobic soils, management of macro and micro nutrients, management of weeds and diseases, such as nematodes in aerobic soil conditions (George et al., 2002; Coyne et al., 2004; Yang et al., 2005).

In general, it has been observed that alternate water management practices such as alternate submerged and non-submerged water regimes save water but reduce rice yields, especially on soils that are freely drained. However, the performance of rice crops on lowland sites that are poorly drained vary from those on freely drained upland sites. For example, in field studies, Diatta and Sahrawat (1997) showed that the performance of four rice varieties, along a toposequence in West Africa, was influenced by the presence or absence of a perched water table (within 30 cm of the soil surface). The presence of perched shallow water table in the growing season increased rice yields and biomass of upland and lowland rice varieties; the lowland rice cultivars outyielded the upland rice cultivars (Diatta and Sahrawat, 1997).

Belder et al. (2004) conducted field experiments under irrigated conditions at two sites, one each in China and the Philippines, to study the comparative effects of continuous submergence and alternate submerged and non-submerged water regimes at two rates of fertilizer N (with no applied N and 180 kg N ha^{-1}) on the performance of lowlandrice cultivars. The experimental sites had silty clay loam soils, shallow groundwater tables and low percolation rates. Grain yields of the hybrid and inbred rice varieties ranged from 4.1 to 5.0 t ha^{-1} with no applied N, and from 6.8 to 9.2 t ha^{-1} with 180 kg N ha^{-1}. Biomass and grain yields did not significantly differ between the two water regimes (continuous submergence and alternate submerged and non-submerged). The amount of water saved with alternate submerged and non-submerged water regime was small (6-14% of total water input and 15-18% of irrigation water input). Water productivity ranged from 0.5 to 1.48 kg m^{-3} of water input at the two sites. The relatively high values of water productivity even at low rice yields (compared with those reported by Bouman et al., 2005) were likely caused by a larger proportion of water being taken up from the shallow groundwater (Belder et al., 2004). There was no significant N by water interaction in the experiments; this was attributed to the particular hydrological conditions at the sites of field experiments. During the periods of non-submergence water regime, the soil remained close to saturation.

Belder et al. (2004) concluded that hydrological characterization and mapping of Asia's lowland rice areas was needed to determine the extent and magnitude of potential water savings that could be made without compromising on rice yield.

More research on improved rice cultivars adapted to aerobic growing conditions is needed. Crop and water management practices need to be developed for the growing of aerobic rice; and there is need to study the sustainability of aerobic rice under continuous cropping (George et al., 2002; Coyne et al., 2004; Bouman et al., 2005).

The results, from studies thus far, indicate that the yields of rice under aerobic soil conditions, with few exceptions on sites with shallow water table (Belder et al., 2004), are lower than those in flooded soils. The research issues relating to the potential of aerobic rice and its sustainability in Asia however, can only be judged by long-term studies in the future, although research in this important area by scientists at the IRRI (International Rice Research Institute) and their collaborators has begun in earnest (Bouman et al., 2005; Yang et al., 2005). The findings of the ongoing and future research should help formulate appropriate water management practices for growing rice with improved water-use efficiency and water productivity.

THE STABILIZATION OF pH IN THE NEUTRAL RANGE AND ITS IMPLICATIONS FOR NUTRIENT AVAILABILITY

Following submergence, the pH of acidic soils increase, while those of alkaline soils decrease (Ponnamperuma, 1972; Narteh and Sahrawat, 1999). The pH of acidic soils increases following submergence because under anaerobic conditions ferric iron is used as an electron acceptor for oxidizing organic matter and during this process acidity is consumed:

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

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

A decrease in the pH of alkali or calcareous soils is the result of accumulation of carbon dioxide in flooded soil, which neutralizes alkalinity. 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 in neutralizing alkalinity in the soil-floodwater system (see equations 2 and 3). Moreover, the submerged soil system provides an ideal environment for reaction between carbon dioxide (carbonic acid) and alkalinity.

