This article was downloaded by: *[Sahrawat, Kanwar L.]*
On: *8 April 2010*
Access details: *Access Details: [subscription number 920996192]*
Publisher *Taylor & Francis*
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK

Archives of Agronomy and Soil Science
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453776

Nitrogen mineralization in lowland rice soils: The role of organic matter quantity and quality

Kanwar Lal Sahrawat [a]
[a] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Global-Theme Agroecosystems, Patancheru (near Hyderabad), India

First published on: 03 November 2009

To cite this Article Sahrawat, Kanwar Lal(2010) 'Nitrogen mineralization in lowland rice soils: The role of organic matter quantity and quality', Archives of Agronomy and Soil Science, 56: 3, 337 — 353, First published on: 03 November 2009 (iFirst)
To link to this Article: DOI: 10.1080/03650340903093158
URL: http://dx.doi.org/10.1080/03650340903093158

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.informaworld.com/terms-and-conditions-of-access.pdf

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Archives of Agronomy and Soil Science
Vol. 56, No. 3, June 2010, 337–353

Taylor & Francis
Taylor & Francis Group

Nitrogen mineralization in lowland rice soils: The role of organic matter quantity and quality

Kanwar Lal Sahrawat*

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Global-Theme Agroecosystems, Patancheru 502 324, Patancheru (near Hyderabad), 502 324 India

(*Received 21 February 2009; final version received 2 June 2009*)

Ammonium production in wetland soils and sediments is the key process that impacts nitrogen (N) availability, wetland productivity and environmental quality. Significant relationships between organic matter content and mineralizable N have been reported for diverse groups of wetland rice soils. However, recent research also showed that in soils under intensified wetland rice production systems, the relationships between organic matter and mineralizable N are poor or not significant. The review of recent research suggests that both organic matter quantity and quality are influenced by prolonged submergence, which in turn affects mineralization and N supply in wetland soils. While organic matter quantity increases following prolonged submergence of soil; submergence also changes the chemistry and quality of soil organic matter, which influences N mineralization. The increase in N mineralization as a result of increase in organic matter quantity is countered by the change in the chemistry and quality of organic matter. The changes in chemical composition of soil organic matter and their influence on N mineralization in submerged soils are discussed with examples from recent research.

Keywords: ammonium production; organic matter fractions and N mineralization; retardation of ammonium release; wetland productivity

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

Introduction

Rice (*Oryza sativa* L.) is the main staple food in Asia, and the crop is typically produced on submerged soils. Indeed, lowland rice makes a major contribution to global rice supply and rice-rice system (where two or three rice crops are continuously grown each year on the same piece of land) is often cited as an example of sustainable production system (De Datta 1981; Sahrawat 2007). The main reason for sustainable maintenance of soil fertility in the lowland rice paddies is the conservation and accumulation of organic matter (organic carbon and nitrogen) under prolonged submerged soil conditions. The preferential accumulation of organic matter in submerged soils as compared to upland systems is primarily caused by slow, incomplete and inefficient decomposition of organic matter under anaerobic (lack of oxygen) condition; and this results in the net accumulation of soil organic matter (for detailed discussion see Sahrawat 2004b). On the other hand, the decomposition of organic matter is rapid in presence of oxygen (O_2) under upland crop or

*Email: klsahrawat@yahoo.com

ISSN 0365-0340 print/ISSN 1476-3567 online
© 2010 Taylor & Francis
DOI: 10.1080/03650340903093158
http://www.informaworld.com

lowland rice-upland cropping systems, resulting in the decline of soil organic carbon (Kyuma 2004; Sahrawat 2004b, 2007; Zhang and He 2004; Nishimura et al. 2008).

Submerged or lowland soils differ considerably from their arable counterparts in physical, chemical and biological properties. This distinction between submerged and arable soils is caused primarily by the absence or lack of molecular oxygen in the soil. Because of a layer of standing water, the diffusion of atmospheric oxygen into the soil is extremely slow. The oxygen entrapped in the soil-water system following the submergence of soil under water is quickly exhausted by microbial activity, and in a few days the submerged soil becomes devoid of free oxygen (Ponnamperuma 1972, 1984).

In submerged or wetland soils and sediments, because of the absence or lack of molecular O_2, nitrogen (N) mineralization, i.e., the conversion of organic N, stops at ammonium-N production (also termed ammonification). Unlike in submerged soils, in upland soils the ammonium formed is readily oxidized to nitrate via nitrite (termed nitrification).

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

Nitrogen mineralization or ammonification is defined as the biological transformation of organic N to ammonium, and the process can occur in either aerobic or anaerobic conditions. However, the ammonification or mineralization process is slower under anaerobic conditions due to less efficient and incomplete decomposition (White and Reddy 2001; Sahrawat 2004a). Ammonium-N is the most reduced form of inorganic N with an oxidation state of -3. Ammonium-N is stable under reduced conditions of wetland soils (Ponnamperuma 1972; Narteh and Sahrawat 1999; White and Reddy 2001).

Ammonification in wetland soils is carried out by a diverse group of heterotrophs (mainly bacteria). Moreover, because of the lack of oxygen, the oxidation of organic matter and the release of ammonium from organic N in submerged soils and sediments depend on the availability of other electron acceptors such as ferric iron and sulfate (D'Angelo and Reddy 1994; Lovley 1995; Sahrawat and Narteh 2001; Roden and Wetzel 2002; Sahrawat 2004a). Throughout this article, N mineralization or ammonification in submerged soils or sediments refers to ammonium production.

Nitrogen is the most important nutrient constraint to the productivity of lowland rice. According to Raun and Johnson (1999), worldwide N recovery efficiency for cereal production including rice is approximately 35%. The N recovery efficiency for lowland rice is even lower than that reported for other arable crops (De Datta 1981, 1986). Low N recovery efficiency means increasing economic loss of fertilizer N, especially with the escalating costs of fertilizer production. Moreover, inefficient use of soil and applied N is also of major concern due to the impact of N losses on environmental quality and un-sustainability of the production systems (Crutzen and Ehhalt 1977; Robertson et al. 2000; Tilman et al. 2002).

The mineralization of organic N or ammonium production is the key process for N nutrition of wetland crops such as rice; and it controls the overall net primary productivity of wetlands. Also, soil N supply in wetlands plays a dominant role in the N nutrition of wetland rice because about half to two-third of total N taken up by rice crop even in N fertilized rice paddies has its source from the soil N pool (Sahrawat 1983a).

For judicious use of externally applied N, which is a prerequisite for making production systems more efficient and maintaining environmental quality, it is imperative to assess the indigenous soil N supplying capacity. Measurement of mineralizable N in soils is used for assessing the soil's indigenous N supplying

capacity. However, most of the tests involving soil incubation for a few days to weeks are time consuming and not easily adapted to situations where rapid estimates of mineralizable N are needed for formulating N fertilization protocols.

