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Ammonium in solution of flooded West African soils

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Abstract

Ammonium production is the key process for N nutrition of lowland rice because the mineralization process stops at ammonium in submerged soils. We studied the changes in ammonium N in the solution of 15 diverse wetland West African soils. Soil samples were held under flooded conditions in the greenhouse pots for 15 weeks, and anoxic solutions, drawn weekly, were monitored for the changes in ammonium N concentrations. The soils differed in the pattern of ammonium accumulation, and had a wide range of ammonium N mobilized in soil solution with mean values ranging from 0.3 to 7.4 mg N kg^{-1} soil. Ammonium N released in solution was related to organic C and total N contents of the soils. The pattern of ammonium N release in solution of the 15 soils, with the exception of two soils, was well-described by an exponential model. The fit to the linear log model was also good for most of the soils but the prediction was less consistent than with the exponential model. Our results indicate that the pattern of ammonium accumulation in soil solution of flooded West African soils can be described by an exponential model.

Keywords: N mineralization; ammonium accumulation; N supplying capacity; soil solution; wetland rice

1. Introduction

Mineralizable N pools in wetland rice soils play a dominant role in the N nutrition of rice even in well-fertilized paddies (Sahrawat, 1983). In submerged

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rice soils, a considerable portion of ammonia $(NH_3 + NH_4OH + NH_4^+)$ may be found in the solution phase depending on the organic matter and texture of the soils. This highly mobile form of ammonia is the direct source of N for the rice plant growing in wetland rice soils (Ponnamperuma, 1965).

The soil solution of flooded soils is a dynamic phase and its composition relative to plant nutrients including N, can be a useful tool for fertility evaluation (Ponnamperuma, 1965; Sahrawat, 1983). Work done at the International Rice Research Institute (IRRI) in the Philippines indicated that ammonia production in submerged soils followed a widely different asymptotic course related to the rate of ammonium production and the cation exchange reactions (Ponnamperuma, 1965; Sahrawat, 1983). The pattern of ammonia N accumulation in solution of submerged soils that are low in organic matter was described by an exponential model. For soils rich in organic matter, the pattern of ammonia N accumulation in solution followed a logarithmic increase with time described by the linear log model. There are no published reports to confirm these results.

We report the first result describing the pattern of ammonium release in soil solution of diverse West African submerged soils. Such information is helpful in assessing the indigenous soil N supply which is an important component of research for N management in wetland rice. Little information are available about the N supplying capacity of soils used for wetland rice production in West Africa (Narteh and Sahrawat, 1997) but these information are needed for judicious use of external inputs of N.

2. Materials and methods

2.1. Soils

Fifteen soils used in the study were surface (0–15 cm) samples collected from different rice growing locations in five countries of West Africa (Narteh and Sahrawat, 1997). Two soils (soils 14 and 15) were uplands and the 13 were wetlands. Soil samples were air dried and ground to pass a 2-mm sieve before analysis.

Background information about the location, classification and characteristics of the soils were described in an earlier paper (Narteh and Sahrawat, 1997). However, physical and chemical properties of the soils relevant to the present study are given in Table 1. For the soil analyses reported in Table 1, pH was measured by a glass electrode using a soil to water ratio of 1:2.5. Particle size analysis was made using the pipette method (Gee and Bauder, 1986). Organic C was determined using the Walkley and Black method (Nelson and Sommers, 1982) and total N was determined as described by Bremner (1965a). Cation exchange capacity (CEC) was determined as described by Chapman (1965).

Table 1
Some physical and chemical properties of the soils used

Soil no.	Texture	pH	Organic C ($g\ kg^{-1}$)	Total N ($mg\ kg^{-1}$)	Clay ($g\ kg^{-1}$)	CEC ($cmol\ kg^{-1}$)
1	Silt loam	4.3	7.8	750	163	5.6
2	Loamy sand	5.2	11.4	600	53	1.4
3	Clay	7.7	46.0	3300	510	30.0
4	Silt loam	4.9	9.8	900	215	6.5
5	Loamy sand	5.4	8.8	700	45	0.8
6	Clay loam	5.1	35.2	2700	350	17.0
7	Silt loam	6.1	13.4	1100	262	11.1
8	Silt loam	5.6	9.2	800	308	14.5
9	Silt loam	5.4	20.0	1500	275	12.5
10	Sandy clay loam	5.6	25.2	1800	220	12.7
11	Silty clay loam	5.5	23.2	1500	330	16.8
12	Silt	5.3	19.6	1200	60	8.8
13	Clay loam	6.1	23.0	1800	318	8.7
14	Sandy loam	6.3	7.4	500	88	2.0
15	Loam	5.0	15.6	1200	298	8.5

2.2. Determination of changes in ammonium N concentration in soil solution

Samples (10 kg dry soil) were kept submerged in distilled water in glazed pots, fitted with a system at the base of each pot for collecting the soil solution under gravity. The system consisted of a rubber stopper with a sintered glass tube passing through it, bent vertically downwards to allow the collection of soil solution under gravity. A layer of 3–5 cm standing water over the samples was maintained throughout the period of study. Samples of soil solution were collected under anoxic conditions from the flooded soils at weekly intervals, using 250 ml Erlenmeyer flasks fitted with glass tubes in rubber stoppers, designed to allow for the displacement of air by N_2 gas. They were analysed for ammonium N content by distilling an aliquot with MgO as described by Bremner (1965b).