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

$$H_2CO_3 + H_2O = H^+ + HCO_3 \qquad (3)$$

Thus accumulation of large amounts of carbon dioxide in submerged soils acts as an ameliorating agent by neutralizing the alkalinity. Adding carbonaceous materials, which generate extra carbon dioxide on decomposition, can enhance the generation of carbon dioxide, especially in soils low in organic matter. However, if the carbon dioxide produced is allowed to escape from the soil-water system it would result in increasing the pH of the soil-water system. Thus, iron reduction and carbon dioxide concentration play key roles in controlling the pH of submerged soils (Ponnamperuma, 1965, 1972). This requires an optimum temperature (between 25°C and 35°C) (Ponnamperuma, 1972), and the availability of easily decomposable organic matter, reducible iron, and other electron acceptors such as sulfate and carbon dioxide (Ponnamperuma, 1984; Sahrawat, 2004b).

The convergence of soil pH to neutrality following submerging of soils benefits wetland rice crop through better availability of nutrients such as ammonium, P, K and exchangeable cations, which are mobilized in soil solution (Ponnamperuma, 1965; Narteh and Sahrawat, 2000; Sahrawat and Narteh, 2002). Aluminum toxicity, which is a serious problem in acidic upland soils, is alleviated; and the acid-related soil infertility problems are reduced by soil submergence.

AMELIORATION OF SALT-AFFECTED SOILS

The growing of wetland rice in submerged soil has been recognized as a component of technology for the reclamation of salt-affected (saline, saline alkali and alkali soils) soils and for keeping these soils productive during the reclamation phase (for review see Gupta and Abrol, 1990; van Asten, 2003). During the reclamation of salt-affected soils, growing of a lowland rice crop allows ponding of water to facilitate leaching of salts after 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 leaching of salts.

GENERAL SOIL FERTILITY

Rice is a sub-aquatic plant, well adapted to flooded soils, and thus is able to derive the benefits following flooding of soil. However, upland rice is also grown in well-drained soils. Paddy rice is perhaps the only food crop, which thrives in submerged soils in monsoon Asia and other regions prone to seasonal or prolonged flooding. Except for germination of rice seed, the rice crop adapts well to submerged soil conditions and has a comparative advantage for growth and production in submerged lands. The adaptation of lowland rice to flooded conditions is due to the presence of aerenchyma or pore space in the rice plant that conduct air from leaves to roots (Ponnamperuma, 1965).

Submerged soils benefit rice crop by providing a more conducive environment for rice roots. The presence of free water on the soil relieves crop growth from water shortages, and improves the availability and accessibility of plant nutrients through mass flow and diffusion. Equally important, the submerging soil system provides effective weed control. 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. In general, soil chemical properties are improved following submergence. Paddy soils also provide a congenial environment for biological nitrogen fixation through a range of aerobic, facultative anaerobes and anaerobic bacteria (Magdoff and

Bouldin, 1970; Ponnamperuma, 1972, 1984; Reddy and Patrick, 1979; Yamaguchi, 1979; Kyuma, 2004; Sahrawat, 2004a).

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 a medium for growing rice or any other wetland crop. The influences of flooding on physical, chemical, and electrochemical properties of soil have been comprehensively researched and reviewed from time to time (Shioiri and Tanada, 1954; Ponnamperuma, 1972, 1984; Gambrell and Patrick, 1978; De Datta, 1981; Rowell, 1981; Yu, 1985; Sahrawat, 1998, 2004a,b; Narteh and Sahrawat, 1999; Kyuma, 2004).

Submerging aerobic soil in water decreases its redox potential, which drops and stabilizes at a fairly stable range of +200 to −300 mV depending on the soil, especially the content of organic matter and reducible nutrient elements (nitrate N, manganic manganese, sulfate and ferric iron), especially iron. However, the redox potential of the surface water and first few millimetres of top soil in contact with the surface water remains relatively oxidized in the redox potential range of +300 to +500 mV (Ponnamperuma, 1972). A range of redox potentials (Eh) is encountered in various soils from well-drained, aerated to waterlogged conditions (Table 1). 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 (Table 2). Soil reduction is influenced by the quality of the decomposable organic matter and the capacity of reduction is controlled by the quantity of easily reducible iron or active iron (Sahrawat, 1998, 2004b).

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

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

Adapted from Patrick and Reddy (1978).