For rapid evaluation of soil's indigenous N supply, chemical indices such as organic carbon (C) and total N have been proposed for assessing the N supplying capacity of wetland rice soils. This is based on the results that showed that organic C content in wetland soils is significantly correlated to mineralizable N (ammonium-N) produced under anaerobic (waterlogged) incubation in a wide range of wetland rice soils. Indeed, significant correlations of organic C with mineralizable N, yield, or N uptake of tropical wetland rice have been reported (Sahrawat 1983a). However, some reports, especially from intensified lowland rice systems, indicated poor or non-significant correlations of organic C and total N with mineralizable N, yield, or N uptake by wetland rice (Sims et al. 1967; Dolmat et al. 1980; Cassman et al. 1996; Adhikari et al. 1999).

The causes of variability in the relationship between organic C and mineralizable N have not been critically assessed, although such information could help in developing N management strategies for increasing N efficiency by crops such as rice as well as for maintaining environmental quality. Moreover, the relationship between organic matter and mineralizable N is a prerequisite for determining the N requirement of wetland production systems.

The objective of this paper, therefore, is to critically review the current literature on the role of organic matter quantity and quality on N mineralization in wetland rice soils and sediments. Throughout this paper, soil organic matter is meant to signify soil organic C and total N. The future research challenges in this important area including the role of organic matter chemistry and quality on N mineralization are also examined.

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

Organic N mineralization in submerged soils

Ammonium in waterlogged or anaerobic soils and sediments is produced by reductive deamination (conversion of amino acid-N to ammonia via saturated acids) of amino acids and degradation of purines, with ammonia, carbon dioxide and volatile fatty acids as the end products (Ponnamperuma 1972; Kyuma 2004). The N mineralization process or conversion of organic N to ammonia in anaerobic soil environments is carried out by heterotrophic microorganisms, mainly bacteria (Kyuma 2004).

A comprehensive review by Harmsen and Van Schreven (1955) covers the research on mineralization of organic N in the soil carried out up to early 1950s. However, a large part of the research reviewed in this paper pertains to arable or upland soils. Perhaps, the review paper by Harmsen and Van Schreven (1955) reflected the focus of soil N research on upland soils at that time, with little emphasis on organic N mineralization in wetland soils (Sahrawat 1983a, 1983b; Narteh and Sahrawat 1997).

A part of ammonium produced as result of the mineralization of organic N in submerged soils becomes a part of soil solution and the rest remains in the adsorbed phase on the soil exchange complex; and there is a dynamic equilibrium between ammonium in solution and in the adsorbed state (Ponnamperuma 1972; Narteh and Sahrawat 2000; White and Reddy 2001). In some submerged rice soils, a considerable portion of ammonia ($NH_3 + NH_4OH + NH_4^+$) may be found in the

solution phase, depending especially on the organic matter content and texture of the soil (Ponnamperuma 1972; Narteh and Sahrawat 2000). The N in the soil solution phase of submerged soils is a ready source of N to the growing rice plant (Ponnamperuma 1972) and forms an important part of the available N pools in wetland rice soils. However, in wetland rice soils rich in decomposable organic matter, very large amounts of ammonium-N in soil solution can be toxic to the young growing rice plant (Ponnamperuma 1972).

Factors influencing N mineralization

The ammonification of soil organic N in wetland soils and sediments is influenced by soil type, environmental and agronomic management factors. Among these factors, temperature, moisture regime, microbial activity and microbial biomass, pH, C:N ratio, redox potential, availability of electron acceptors, cation exchange capacity, amount and nature of clay, nature and amount of salts, inputs and nature of organic materials, soil organic matter content and quality and the supply of nutrients such as phosphorus (P) among others, are important for ammonium production in submerged rice soils (Broadbent 1979; Savant and De Datta 1982; Sahrawat 1983a; Updegraff et al. 1995; Clement et al. 1995; Ireneo et al. 1996; White and Reddy 2001; Li et al. 2003; Sano et al. 2006; Inamura et al. 2009). Temperature and moisture regime are perhaps the most important factors controlling the release of ammonium-N in submerged soils. Laboratory incubation studies show that the mineralization of organic N in soils under waterlogged condition increases with increase in temperature up to 50°C (Ponnamperuma 1972; Sahrawat 1983a, 1998b).

The mineralization of organic N in aerobic soils, on the other hand, results in the formation of nitrate-N as the final inorganic N; and nitrification has been reported to be more sensitive than ammonification to high temperature (for review see Sahrawat 2008). However, aerobic mineralization is equally influenced by content of organic matter and organic matter quality, microbial biomass, the inputs and quality of organic materials (Hassink 1992; Collins and Allinson 2002; Balkcom et al. 2009).

As mentioned in the introduction, ammonification or mineralization of organic N can take place under both aerobic and anaerobic conditions of drained and waterlogged soils, respectively. However, the decomposition of organic matter is less efficient and incomplete under anaerobic conditions of submerged soils and consequently the production of ammonium is slower under anaerobic conditions than under aerobic conditions (White and Reddy 2001; Sahrawat 2004b). Under aerobic conditions, oxygen is the most efficient electron acceptor involved in the decomposition of organic matter and the release of ammonium. While under anaerobic conditions the decomposition of organic N is dependent on the availability of alternate electron acceptors such as ferric iron and sulfate, which are far less efficient electron acceptors than O_2 is (Sahrawat 2004a).

Ammonium-N is the most reduced form of inorganic N and accumulates under submerged conditions because it is stable under reduced conditions of submerged soils. This is the reason why ammonium accumulates in wetland soils and sediments at times in toxic concentrations, especially in soils high in soil organic matter or when easily decomposable organic matter is added in high amounts (Ponnamperuma 1984; Narteh and Sahrawat 1999, 2000). On the other hand, in aerobic or well-drained upland soils, the ammonium formed is rapidly converted to nitrate via nitrite. As a result, nitrate is the dominant inorganic N form and ammonium is in the

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

transient phase in aerobic, upland soils (Savant and De Datta 1982; White and Reddy 2001; Sahrawat 2008).

However, nitrification can be supported at the rice plant root-soil interface in wetlands soils by O_2 transport through the air spaces or aerenchyma tissue of the stem and roots of rice plant. Under submerged conditions, the nitrate formed diffuses to the adjacent anaerobic zone of the flooded soil system where it is lost by denitrification. Indeed, Reddy et al. (1989) demonstrated the occurrence of nitrification-denitrification process in the root zone of three aquatic macrophytes: Rice (*Oryza sativa* L.), pickerel weed (*Pontederia cordata* L.) and soft rush (*Juncus effuses* L.) grown in submerged soil columns using ^{15}N labeled ammonium-N as the source of N. The detection of gaseous $^{15}N_2$ in the air above the flood water of the soil column with the three aquatic plants provided direct evidence of nitrification-denitrification in the root zone. On the other hand, such losses of N were not measurable in soil columns without the plants (Reddy et al. 1989).

