Communications in Soil Science and Plant Analysis, 37: 787–796, 2006

ISSN 0010-3624 print/1532-2416 online
DOI: 10.1080/00103620600564034

Organic Matter and Mineralizable Nitrogen Relationships in Wetland Rice Soils

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Abstract: Soil nitrogen (N) supply plays a dominant role in the N nutrition of wetland rice. Organic matter has been proposed as an index of soil N availability to wetland rice. This is based on the finding that mineralizable N produced under waterlogged conditions is related to soil organic carbon (C) and total N. The relationship between organic matter and mineralizable N is a prerequisite for determining the N requirement of wetland rice. However, no critical analysis of recent literature on organic matter–mineralizable N relationships has been made. This article evaluates current literature on the relationships of mineralizable N or ammonium N production with soil organic C in wetland rice soils. A number of studies with diverse wetland rice soils demonstrate a close relationship of N mineralized (ammonium-N) under anaerobic conditions with organic C or total N. However, a few recent studies made on sites under long-term intensive wetland rice cropping showed that strong positive relationships of mineralizable N with organic C or total N do not hold. Clearly, both quantity and quality of organic matter affect N mineralization in wetland rice soils. Future research is needed to clarify the role of quality of organic matter, especially its chemistry, as modified by the chemical environment of submerged soils, on the mineralization of organic N in wetland rice soils.

Keywords: Factors affecting organic matter mineralization, mineralizable N, quantity and quality of organic matter, sources of N other than soil organic matter, submerged soils

Received 4 January 2004, Accepted 18 May 2005
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INTRODUCTION

Rice is the staple food for the world's population that lives in Asia (about approximately one-half). It is estimated that more than 90% of global rice is produced and consumed in Asia. In South Asia, rice production has kept pace with or exceeded population growth from the mid-1960s to the early 1990s (Hossain and Fischer 1995). This has been achieved by growing two to three crops of rice in intensive, continuous rice systems. Availability of irrigation water is the important consideration in such systems.

The intensified lowland rice systems make a major contribution to global rice supply. Nitrogen (N) deficiency is the major constraint to increasing the productivity of lowland rice. The mineralization of organic nitrogen or ammonium production is the key process for the N nutrition of wetland rice because N mineralization stops at ammonium production and nitrification is at low ebb in submerged soils. Moreover, soil N supply plays a dominant role in the N nutrition of wetland rice because half to two-third of total nitrogen taken up by rice crops even in N fertilized rice paddies comes from the soil N pool (Sahrawat 1983a).

It is estimated that continuous annual- or double-crop rice production systems are practiced on more than 12 million ha and account for about 25% of world rice production (Cassman and Pingali 1995). In these production systems N deficiency is the major constraint. The relationship between soil organic matter and N-supplying capacity of soils is of crucial importance for determining the N fertilizer requirements of wetland rice and for efficient and judicious use of external N inputs. However, no critical analysis of recent literature on the relationship between organic matter and mineralizable N has been made, although reviews on other aspects of fertility and fertilizer management in wetland rice soils have received attention.

For example, Sahrawat (2004a) reviewed recent literature on accumulation of organic matter in submerged soils and sediments. The review discussed several short- and long-term studies on the accumulation of organic matter in wetland soils in intensified rice systems. The review of recent literature demonstrated that organic matter preferentially accumulates in soils that remain submerged for prolonged periods (such as the soils under intensified lowland rice systems). The principal mechanisms involved in organic matter accumulation in submerged soils include slower, incomplete, and inefficient decomposition of added or soil organic matter in the absence of oxygen, stabilization of organic matter, accumulation of antimicrobial toxicants, and higher net primary productivity of wetlands.

Another important finding relating to organic matter and fertility status of wetland rice soils is the role of electron acceptors, especially reducible iron, in controlling the decomposition of organic matter and the release of ammonium under submerged conditions. Recent research with tropical wetland rice soils showed that production and release of ammonium-N and other nutrients in soil solution in submerged soils is controlled by the organic C and reducible iron (extracted by EDTA or ammonium oxalate) status of the soil (Sahrawat and Narteh 2002; Sahrawat and Narteh 2003; Sahrawat 2004b).