TABLE 2. The range of redox potentials in which the main oxidized components in submerged soils become unstable.

Reaction	Redox potential (mV)
O_2–H_2O	+380 to +320
NO_3–N_2, Mn–Mn	+280 to +2220
Fe^{3+}–Fe^{2+}	+180 to +150
SO_4^{2-}–S^{2-}	−120 to −180
CO_2–CH_4	−200 to −280

Adapted from Patrick and Reddy (1978).

NUTRIENT AVAILABILITY

It has been shown that pre-flooding of soil for about four weeks prior to transplanting of the rice seedlings leads to the release of ammonium, phosphate, K and other exchangeable ions in soil solution, which are good for the growth of the rice plant. These may allow the farmer to skip the basal application of N; and reduce the amounts of P and K in some cases. The extent and release of ammonium and other cations and anions will depend on soil chemical characteristics including pH, organic matter and texture (Ponnamperuma, 1965, 1972; Narteh and Sahrawat, 1999, 2000).

Flooding is a great pH neutralizer in problem soils. This has brought about the neutralization of acidity in acidic soils and alkalinity in alkaline soils following flooding, thereby generally influencing favorably the release and availability of plant nutrients.

Soils with moderate to high content of inherent or added organic matter can help bring soil pH to neutral range, favoring nutrient uptake by wetland rice. Submergence of soil improves the availability of ammonium-N, P, K, Ca, Mg, Fe, 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 sulfur (S) may be reduced due to sulfate reduction in flooded soils. The supply of micronutrients such as copper (Cu) and molybdenum (Mo) is generally adequate. The availability of Zn is reduced in submerged soils.

There are also undesirable effects of flooding on the growth and production of the lowland rice crop. For example, reducing conditions following flooding of iron-rich, acidic soils leads to accumulation of excessive concentrations of ferrous iron in soil solution. This could cause iron toxicity to lowland rice (Sahrawat, 2004c). Also, submerged soils with high amount of organic matter or when 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 (Ponnamperuma, 1984; Kyuma, 2004). A summary of the generalized results of the influence of flooding on soil fertility and nutrient availability is provided in Table 3.

ORGANIC MATTER ACCUMULATION

The supply of organic matter and the availability of electron acceptors in submerged soils play critical role in deriving soil reduction and its benefits to the rice crop (Sahrawat, 2004b). Application of organic matter increases the supply of N. To sustain N supply, regular applications of fresh organic matter are necessary to maintain a pool of available N (Sahrawat, 1983).

TABLE 3. Changes in organic matter and availability of plant nutrients in soils following flooding.

Chemical property	Change(s) following soil submergence
Organic matter	Favors accumulation of organic C and N, but organic acids and sulfide can be toxic
pH	Favors convergence of pH to neutral range
Ammonium-N	Release and accumulation of ammonium favored
P	Improves P availability, especially in soils high in Fe and Al oxides
K	K availability improves through exchange of K
Ca, Mg, and Na	Favors release of Ca, Mg and Na in soil solution
S	Sulfate reduction may reduce S availability
Fe	Fe availability improves in alkali and calcareous soils, but Fe toxicity may occur in acidic soils high in reducible Fe
Mn	Solubility reduced
Cu, Zn and Mo	Improves availability of Cu and Mo, but not of Zn
Al	Al toxicity absent, except perhaps in acid sulfate soils
Reduction products	Production of sulfide and organic acids, especially in degraded soils may cause toxicity or injurious effects to growing rice plants

In soils with low organic matter, soil reduction slows down, thereby providing less benefits in terms of soil fertility under flooded condition (Sahrawat, 1998). Soil organic matter plays a dominant role in N supply to wetland rice because nearly half to two-thirds of N taken up by the rice comes from the soil organic matter pool (Sahrawat, 1983). Soils used for flooded rice production maintain a moderate level of N, even without application of N. This is due to the addition of N through biological fixation (De, 1936; Yamaguchi, 1979; Kyuma, 2004; Sahrawat, 2004a).

In addition to the favorable effects of soil submergence on fertility in general and N fertility in particular, wetland rice cultivation maintains or in some cases improves the organic matter status of paddy soils (Sahrawat, 2004a; Sahrawat et al., 2005). 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 (Sahrawat, 2004a).