The diffusion of O_2 into the soil is highly restricted by the column of flood water and this is further influenced by the depth of flood water. A greater depth of flood water further reduces the diffusion of O_2 into the floodwater-soil system. Moreover, the consumption of O_2 in the flooded soil system is high and the small amount of O_2 that reaches the soil is quickly exhausted; and the flooded soil becomes devoid of O_2. However, the transport of O_2 through the air spaces remains the mechanism to keep the rhizosphere at least partially oxidized (Reddy et al. 1978; Ponnamperuma 1984; Reddy and Patrick 1986; White and Reddy 2001).

Another important factor that greatly influences the ammonification in submerged soils is the redox potential (Lindau et al. 1989; White and Reddy 2001), which in turn is controlled by the quantity of organic matter and organic matter quality and loading of alternate electron acceptors (Narteh and Sahrawat 1999; White and Reddy 2001; Sahrawat 2004a, 2004b; Alewell et al. 2008).

It has been shown that redox potential has impact on organic N mineralization in flooded soils; and aerobic mineralization of a wetland soil was 4, 7 and 12 times greater than that under nitrate-reducing, sulfate-reducing, and methanogenic conditions, respectively (White and Reddy 2001). The N mineralized in surface samples (0–10 cm) of wetland soils after 15 days of incubation followed the order: Oxygen or aerobic (143 mg kg^{-1} soil) > nitrate reducing redox potential (17 mg kg^{-1} soil) > sulfate reducing redox potential (9 mg kg^{-1} soil) > methanogenic redox potential (5 mg kg^{-1} soil) (White and Reddy 2001). Clearly, the mineralization of organic N was influenced by the degree of soil reduction measured by redox potential; and amount of mineralized N released was highest under aerobic condition and the lowest under highly reduced conditions (methanogenic). A range of redox potentials are found in wetland soils (Table 1)

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).

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

depending on the soil moisture regime, quantity and quality of organic matter and the loadings of electron acceptors (Ponnamperuma 1972; Sahrawat 1998a, 2004a). The loadings of electron acceptors such as O_2, nitrate, ferric iron, sulfate and carbon dioxide influence redox potential in submerged soils; and the reduction process in submerged soils follows the sequence: Oxygen, nitrate, manganese, iron, sulfate and carbon dioxide (Table 2).

Sahrawat (1998b) studied the mineralization of soil organic N in the profiles of an Alfisol (Udic Rhodustalf) and a Vertisol (Typic Palustert). Three versions of anaerobic incubation procedure were used to determine the production of ammonium; they involved the incubation of soil samples at 30°C for 14 days, at 40°C for 7 days, and 50°C for 2 days (Sahrawat 1998b). The results showed that the rates of N mineralization increased with increase in temperature from 30–50°C; and the rate of ammonium-N released from the soil organic matter was highest in the Ap horizon compared to other soil sub-horizons of the two soils. The rates of ammonium production in the lower horizons of the Vertisol profile were similar and showed little variability, whereas the rate of ammonium production decreased gradually with soil depth in the Alfisol profile. The temperature coefficients, or Q10 values, for soil N mineralization in the profiles of the Alfisol and Vertisol soils in the temperature range of 30–40°C and 40–50°C varied from 2.2–2.8 (Sahrawat 1998b).

Soil drying followed by flooding enhances soil N mineralization. For example, Sahrawat (1981a) found that in permanently waterlogged Histosols from the Philippines, there was virtual absence of N mineralization. However, air-drying of the soils, before incubation under anaerobic conditions, led to a surge in the release of ammonium-N. Similarly, imposing of alternate flooding and drying moisture regimes on mineral wetland rice soils enhanced soil N mineralization (Sahrawat 1980; Savant and De Datta 1982). The drying effect on the mineralization of soil N and its availability to growing plants in paddy rice in the field was reported by Shiga and Ventura (1976) and Sahrawat (1981b).

Although soil characteristics such as pH, cation exchange capacity (CEC), clay and reducible iron may not be directly significantly correlated to N mineralized under anaerobic condition, the inclusion of these soil properties along with organic C or total N, using multiple regression or principal component analysis, have been found to improve the prediction of mineralizable N in a range of wetland rice soils from Asia and West Africa (see, e.g., Sahrawat 1983b; Narteh and Sahrawat 1997).

In a study of 15 rice soils from the humid zone in West Africa, it was found that ammonium production under anaerobic incubation was controlled by organic C and reducible iron extracted by EDTA or ammonium oxalate (Sahrawat and Narteh

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
$NO_3^- - N_2$, $Mn^{4+} - Mn^{2+}$	+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

*Adapted from Patrick and Reddy (1978).

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

2001, 2003). The inclusion of EDTA or ammonium oxalate extractable (a measure of reducible iron) iron with organic C improved the prediction of ammonium production in diverse West African rice soils (Sahrawat and Narteh 2003). Clearly, in wetland soils and sediments, which generally are rich in iron, the reducible iron plays an important role as an electron acceptor in the oxidation of organic matter and the release of ammonium-N and other nutrients (Lovley 1995; Sahrawat 2002, 2004a; Sahrawat and Narteh 2002).

In addition to soil and environmental factors, the incorporation of organic matter as crop residues (e.g., rice straw) or in any other form influences soil N mineralization. For example, Acharya (1935) demonstrated that, although the decomposition of crop residues was slower under anaerobic condition, the net immobilization and nitrogen factor were lower for the anaerobic decomposition than for aerobic decomposition.

Among the organic matter-related factors, both quantity and quality of organic matter are important for ammonium production and N supplying capacity. In practical terms, the quantity and quality of organic matter (e.g., C:N ratio, lignin content, lignin:N ratio) added influence ammonium production and N availability in submerged soils and sediments (Mitsuchi 1974; Savant and De Datta 1982; Sahrawat 1983a; Updegraff et al. 1995; Kumar and Goh 2000; Kyuma 2004).

Agronomic management factors that influence ammonification in submerged rice soils include land preparation and tillage practices, soil drying, cropping pattern, especially those involving other upland crops, nature and length of the fallow period and the applications of amendments including nutrients, liming materials, pesticides and other agricultural chemicals (De Datta 1981; Savant and De Datta 1982; Sahrawat 1983a). The preparation of land by puddling (cultivation of soil in the flooded or saturated state) has been reported to stimulate soil N mineralization, as do other tillage operations (Kyuma 2004). Similarly, soil drying during the fallow period has also been found to enhance organic matter oxidation and the release of mineral N (De Datta 1981; Sahrawat 1983a; Calderon and Jackson 2002; Kyuma 2004).

From this discussion on the factors influencing ammonium production in submerged soils and sediments, it can be summed up that the main environmental factors that govern the decomposition of organic matter and release of ammonium-N, which also govern the primary productivity of wetlands, include temperature, water regime and the availability of electron acceptors (in anaerobic conditions) (Sahrawat 2004a, 2004b; Kyuma 2004).