Organic carbon (C) content in soils has been used as an index of N-supplying capacity of soils. This is based on the finding that organic C content in soils is significantly correlated to potentially mineralizable N in a wide range of soils. The relationships between organic C and potentially mineralizable N are closer in tropical wetland rice soils, and significant correlations have been reported not only between organic C and mineralizable N but also between organic C and rice yield or N uptake by the rice crop (Sahrawat 1983a).

However, a few reports, especially from intensified rice systems, also show poor or nonsignificant relationships between organic C and mineralizable N, yield, or N uptake by wetland rice. The causes of variability in results on the relationships between organic C and potentially mineralizable N have not been critically evaluated, although information on this aspect could help in developing suitable N management strategies for wetland rice. The objective of this article, therefore, is to critically review the current literature on the relationship between organic C and mineralizable N in wetland rice soils. The need for future research in the area is also examined.

RELATIONSHIPS BETWEEN ORGANIC MATTER AND MINERALIZABLE NITROGEN

Studies made with a number of diverse sets of Asian wetland soils showed that organic N mineralized or ammonium released under anaerobic incubation is significantly correlated with soil organic matter (organic C or total N) content [see Sahrawat (1983a) for a review]. For example, Ponnamperuma and Sahrawat (1978) found that the N-supplying capacity of 506 diverse Philippine wetland rice soils, measured by anaerobic incubation, ranged from 13 to 637 $mg\,N\,kg^{-1}$ of soil, and the mineralized N was highly significantly correlated with soil organic C. Sahrawat (1983a) reviewed literature on the N-supplying capacity of submerged rice soils and, based on the compilation of results for more than 750 diverse soils from the Philippines, he reported that ammonium produced under waterlogged incubation was highly significantly correlated with soil organic C. Ammonium N released in the soils was also highly significantly correlated with total N content (Table 1).

In another study, ammonium N released under anaerobic incubation in 39 diverse wetland rice soils from the Philippines was highly positively correlated with organic C and total N content and negatively correlated with the C/N ratio of the soils. The soils studied had a wide range in ammonium produced and the mineralized N formed 1.8 to 26% of the total N (Sahrawat 1983b). Studies made in India also showed that the N-supplying

Table 1. Correlations between ammonium-N produced under anaerobic incubation and organic C and total N content of Philippine soils (adapted from Sahrawat 1983a)

No. of soil samples	Correlation coefficient (r)		Reference
	NH_4^+ versus organic C	NH_4^+ versus total N	
483	0.72	0.79	IRRI (1973)[a]
280	NA	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	0.897	0.91	Sahrawat (1982a)[a]

NA, not available; correlation coefficient r is significant at $p = 0.01$.
[a]These references are cited in Sahrawat, 1983a.

capacity of lowland rice soils could be assessed by organic matter content of the soils. Organic C or total N content of the soils was significantly correlated to N uptake and yield of the rice crop (Stalin et al. 1996; Thiyagrajan et al. 1997).

Narteh and Sahrawat (1997) studied potentially mineralizable N in 15 diverse West African rice soils. Ammonium N released under waterlogged incubation varied from 21 to 166 mg kg^{-1} of soil and the mineralized N released under anaerobic incubation was highly significantly correlated with soil organic C ($r^2 = 0.62$, $n = 15$) and total N ($r^2 = 0.62$, $n = 15$). The mineralized N released under anaerobic incubation at 30°C for 2 weeks constituted 2 to 7% of total soil N (Narteh and Sahrawat 1997).

However, it has been shown that the prediction of mineralizable N in wetland rice soils can be further improved by considering other soil characteristics along with organic C because the mineralization of organic N in submerged soils is influenced through the modifying effects of pH, CEC, clay, and the presence of electron acceptors (such as ferric iron and sulfate) on the relationship between organic matter and ammonium production (Narteh and Sahrawat 1997; Sahrawat and Narteh 2001).

Sahrawat (1983b) studied 39 diverse Philippine soils to determine the relationships between mineralizable N produced under anaerobic incubation and other soil properties. Study of simple correlation showed that soil pH, CEC, and clay were not significantly correlated to mineralizable N. However, multiple regression analyses showed that the inclusion of these properties improved the prediction of ammonium N over that predicted by organic C or total N alone. Narteh and Sahrawat (1997) reported similar results on the influence of soil properties, especially pH, CEC, and reducible iron, on mineralizable N in West African soils.