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. This was shown in an experiment 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. Results of soil analysis showed a net gain in soil organic C and total N under the rice-rice system and a net decline under the maize-rice system (Table 4). Replacement of dry season flooded rice crop by maize caused a reduction in C and N sequestration in the soil. The results of this study demonstrate the capacity of continuous irrigated lowland rice system to sequester C and N during relatively short time periods.

Results from long-term experiments suggest that soil organic matter levels under rice-wheat system in the Indo-Gangetic Plains have declined (Abrol et al., 2000; Yadav et al., 2000; Bhandari et al., 2002; Regmi et al., 2002). On the other hand, prolonged submerged soil conditions stimulate organic matter accumulation and C sequestration in wetland soils and sediments (Mitsch et al., 1998; Bouchard and Cochran, 2002; Sahrawat, 2004a; Sahrawat et al., 2005).

In a recent study of long-term lowland rice and arable cropping effects on C and N status of eight Indian calcareous soils, Sahrawat et al. (2005) found that surface samples from sites under lowland rice double

TABLE 4. Estimated soil organic C (SOC) and total soil N (TSN) 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}	
SOC 1993 wet season	19130 (827)[2]	19222 (791)
SOC 1995 wet season	20973 (494)	19105 (403)
Change in SOC	+1843 (440)	−216 (502)
	Total soil N, kg ha^{-1}	
TSN 1993 wet season	1811 (47)	1771 (56)
TSN 1995 wet season	1863 (49)	1720 (29)
Change in TSN	+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.

cropping had greater organic C and total N content than those from soils under rice in rotation with an upland crop or other arable systems. The soil organic C:N ratio was higher in soil samples from sites under lowland rice compared with those under other arable systems, which had lower soil organic C:N ratios. Samples from soils under lowland rice system tend to have a narrower soil inorganic C:N ratio than those under arable cropping, indicating that the sites under paddy rice maintained a better pedoenvironment. These results are consistent with findings that sites under continuous wetland rice accumulate soil organic matter compared with sites under drained or arable systems (Sahrawat, 2004a).

Prolonged cultivation of lowland rice permits the accumulation of organic matter. For a detailed discussion of organic matter accumulation in submerged soils and sediments, readers are referred to a recent review by Sahrawat (2004a).

The decomposition of organic matter in aerobic soils is rapid in the presence of oxygen, which is the most efficient electron acceptor. On the other hand, in flooded soils and sediments in the absence of oxygen decomposition of organic matter depends on the availability of alternate electron acceptors such as nitrate, sulfate or ferric iron. Since iron is present in high amounts in rice soils, the ferric-ferrous iron redox reaction plays a dominant role in the oxidation of organic matter and its mineralization in submerged soils and sediments (Lovley, 1995; Sahrawat, 2002, 2004b). Compared with arable soils, the decomposition of organic materials in submerged soils is slower, incomplete and inefficient, leading to net accumulation of organic matter (Sahrawat, 2004a).

It has been observed that intensive cropping of soils with flooded rice and the submergence decrease the amount of easily reducible iron in the soil (Mahieu et al., 2002). Wetland soils that become deficient in electron acceptors such as easily reducible iron, may have reduced rates of organic matter oxidation and mineralization of soil organic N (Sahrawat and Narteh, 2001; Sahrawat, 2002; Roden and Wetzel, 2002).

Deficiencies of nutrients such as N, P and S affect the growth of bacteria, which in turn influence C fixation, storage and release in wetland ecosystems (Sahrawat, 2004a). The formation of recalcitrant complexes stabilizes organic matter, making organic matter less accessible for decomposition by microbial activity and hence its accumulation. In addition, the production of compounds in submerged soils and sediments, which are toxic to microbial population, also retard soil organic matter decomposition (McLatchey and Reddy, 1998; Olk et al., 1996; Kang and Freeman, 1999; Freeman et al., 2004; Sahrawat, 2004a).