Organic matter quantity and soil organic nitrogen mineralization in submerged soils

The results of studies made with a number of diverse sets of wetland soils from Asia showed that ammonium produced under waterlogged incubation is significantly correlated with organic matter, as determined by organic C and total N (Sahrawat 1983a). Ponnamperuma and Sahrawat (1978) reported that the N-supplying capacity of 506 diverse wetland rice soils from the Philippines, measured by anaerobic incubation, ranged from 13–637 mg N kg^{-1} soil, and the mineralized N was highly significantly correlated with soil organic C.

Sahrawat (1983a) reviewed literature on the N-supplying capacity of rice soils. Based on the review of results for more than 750 diverse soils from the Philippines, he reported that ammonium-N produced under waterlogged incubation was highly

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

significantly correlated with organic C and total N content. The results on the correlation between ammonium-N produced under anaerobic incubation and organic C and total N content of 885 lowland Philippine soils are summarized in Table 3.

In a study of organic N mineralization under waterlogged incubation in 39 diverse wetland rice soils from the Philippines, it was found that ammonium-N produced was highly positively correlated with organic C ($r = 0.91$, $p < 0.01$) and total N ($r = 0.94$, $p < 0.01$). The soils had a wide range in ammonium-N produced and the mineralized N formed, termed 'N mineralization quotient', varied from 1.8–26.0% of the total N (Sahrawat 1983b). The N mineralization quotient is defined as the percentage of total N mineralized during a defined period of time in a study in laboratory, greenhouse or field conditions. The results also showed that C/N ratio of the soils was significantly negatively correlated to mineralizable N. Although, simple correlation study showed that soil pH, cation exchange capacity (CEC), and clay were not significantly correlated to mineralizable N, multiple regression analyses showed that the inclusion of these soil characteristics improved the prediction of ammonium production over that predicted by organic C or total N alone (Sahrawat 1983b).

Zhu et al. (1984) reported results of experiments made to determine the influence of organic matter and other soil properties on the mineralization of soil organic N in 68 soil samples from the Tai Lake region of China. Anaerobic incubation method was used to determine mineralizable N. The soil samples had a range in mineralizable N, which varied from 80 to 160 mg N kg^{-1} soil. The mineralizable N constituted 0.8–7.6% of total soil N. The mineralized N was significantly correlated to total N ($r = 0.689$; $p < 0.01$; $n = 68$); and there was a significant negative correlation between mineralization percentage and soil pH ($r = -0.542$; $p < 0.01$; $n = 68$; soil pH ranged from 5.6–8.5). A significant positive correlation was also observed between mineralizable N and amorphous iron oxide ($r = 0.46$; $p < 0.01$; $n = 59$; soil amorphous iron oxide varied from 0.27–2.19%). Amorphous iron oxide participates in ferric-ferrous redox reactions; and ferric iron acts as an electron acceptor in organic matter decomposition and release of ammonium-N (Sahrawat 2004a). Moreover, the amorphous iron in tropical rice soils is also involved in the sorption or fixation of ammonium, especially during submerged-nonsubmerged water regimes (Sahrawat 1979).

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

Table 3. Correlations between ammonium-N produced under anaerobic incubation and organic C and total N content of 885 Philippine rice soils.

No. of soil samples	Correlation coefficient (r)		References
	NH_4^+ vs. organic C	NH_4^+ vs. total N	
483	0.72	0.79	IRRI (1973)[a]
280	NA[b]	0.79	IRRI (1978)[a]
43	0.86	0.85	Gaballo (1973)[a]
39	0.91	0.94	Sahrawat (1983b)
31	0.81	NA	IRRI (1964)[a]
9	0.90	0.91	Sahrawat (1982a)[a]

[a]These references are cited in Sahrawat 1983a; [b]NA, not available. Source: Adapted from Sahrawat (1983a).

Narteh and Sahrawat (1997) reported similar results on the influence of soil characteristics, especially pH, CEC, and easily reducible iron, on the mineralizable N in 15 diverse West African rice soils. The potentially mineralizable N released in the 15 West African rice soils under waterlogged incubation varied from 21–166 mg kg^{-1} soil; the mineralized N released was highly positively correlated with soil organic C ($r^2 = 0.62$, $p < 0.01$) and total N ($r^2 = 0.62$, $p < 0.01$). The mineralizable N released under waterlogged incubation constituted 2–7% of total soil N (Narteh and Sahrawat 1997).

Manguiat et al. (1996) studied the N mineralization potential using anaerobic incubation method in 30 diverse flooded rice soils from the Philippines, Indonesia, Malaysia and Thailand. The soils had a wide range in pH (4.6–7.9), organic C (0.39–2.55%) and total N (200–2800 mg N kg^{-1}). The results showed that the mineralizable N was significantly related to organic C, total N, soluble carbohydrates and microbial biomass; the correlation coefficients of soluble carbohydrates with N mineralization were the largest. However, the results indicated that the prediction of N mineralization from soil properties was highly variable and not satisfactory. These results are in accord with those earlier reported by Inubushi and Wada (1987) who found that the quantity of water-soluble carbohydrates was closely related to N mineralizable potential of easily decomposable organic matter in lowland rice soils.

A study of the relationships of indigenous N supply in lowland rice soils, determined by anaerobic incubation of soil samples using an ion exchange capsule procedure, with organic C and total N in surface soils of a long-term experiment at 11 sites in Asian countries, showed that ammonium-N released in soil samples was poorly correlated with soil organic C or total N (Cassman et al. 1996). It was hypothesized that inputs of N from sources other than N mineralization of organic matter and the differences in soil organic matter chemistry and quality related to intensive cropping in submerged soils influenced the relationships between mineralized N and soil organic matter (Cassman et al. 1996).

The results by Cassman et al. (1996) support the findings from field studies, which showed that soil organic C or total N was a poor predictor of N supply to the rice crop (Sims et al. 1967; Dolmat et al. 1980; Adhikari et al. 1999).

The review of research indicates that organic matter quantity, as measured by organic C and total N, plays a critical role in contributing to the pool of mineralizable N in paddy soils. It is also clear that in addition to organic C and total N or organic matter, other soil properties directly or indirectly impact and contribute to the release of mineralizable N. A review of selected literature on the relationship between N mineralization and organic C or total N in submerged rice soils clearly suggest a close relationship between organic C or total N and N mineralization under anaerobic conditions. However, some research does indicate weak or non-significant relationship between N mineralization and organic C or total N (Table 4). But as can be seen from the review of literature, the majority of the authors have reported a close relationship between N mineralization and organic matter as measured by organic C and total N. It should, however, be noted that organic matter is the substrate for ammonification or mineralization, but also other factors, especially those related to the nature or quality of organic matter (easily decomposible fraction of soil organic matter), are important. Moreover, N mineralization is also greatly modified by soil characteristics including soil status relative to nutrients other than N and environmental factors (Sahrawat 1983a, 2004a, 2004b; Inubushi and Wada 1987; Ireneo et al. 1996).