Cassman et al. (1996) studied the relationships of indigenous N supply (determined by anaerobic incubation of soil samples using an ion-exchange resin capsule procedure) with soil organic C or total N in surface soil of a long-term fertility experiments at 11 sites in Asian countries. The results showed that ammonium N released in soil samples was poorly correlated with soil organic C or total N. The authors hypothesized that inputs of N from sources other than N mineralization of soil organic matter in surface soil and the differences in soil organic matter quality related to intensive cropping in submerged soil influenced the relationships between mineralized N and soil organic matter (Cassman et al. 1996). These results are in agreement with the findings from field studies, which showed that organic C or total N was a poor predictor of N supply to the rice crop (Sims, Wells, and Tackett 1967; Dolmat, Patrick, and Peterson 1980; Adhikari et al. 1999).

The effect of soil organic matter quality on mineralizable N, although of critical importance, has not received much research attention in the past. Recent research, however, showed that the proportion of organic N fractions and chemical structure of specific soil organic matter pools and the chemical environment of submerged soil have a greater influence on the mineralization of N, especially on slow-phase N mineralization rates, than soil organic C or total N (Yonebayashi and Hattori 1986; Olk et al. 1996).

Recent studies have shown that the stabilization of applied organic matter and fertilizer N into humic fractions of soil organic matter under waterlogged conditions of lowland rice soils influences mineralization of organic matter and release of mineral N (Devévre and Horwath 2001; Bird, van Kessel, and Horwath 2003). Such effects are caused by formation of stable complexes of humic substances with cations such as ferrous iron, which protects them from degradation (Schnitzer and Skinner 1966; Kalbitz et al. 2005). Also, the accumulation of lignin and the phenolic subunits of lignin that are resistant to degradation in the absence of oxygen contribute to the changes in the quality of organic matter in submerged soil (Colberg 1988; Olk et al. 1996).

Recently, Schmidt-Rohr Mao, and Olk, (2004) showed that the significant amounts of amide nitrogen is directly bonded to aromatic rings in a humic acid fraction extracted from a continually submerged triple-cropped rice soil from a long-term experiment in the Philippines. Because nitrogen bonded to an aromatic ring is not readily available to plants, this finding can explain the rice yield decline (Cassman et al. 1995).

Detailed studies of a humic acid fraction showed that this humic acid is rich in lignin derivatives (>45% of all carbon) in the continually submerged soil, whereas the corresponding humic acid fraction extracted from an aerobic, single-cropped rice soil contains less lignin and less lignin bonded to aromatic rings (Schmidt-Rohr, Mao, and Olk 2004). The stabilization of soil organic matter by chemical agents in submerged soils is probably the reason for preferential accumulation of organic matter and also poor or no relationships between organic matter and mineralizable N in lowland rice soils (Sahrawat 2004a).

In addition to these factors, the availability of electron acceptors also affects organic matter oxidation and ammonium production or N mineralization in submerged soils and sediments. The role of electron acceptors has recently been recognized, especially in soils and sediments that remain flooded for prolonged periods. For example, easily reducible iron or iron that participates in the iron redox reactions in soils plays a dominant role in the oxidation of organic matter and the production of ammonium N in submerged soils and sediments (Lovley 1995; Sahrawat and Narteh 2001; 2002; 2003; Sahrawat 2004b; Roden and Wetzel 2002).

In a study of 15 West African soils, Narteh and Sahrawat (1997) found that although extractable iron was not directly correlated to ammonium produced under waterlogged conditions, its inclusion in the multiple regression analysis improved the prediction of ammonium produced over that predicted by organic C or total N alone. Follow-up research showed that ammonium produced under anaerobic condition was significantly correlated to organic C ($r = 0.79$, $P < 0.0005$; $n = 15$) and iron extracted by EDTA ($r = 0.86$, $P < 0.0001$) or ammonium oxalate ($r = 0.75$, $P < 0.0014$). Multiple regression analysis of the data showed that ammonium production in soils under submerged conditions could be predicted from organic C and EDTA or ammonium oxalate extractable iron (Sahrawat and Narteh 2001).