It has been suggested that the most important factor responsible for net accumulation of organic matter in wetland soils and sediments is their high net primary productivity (Neue et al., 1997; Sahrawat, 2004a). In essence, slow decomposition of organic matter and higher net primary productivity of submerged rice soils lead to net accumulation of organic matter and N in submerged soils and sediments.

GREENHOUSE GAS EMISSIONS

A negative aspect associated with the addition of organic matter in various forms to submerged soils is that it may increase emission of greenhouse gases, especially methane. Reviews of recent literature are available providing in-depth discussions of various aspects related to methane emissions from rice fields and the mitigation options (Neue, 1993; Aulakh et al., 2001; Conrad, 2002; Sahrawat, 2004d,e).

Organic matter application contributes to general improved soil fertility and nutrient supply, and equally important to methane production in submerged rice soils. Also, in the recent years the area under flooded rice is showing a declining trend. With this scenario, the global methane emissions from rice fields are unlikely to increase in the future. Moreover, alternately submerged and non-submerged water regimes, proposed to save water and increase water productivity, can result in increased emission of nitrous oxide, especially from soils high in organic matter or fertilized with N. Nitrous oxide emission is generally very low or not detectable when the rice crop is grown under normal submerged conditions without draining or drying the soil during the growing season. In reduced soils, nitrous oxide formed is reduced to N_2 (Sahrawat and Keeney, 1986; Bronson et al., 1997). Moreover, nitrous oxide is a more powerful greenhouse gas than methane contributing toglobal warming (Mosier, 1998; Robertson et al., 2000; Sahrawat, 2004d).

PERSPECTIVES

The review of recent researches on the benefits of growing rice in submerged soils show that growing rice in submerged state not only imparts stability to rice production by alleviating water shortage, effective weed control, but also forms the basis for soil fertility and organic matter conservation and maintenance. Soil erosion is not a problem in wetlands and indeed in some cases (e.g., in the case of inland valley system) wetlands receive sediments from flowing water from the adjoining upland areas, which add to the organic matter and nutrient pools (Sahrawat, 1994).

Wetlands conserve soil fertility and organic matter by net gains through various physical, chemical and biological processes. Wetlands also have relatively large capacity to sequester and store organic matter (organic C and N) (Mitsch et al., 1998; Bouchard and Cochran, 2002; Bird et al., 2003). Carbon sequestration under soil submergence is the foundation of sustainable fertility maintenance in wetland rice soils (Sahrawat, 2004a) and is also a strategy to reduce atmospheric carbon dioxide concentration and mitigate climate change (Lal, 2004). However, this benefit of carbon sequestration is negated because the methane emissions from flooded rice fields result in net increased emissions of carbon. Therefore, the approach for net carbon sequestration in wetland rice soils should be in terms of carbon sequestration or carbon balance, it should not be isolated as only a carbon dioxide issue.

Net accumulation of organic matter in submerged soils provides a means to sustain fertility of wetland rice soils (Sahrawat, 1983). Soils under an upland production system or in a wetland-upland system in sequence are not as efficient as those under submerged conditions in maintaining soil fertility in general and organic matter in particular. Research also indicates that growing rice under alternate water management practices such as alternate submerged and non-submerged water regimes lead to rapid loss of organic matter and fertility; the lowland-upland systems in sequence, compared with the submerged rice system, have a negative effect on the accumulation of organic matter and general maintenance of fertility in the long term. In short, the maintenance of organic matter and fertility in soils under tropical upland conditions is more difficult to achieve than in soils under wetland rice conditions (Sahrawat, 1994, 2004a).

Based on review of recent literature on the fertility advantages of submerged rice systems, it is argued that wetland rice culture should be targeted to lands that are prone to submergence during the monsoon season or to lands that have shallow water tables (within 30 cm of the soil surface) during the rice-growing season. In such niches, wetland rice yields well by deriving the benefits of flooded soil; the wetland rice system also helps in maintaining fertility and sustainability of rice systems in the long term. It is hoped that information presented in this article will stimulate further research that would facilitate practical, informed decisions for the future growing of Asia's most important staple, rice.

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RECEIVED: 06/16/06
REVISED: 10/14/06
ACCEPTED: 11/08/06

doi:10.1300/J064v31n03_03

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