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

Table 4. Selected references on the relationships between N mineralization and soil organic C or total N in submerged rice soils.

Authors	Main findings of the study
Ponnamperuma and Sahrawat (1978)	N mineralization in 506 diverse soil samples, collected from lowland rice soils from the Philippines, was significantly correlated to soil organic C and total N.
Sahrawat (1983b)	N mineralization in 39 lowland rice soils, collected from the Philippines, was significantly correlated to organic C and total N. Anaerobic incubation test was used for determining N mineralization.
Zhu et al. (1984)	N mineralization in 68 soil samples, collected from Tai Lake region of China, was significantly correlated to total N
Narteh and Sahrawat (1997) and Sahrawat and Narteh (2003)	N mineralization in 15 lowland rice soils, collected from the West Africa region, was significantly correlated to organic C and total N. The correlation was further improved by the inclusion of reducible iron in the regression analysis (Sahrawat and Narteh 2003).
Mangiuat et al. (1996)	N mineralization in 30 lowland rice soils, collected from the Asian countries, was significantly correlated to organic C and total N, but the prediction of N mineralization was influenced by the amount of easily decomposable organic matter.
Cassman et al. (1996)	N mineralization in soil samples, collected from 11 sites under submerged rice in Asia, was poorly correlated to organic C and total N. N mineralization was measured using an ion exchange capsule procedure.
Nguyen et al. (2004a)	N mineralization in soil samples, collected from 12 sites under continuous submerged rice culture in Asia, had a weak simple correlation with organic C. The correlation between N mineralization and soil organic C or total N was curvilinear in nature.
Pampolino et al. (2008)	N mineralization in soil samples, collected from four long-term experiments under submerged rice, was significantly correlated to soil organic C and total N. N mineralization pool in the surface soil was maintained by balanced fertilization of lowland rice under irrigated conditions.

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

Moreover, the role of organic matter in contributing to mineralizable N is modified by the changes in the chemistry and quality of soil organic matter by prolonged submergence, as found under continuous lowland rice cropping systems. Obviously, both organic matter quantity and quality contribute to mineralizable N pools. The next section discusses the role of organic matter chemistry and quality on N mineralization in submerged soils and sediments.

Organic matter quality and soil nitrogen mineralization in submerged soils

Evidently, the role of organic matter quantity on organic N mineralization in submerged soils and sediments is modified by the quality of organic matter; and the

change in the chemistry and quality of organic matter are brought about by prolonged submergence, for example, in soil under continuous rice cropping systems. The influence of soil organic matter composition or quality on mineralizable N, although of critical importance, has not received the research attention it merits (Cassman et al. 1996; Witt et al. 2000; Olk et al. 2007).

Nevertheless, research reported by Yonebayashi and Hattori (1986) and Olk et al. (1996) indicated that the proportion of soil organic N fractions and chemical structure of specific soil organic matter pools and the chemical environment of submerged soil have a far greater influence on the mineralization of N, especially on the slow-phase N mineralization rates, than that by soil organic C or total N. Indeed, Devêvre and Howarth (2001) and Bird et al. (2003) reported that the stabilization of applied organic matter and fertilizer N in the humic fractions of organic matter in submerged conditions of lowland rice soils influenced mineralization of organic N and release of ammonium-N.

The retardation of soil organic N mineralization is caused by formation of stable complexes of humic substances with cations such as ferrous iron that protects the humic substances from degradation (Schnitzer and Skinner 1966; Kalbitz et al. 2005). Moreover, the accumulation of lignin and the subunits of lignins, which are resistant to degradation in the absence of oxygen, contribute to the changes in chemistry and quality of organic matter in submerged soils (Colberg 1988; Olk et al. 1996, 2002). Also, accumulation of phenol in the mobile humic acid fraction of soil organic matter has been linked to the retardation of N mineralization in tropical lowland rice under continuous wetland rice cropping (Olk 2006).

Schmidt-Rohr et al. (2004) studied the mobile humic acid fraction extracted from two similar soils on the research farm of the International Rice Research Institute in Los Banos, Laguna, Philippines. One soil has been triple-cropped to irrigated lowland rice for 30 years before sampling; the other soil had been annually to dryland rice under rainfed conditions for at least 30 years. The results revealed that almost 45% of the N was bonded to aromatic carbons, whereas this fraction was less than 30% of total N in the dryland mobile humic acid fraction. The mobile humic acid fraction from the submerged rice soil was also rich in lignin-derived residues ($>45\%$). In comparison, the mobile humic acid fraction from the dryland rice soil had less than half the content of lignin and anilide N. Because N bonded to an aromatic ring is not readily mineralized and thus is less available to rice plant. It was suggested that the significant excess of anilide N in the mobile humic acid fraction of the triple cropped, submerged rice can explain the rice yield decline (Schmidt-Rohr et al. 2004), earlier reported by Cassman et al. (1995).

Moreover, the stabilization of soil organic matter by formation of complexes with lignin and lignin derivatives in submerged soils is the reason not only for preferential accumulation of organic matter in submerged soils (Sahrawat 2004b), but also for poor or nonsignificant correlations between organic matter (organic C and total N) and mineralizable N, mainly due to changes in the chemistry and quality of organic matter in intensified wetland rice soils (Nguyen et al. 2004b).

Nguyen et al. (2004a) studied the influence of two humic acid fractions, mobile humic acid and calcium humate, on N mineralization in lowland rice soils of the Philippines and Vietnam. The prediction of N mineralization parameters was improved with the inclusion of properties of two distinct humic acid fractions, the mobile humic acid and calcium humate, which together contained 15–30% of total soil N. The results further showed that the degree of humification in these humic acid

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

fractions was negatively associated with net N mineralization, suggesting that more recalcitrant forms of these humic acids are formed under anaerobic conditions, which result in retarded rates of N mineralization per unit of accumulated N in mobile humic acid and calcium humate pools.

The results by Nguyen et al. (2004a, 2004b) clearly demonstrated the relevance and role of extracted humic acid fractions on soil N mineralization and N supply to wetland rice in intensified, irrigated systems of tropical Asia. The results further showed that mobile humic acid and calcium humate fractions of soil organic matter are significant contributors to N mineralization in lowland rice soils, as measured by anaerobic incubation procedure. Also, the rate of N mineralization in these humic acid fractions in submerged soils is controlled by their chemical composition (Nguyen et al. 2004a, 2004b). Nitrogen mineralization is retarded by reduced and incomplete humification of soil organic matter, whereas the decreased humification of soil organic matter enhances the accumulation of organic matter in submerged soils (Sahrawat 2004b). Similarly, the stabilization of soil organic matter results in organic matter accumulation, but at the same time it reduces the availability of soil organic matter for decomposition, leading to reduced rate of release of ammonium-N. Also, the accumulation of phenol in the mobile humic acid fraction of soil organic matter is reported to inhibit the mineralization of soil organic N (Olk 2006). It is suggested that the chemical fractionation is suitable for studying N dynamics, especially in wetland rice soils enriched in phenolic compounds, for establishing linkage of soil organic matter with chemical composition (for review, see Olk 2006).