Based on research with West African wetland soils, Sahrawat and Narteh (2001; 2003) proposed a chemical index, based on soil organic matter and reducible iron, for predicting ammonium production in submerged soils. Multiple regression equations relating organic C and reducible iron to ammonium N produced were developed for measuring potentially mineralizable N in 15 wetland rice soils. The regression equations were represented by the following equations:

$$\text{Mineralizable N (mg kg soil}^{-1}) = 16.4 + 1.320 \text{ organic C (g kg}^{-1}) + 0.0369 \text{ EDTA-Fe (mg kg}^{-1}) \quad (1)$$

where $R^2 = 0.85$, and

$$\text{Mineralizable N} = 11.14 + 1.805 \text{ organic C} + 0.00469 \text{ ammonium oxalate-Fe,} \quad (2)$$

where $R^2 = 0.81$.

The results further showed an association of mineralizable N with organic C and reducible iron extracted by EDTA or ammonium oxalate. Soils high in both organic C and reducible iron were high also in mineralizable N. On the other hand, soils low in organic C or reducible iron had relatively lower contents of mineralizable N (Table 2). This was also evident from the results that showed a highly significant correlation of mineralizable N with

Table 2. Distribution of 15 West African soils according to mineralizable N (min-N) produced under anaerobic incubation and associated organic C and EDTA (EDTA-Fe) or ammonium oxalate extractable Fe (Amox-Fe) (adapted from Sahrawat and Narteh 2003)

Min-N ($mg\ kg^{-1}$ soil)	No. of soils	Organic C ($g\ kg^{-1}$) soil	EDTA-Fe ($mg\ kg^{-1}$) soil	Amox-Fe ($mg\ kg^{-1}$ soil)
86–166	4	23.0–46.0	150–2200	1875–11412
55–77	5	9.2–23.2	325–800	1100–6750
21–50	6	7.4–15.6	125–600	925–3562

organic C and reducible iron extracted by EDTA or ammonium oxalate (Sahrawat and Narteh 2001).

PERSPECTIVES

A substantial proportion of N utilized by wetland rice is derived from mineralization of soil organic matter. Reliable prediction of mineralizable N in wetland soils would help in an efficient and judicious use of fertilizer N. An understanding of the relationship between mineralizable N and organic matter is needed for use of organic C or total N as measured by soil organic matter for determining the N requirement for wetland rice. Recent literature on mineralizable N–organic matter relationships in wetland rice soils is reviewed.

Organic matter preferentially accumulates in wetland rice soils. Also, organic matter accumulation in soils generally leads to increases in organic C and total N, which in turn contribute to the soil mineralizable N pool. Thus a linear relationship between soil organic matter and mineralizable N is expected and not entirely surprising. However, both quantity and quality of organic matter contribute to the pool of mineralizable N in soil (Sahrawat 1983a; Cassman et al. 1996; Sahrawat 2004a).

The chemical environment of submerged soils affects the quality of organic matter, especially the proportion of organic N fractions and chemical structure of specific soil organic matter pools, which contribute to the mineralization of N. The changes in the chemistry of soil organic matter are more pronounced and expressed under long-term wetland rice production systems. These changes in the chemistry of organic matter result from several factors operating in submerged soils, although the mechanisms involved are not fully understood (Sahrawat 2004a). However, it is clear that the quality of organic matter, especially the humic acid fractions of organic matter that participate in N supply to the rice crop through the mineralization organic N in continually submerged soils used for intensified wetland rice production systems, is chemically modified (Olk et al. 2002;

Nguyen, Olk, and Cassman 2004a; 2004b; Schmidt-Rohr, Mao, and Olk 2004).

Future research is needed for understanding the effects of soil submergence on organic matter fractions that contribute to N mineralization and release of ammonium N in wetland soils. Such information is a prerequisite for developing more appropriate methods of assessing the indigenous N-supplying capacity of wetland rice soils and for efficient and judicious use of external inputs of N.

It is hypothesized that the factors or mechanisms involved in the accumulation of organic matter in submerged rice soils also contribute to the changes in the chemistry of organic matter and its fractions that drive ammonium production or N mineralization in rice paddies. The future research should focus on the link of the accumulation of organic matter (quantity) and changes in specific organic matter fractions (quality) to N mineralization and N-supplying capacity of wetland rice soils with varying intensity of submergence.

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