Pampolino et al. (2008) studied the changes in soil carbon and nitrogen under long-term continuous lowland rice. The authors sampled four long-term experiments in the Philippines, with two or three rice crops grown each year with continuous soil submergence, to determine the effects of nutrient management on long-term changes in soil C and N, N balance and anaerobic nitrogen mineralization potential. The result showed that anaerobic N mineralization in the top soil was maintained during 15 years of continuous rice cropping with N-P-K fertilization in all four experiments. The results also suggested that continuous cultivation of irrigated rice on submerged soils maintained or increased soil organic matter and maintained soil N-supplying capacity. It was concluded from the study that submerged soils can sustain a long-term N-supplying capacity even when cultivated intensively with two or three rice crops per year. More importantly, the results of this study across four experiments found consistently no evidence for a net decline in N-supplying capacity during 15 years of continuous cropping (Pampolino et al. 2008).

Discussion and perspectives

The review of literature on the role of organic matter quantity and quality (chemical composition) on N mineralization in lowland soils shows that: (i) Significant relationships between ammonium-N produced under anaerobic incubation and organic C and total N content in wetland rice soils have been reported with diverse sets of lowland rice soils (see e.g., results in Table 3), and that (ii) the role of soil organic matter quantity in intensified, irrigated lowland rice systems is modified by changes in the chemical composition of soil organic matter. The continuous growing of lowland rice crop on the same piece of land for prolonged period leads to the accumulation of organic matter with decreased humification of the organic matter. It has been reported that lowland rice soils had a lower proportion of extractable

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

humus in total C than upland soils. Lowland rice and upland soils differed in the composition of humic acids in the soil layers below the layer that had accumulated iron. Furthermore, the humification degree of the sodium pyrophosphate-extractable humic acids decreased with depth in the upland soils, but was high even in deeper layers of Japanese lowland paddy soils (Maie et al. 2000). However, it should be noted that the humification process in soils is affected by climatic conditions, especially soil water regime and temperature, and the humification processes in soils of the tropical climates may differ from those in temperate climates (Haider 1992; Sahrawat 2004b). Nevertheless, prolonged soil submergence has an over-riding influence on humification of soil organic matter (Sahrawat 2004b).

It has been hypothesized that prolonged submerged soil conditions as found in rice paddies, where two or three crops of lowland rice have been grown over a long period, the changes in the chemistry or quality of organic matter lead to retarded rates of organic matter mineralization and release of ammonium-N (Olk et al. 1996, 2002, 2007). For example, Olk et al. (2007) showed that at site, where lowland rice crop has been grown continuously for prolonged periods, phenol that accumulated in a young humic fraction in the soil was associated with the retardation of soil N mineralization from that fraction during the rice growing season. It was postulated that decreased N mineralization was caused by covalent binding of soil organic N with the phenols, resulting in the formation of N compound that is more recalcitrant under submerged conditions of lowland rice than are other organic N compounds (Schmidt-Rohr et al. 2004; Olk et al. 2007). This organic N fraction was found to decompose very slowly and hence the release of ammonium-N was retarded as compared to soil under lowland rice upland cropping systems (Schmidt-Rohr et al. 2004; Olk et al. 2007). Thus, according to these authors, the changes in organic matter chemistry probably provide a plausible explanation for the poor or nonsignificant relationships between organic matter and mineralizable N in soils that remain in prolonged submergence state. The results of this research also showed that the inclusion of properties of humic acid fractions that contribute to N mineralization improved the predictability of mineralized N in lowland rice soils (Schmidt-Rohr et al. 2004).

However, recent study of organic N mineralization in soils under continuous long-term lowland rice culture at four locations in the Philippines (Pampolino et al. 2008) showed that the anaerobic N mineralization in the top soil was not retarded but maintained during 15 years of continuous rice cropping in all four experiments. These results do not support the hypothesis that the mineralization of organic N is retarded by continuous long-term lowland rice culture as put forward by Schmidt-Rohr et al. (2004) and Olk et al. (2007). The authors (Pampolino et al. 2008) suggested that continuous cultivation of irrigated rice with balanced fertilization on submerged soils maintained or slightly increased soil organic matter and maintained soil N supplying as measured by anaerobic incubation method. Probably, balanced fertilization helped not only in maintaining the soil organic matter level but also alleviated the problem related to the retardation in soil N mineralization as observed by Olk et al. (2007).

Obviously, more research is needed in the future to further elucidate the role of the chemistry of soil organic matter fractions that contribute to N mineralization. Also, the role of balanced fertilization and addition of fresh organic matter appear to influence the decomposition of soil organic matter and N mineralization in continuously submerged rice soils, where two or three crops of rice are grown on a long-term basis (e.g., see Sahrawat 2004b).

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

Conclusion

Ammonium production in wetland soils is the key process, which impacts N availability, wetland productivity and environmental quality. Organic matter is the substrate for N mineralization; and both organic matter content and quality influence the N mineralization process. A large body of literature suggests that generally organic matter is correlated to potential N mineralization in wetland soils and sediments. While organic matter quality impacts N mineralization, the results are contradictory and there is a need to further elucidate the role of the chemistry of soil organic matter on N mineralization in wetland rice soils maintained under prolonged submerged condition.

References

Acharya CN. 1935. Studies on the anaerobic decomposition of plant materials. III. Comparison of the course of decomposition under anaerobic, aerobic, and partially aerobic conditions. Biochemical J. 29:1116–1120.

Adhikari C, Bronson KF, Panuallah GM, Regmi AP, Saha PK, Dobermann A, Olk DC, Hobbs PR, Pasuquin E. 1999. On-farm soil N supply and N nutrition in the rice-wheat system of Nepal and Bangladesh. Field Crops Res. 64:273–286.

Alewell C, Paul S, Lischeid G, Storck FR. 2008. Co-regulation of redox processes in freshwater wetlands as a function of organic matter availability? Sci Total Environ. 404:335–342.

Balkcom KS, Blackmer AM, Hansen DJ. 2009. Measuring soil nitrogen mineralization under field conditions. Communic Soil Sci Plant Anal. 40:1073–1086.

Bird JA, van Kessel C, Horwath WR. 2003. Stabilization of ^{13}C-carbon and immobilization of ^{15}N-nitrogen from rice straw in humic fractions. Soil Sci Soc Am J. 67:806–816.

Broadbent FE. 1979. Mineralization of organic nitrogen in paddy soils. In: Nitrogen and rice. Los Baños, Philippines: International Rice Research Institute. p. 105–118.

Calderon FJ, Jackson LE. 2002. Rototillage, disking, and subsequent irrigation: Effects on soil nitrogen dynamics, microbial biomass, and carbon dioxide efflux. J Environ Qual. 31:752–758.

Cassman KG, De Datta SK, Olk DC, Alcantara JM, Samson MI, Descalsota JP, Dizon MA. 1995. Yield decline and nitrogen economy of long-term experiments on continuous, irrigated rice systems in the tropics. In: Lal R, Stewart BA, editors. Soil management: Experimental basis for sustainability and environmental quality. Boca Raton (FL): Lewis/CRC. p. 181–222.

Cassman KG, Dobermann A, Sta Cruz PC, Gines GC, Samson MI, Descalsota M, Alcantara JM, Dizon MA, Olk DC. 1996. Organic matter and the indigenous nitrogen supply of intensive irrigated systems in the tropics. Plant Soil. 182:267–278.

Clement A, Chalifour FP, Ladha JK. 1995. Crop residue effects on nitrogen mineralization, microbial biomass, and rice yield in submerged soils. Soil Sci Soc Am J. 59:1595–1603.

Colberg PJ. 1988. Anaerobic microbial degradation of cellulose, lignin, oligolinols, and monaromatic lignin derivatives. In: Zender AJB, editor. Biology of anaerobic microorganisms. New York: Wiley. p. 333–372.

Collins A, Allinson DW. 2002. Nitrogen mineralization in soil from perennial grassland measured through long-term laboratory incubations. J Agric Sci. 138:301–310.

Crutzen PJ, Ehhalt DH. 1977. Effect of nitrogen fertilizers and combustion on the stratospheric ozone layer. Ambio 6:112–117.

De Datta SK. 1981. Principles and practices of rice production. New York: John Wiley and Sons.

De Datta SK. 1986. Improving nitrogen fertilizer efficiency in lowland rice in tropical Asia. Fertilizer Res. 9:171–186.

D'Angelo EM, Reddy KR. 1994. Diagenesis of organic matter in a wetland receiving hypereutrophic lake water: II. Role of inorganic electron acceptors in nutrient release. J Environ Qual. 23:937–943.

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

Devêvre OC, Howarth WR. 2001. Stabilization of fertilizer nitrogen-15 into humic substances in aerobic vs. waterlogged soil following straw incorporation. Soil Sci Soc Am J. 65:499–510.
Dolmat MT, Patrick WH Jr, Petersen FJ. 1980. Relation of available soil nitrogen to rice yield. Soil Sci. 129:229–237.
Haider K. 1992. Problem related to the humification process in soils of temperate climates. In: Stotzky G, Bollag JM, editors. Soil biochemistry. New York: Dekker. p. 55–94.
Harmsen GW, Van Schreven DA. 1955. Mineralization of organic nitrogen in soil. Adv Agron. 7:299–398.
Hassink J. 1992. Effects of soil texture and structure on carbon and nitrogen mineralization in grassland soils. Biol Fertility Soils. 14:126–134.
Inamura T, Mukai Y, Maruyama A, Ikenaga S, Li G, Bu X, Xiang Y, Qin D, Amano T. 2009. Effects of nitrogen mineralization on paddy rice yield under low input conditions in irrigated rice-based multiple cropping with intensive cropping of vegetables in Southwest China. Plant Soil. 315:195–209.
Inubushi K, Wada H. 1987. Easily decomposable organic matter in paddy soil. VII. Effect of various pretreatments on N mineralization in submerged soils. Soil Sci Plant Nutrit. 33:567–576.
Ireneo JM, Iwao W, Grace BM, Jasper GT. 1996. Nitrogen mineralization in tropical wetland Soils: I. Relationship with temperature and soil properties. Soil Sci Plant Nutrit. 42:229–238.
Kalbitz K, Schwesig D, Rethemeyer J, Matzner E. 2005. Stabilization of dissolved organic matter by sorption to the mineral soil. Soil Biol Biochem. 37:1319–1331.
Kumar K, Goh KM. 2000. Crop residue management: Effects on soil quality, soil nitrogen dynamics, crop yield, and nitrogen recovery. Adv Agron. 68:197–319.
Kyuma K. 2004. Paddy soil science. Kyoto, Japan: Kyoto University Press.
Lindau CW, Reddy KR, Khind CS, Pardue JH, Patrick WH Jr. 1989. Effect of redox potential on urea hydrolysis and nitrification in soil suspensions. Soil Sci. 148:184–190.
Li H, Han Y, Cai ZC. 2003. Nitrogen mineralization in paddy soils of the Taihu Region of China under anaerobic conditions: dynamics and model fitting. Geoderma 115:161–175.
Lovley DR. 1995. Microbial reduction of iron, manganese, and other metals. Adv Agron. 54:175–231.
Maie N, Watanabe A, Taki K, Yano H, Kimura M. 2000. Comparison of humus composition in the subsoil of Japanese paddy and upland fields. Soil Sci Plant Nutrit. 46:163–175.
Manguiat IJ, Watanabe I, Mascarina GB, Tallada JG. 1996. Nitrogen mineralization in tropical wetland rice soils. I. Relationship with temperature and soil properties. Soil Sci Plant Nutrit. 42:229–238.
Mitsuchi M. 1974. Characters of humus formed under rice cultivation. Soil Sci Plant Nutrit. 20:249–259.
Narteh LT, Sahrawat KL. 1997. Potentially mineralizable nitrogen in West African lowland rice soils. Geoderma 76:145–154.
Narteh LT, Sahrawat KL. 1999. Influence of flooding on electrochemical and chemical properties of West African soils. Geoderma 87:179–207.
Narteh LT, Sahrawat KL. 2000. Ammonium in solution of flooded West African soils. Geoderma. 95:205–214.
Nguyen VB, Olk DC, Cassman KG. 2004a. Characterization of humic acid fractions improves estimates of nitrogen mineralization kinetics for lowland rice soils. Soil Sci Soc Am J. 68:1266–1277.
Nguyen VB, Olk DC, Cassman KG. 2004b. Nitrogen mineralization from humic acid fractions in rice soils depends on degree of humification. Soil Sci Soc Am J. 68:1278–1284.
Nishimura S, Yonemura S, Sawamoto T, Shirato Y, Akiyama H, Sudo S, Yagi K. 2008. Effect of land use change from paddy rice cultivation to upland crop cultivation on soil carbon budget of a cropland in Japan. Agric, Ecosyst Environ. 125:9–20.
Olk DC. 2006. A chemical fractionation for structure-function relations of soil organic matter in nutrient cycling. Soil Sci Soc Am J. 70:1013–1022.
Olk DC, Cassman KG, Randall EW, Kinchesh P, Sanger LJ, Anderson JM. 1996. Changes in chemical properties of organic matter with intensified rice cropping in tropical rice soil. Eur J Soil Sci. 47:293–303.

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

Olk DC, Dancel MC, Moscoso E, Jimenez RR, Dayrit FM. 2002. Accumulation of lignin residues in organic matter fractions of lowland rice soils: A pyrolysis-GC-MS study. Soil Sci. 167:590–606.
Olk DC, Samson MI, Gapas P. 2007. Inhibition of nitrogen mineralization in young humic fractions by anaerobic decomposition of rice crop residues. Eur J Soil Sci. 58:270–281.
Pampolino MF, Laureles EV, Gines HC, Buresh RJ. 2008. Soil carbon and nitrogen changes in long-term continuous lowland rice cropping. Soil Sci Soc Am J. 72:798–807.
Patrick WH, Jr, Reddy CN. 1978. Chemical changes in rice soils. In: Soil and rice. Manila, Philippines: International Rice Research Institute. p. 361–379.
Ponnamperuma FN. 1972. The chemistry of submerged soils. Adv Agron. 24:29–96.
Ponnamperuma FN. 1984. Effects of flooding on soils. In: Kozlowski T, editor. Flooding and plant growth. New York: Academic Press. p. 9–45.
Ponnamperuma FN, Sahrawat KL. 1978. Nitrogen supplying capacity of wetland rice soils. In: Agronomy abstracts. Madison (WI): ASA, SSSA, and CSSA. p. 160.
Raun W, Johnson GV. 1999. Improving nitrogen use efficiency for cereal production. Agron J. 91:357–363.
Reddy KR, Patrick WH Jr. 1986. Fate of fertilizer nitrogen in the rice root zone. Soil Sci Soc Am J. 50:649–651.
Reddy KR, Patrick WH Jr, Lindau CW. 1989. Nitrification-denitrification at the plant root-sediment interface in wetlands. Limnol Oceanogr. 34:1004–1013.
Reddy KR, Patrick WH Jr, Phillips RE. 1978. The role of nitrate diffusion in determining the order and rate of denitrification in flooded soil: I. Experimental results. Soil Sci Soc Am J. 42:268–272.
Robertson GP, Paul EA, Harwood RR. 2000. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radioactive forcing of the atmosphere. Science 289:1922–1925.
Roden EE, Wetzel RG. 2002. Kinetics of microbial Fe (III) oxide reduction in freshwater sediments. Limnol Oceanogr. 47:198–211.
Sahrawat KL. 1979. Ammonium fixation in some tropical rice soils. Communic Soil Sci Plant Anal. 10:1005–1013.
Sahrawat KL. 1980. Soil and fertilizer nitrogen transformations under alternate flooding and drying moisture regimes. Plant Soil. 55:225–233.
Sahrawat KL. 1981a. Ammonification in air-dried lowland Histosols. Soil Biol Biochem. 13:323–324.
Sahrawat KL. 1981b. Influence of water regime on growth, yield and nitrogen uptake of rice. Communic Soil Sci Plant Anal. 12:919–932.
Sahrawat KL. 1983a. Nitrogen availability indexes for submerged rice soils. Adv Agron. 36:415–451.
Sahrawat KL. 1983b. Mineralization of organic nitrogen under waterlogged conditions in relation to other soil properties of tropical rice soils. Austral J Soil Res. 21:133–138.
Sahrawat KL. 1998a. Flooding soil: A great equalizer of diversity in soil chemical fertility. Oryza 35:300–305.
Sahrawat KL. 1998b. Short-term incubation method for mineralizable nitrogen. Arid Soil Res Rehabil. 12:291–295.
Sahrawat KL. 2002. Reducible iron affects organic matter oxidation and ammonium production in wetland soils and sediments. Curr Sci. 83:1434–1435.
Sahrawat KL. 2004a. Ammonium production in submerged soils and sediments: The role of reducible iron. Communic Soil Sci Plant Anal. 35:399–411.
Sahrawat KL. 2004b. Organic matter accumulation in submerged soils. Adv Agron. 81:169–201.
Sahrawat KL. 2007. Soil fertility advantages of submerged rice cropping systems: A review. J Sustain Agric. 31:5–23.
Sahrawat KL. 2008. Factors affecting nitrification in soils. Communic Soil Sci Plant Anal. 39:1436–1446.
Sahrawat KL, Narteh LT. 2001. Organic matter and reducible iron control of ammonium production in submerged soils. Communic Soil Sci Plant Anal. 32:1543–1550.
Sahrawat KL, Narteh LT. 2002. A fertility index for submerged rice soils. Communic Soil Sci Plant Anal. 33:229–236.

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010

Sahrawat KL, Narteh LT. 2003. A chemical index for predicting ammonium production in submerged rice soils. Communic Soil Sci Plant Anal. 34:1013–1021.
Sano S, Yanai J, Kosaki T. 2006. Relationships between labile organic matter and nitrogen mineralization in Japanese agricultural soils with reference to land use and soil type. Soil Sci Plant Nutrit. 52:49–60.
Savant NK, De Datta SK. 1982. Nitrogen transformations in wetland rice soils. Adv Agron. 35:241–302.
Schmidt-Rohr K, Mao J-D, Olk DC. 2004. Nitrogen-bonded aromatics in soil organic matter and their implications for a yield decline in intensive rice cropping. Proc Nat Acad Sci USA. 101:6351–6354.
Schnitzer M, Skinner SIM. 1966. Organo-metallic interaction in soils, 5: Stability constants of Cu^{2+}-, Fe^{2+}- and Zn-fulvic acid complexes. Soil Sci. 102:361–365.
Shiga H, Ventura W. 1976. Nitrogen supplying ability of paddy soils under field conditions. Soil Sci Plant Nutrit. 22:387–399.
Sims JL, Wells JP, Tackett DL. 1967. Predicting nitrogen availability to rice, 1: Comparison of methods for determining available nitrogen to rice from field and reservoir soils. Soil Sci Soc Am Proc. 31:672–676.
Tilman D, Cassman KG, Matson PA, Naylor RL, Polasky S. 2002. Agricultural sustainability and intensive production practices. Nature 418:671–677.
Updegraff KJ, Pastor J, Brigham S, Johnston C. 1995. Environmental and substrate controls over carbon and nitrogen mineralization in Northern wetlands. Ecolog Applic. 5:151–163.
White JR, Reddy KR. 2001. The effects of select electron acceptors on organic nitrogen mineralization in northern Everglades soils. Soil Sci Soc Am J. 65:941–948.
Witt C, Cassman KG, Olk DC, Biket U, Liboon SP, Samson MI, Ottow JCG. 2000. Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems. Plant Soil. 225:263–278.
Yonebayashi K, Hattori T. 1986. Patterns and factors controlling nitrogen mineralization in paddy soils in tropical and temperate regions. Soil Sci Plant Nutrit. 32:407–420.
Zhang M, He Z. 2004. Long-term changes in organic carbon and nutrients of an Ultisol under rice cropping in southeast China. Geoderma 118:167–179.
Zhu ZL, Liu CQ, Jiang BF. 1984. Mineralization of organic nitrogen, phosphorus, and sulfur in some paddy soils of China. In: Organic matter and rice. Los Baños, Philipinnes: International Rice Research Institute. p. 259–272.

Downloaded By: [Sahrawat, Kanwar L.] At: 04:12 8 April 2010