2.3. Fitting the ammonium data to exponential and linear log models

The data on ammonium N content in soil solutions of soils collected weekly during 12 weeks of flooding were fitted to exponential and linear log models (Sahrawat, 1983).

A fit to the exponential model was tested using the following equation:

$$(A-Y)/A = e^{-ct} \quad (1)$$

where A is the mean maximum amount of ammonium in solution, expressed in mg N kg^{-1} soil, Y is the actual amount of ammonium in the solution t weeks after submergence, and c is the parameter controlled by the soil.

The linear log model was fitted using the following equation:

$$Y = a + b \log t \quad (2)$$

where Y is the total amount of ammonium N released in soil solution, a is the amount of ammonium in soil solution 1 week after flooding, b is the parameter highly correlated to organic C and total N contents of the soil, and t is weeks of flooding.

The data fitting to the two models was done using the SAS statistical package (SAS, 1987).

3. Results and discussion

The soils used in the study have a wide range of pH values (4.3–7.7), clay (45–510 g kg^{-1}), organic C (7.4–46.0 g kg^{-1}), total N (500–3300 mg kg^{-1}) and CEC (0.8–30.0 cmol kg^{-1}) (Table 1).

Changes in the concentration of ammonium N in the solutions of 15 soils (Fig. 1) indicated that they had a wide range in ammonium N. Based on mean ammonium N in solutions during 15 weeks under flooded conditions, soil 10 released the highest ammonium (7.4 mg N kg soil^{-1}) and soil 8 the lowest (a mean value of 0.3 mg N kg^{-1}), and clearly reflected the extent of variability in the soils' capacity to mobilize ammonium. A wide range in the amounts of

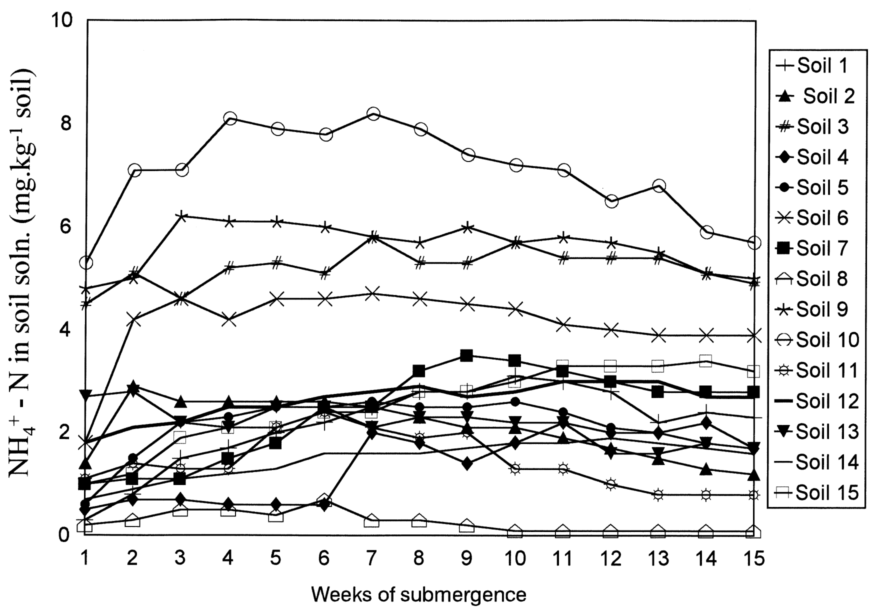

Fig. 1. Changes in the concentration of ammonium N in solution of 15 flooded West African soils.

Table 2
The range, mean and standard error (SE) of ammonium N in soil solution of 15 West African soils held under flooded conditions for 12 weeks

Soil no.	Ammonium in solution (mg N kg^{-1})		
	Range	Mean	SE
1	0.3–3.1	2.1	0.3
2	1.4–2.9	2.3	0.1
3	4.5–5.8	5.3	0.2
4	0.5–2.2	1.2	0.2
5	0.6–2.6	2.1	0.2
6	1.8–4.7	4.2	0.2
7	1.0–3.5	2.3	0.3
8	0.1–0.7	0.3	0.05
9	4.8–6.2	5.7	0.1
10	5.3–8.2	7.4	0.2
11	1.0–2.4	1.6	0.1
12	1.8–3.0	2.5	0.1
13	1.6–2.8	2.3	0.1
14	0.7–1.9	1.4	0.1
15	1.0–3.4	2.4	0.2

ammonium N released in solutions of the 15 soils was also evident from the values of range, mean and SE of ammonium N over 12 weeks (Table 2).

Ammonium N content in soil solution was significantly correlated to organic C and total N but not with CEC and Clay contents of the soils (Table 3). In general, the correlation coefficients of ammonium N in solution were higher with organic C than that with total N. The highest coefficients of correlation

Table 3
Correlation coefficients (r) of ammonium in soil solution of 15 West African soils during 12 weeks of flooding and some soil characteristics (probability levels, p in parentheses)

Weeks	Organic C	Total N	CEC	Clay
1	0.68(0.005)	0.65(0.008)	0.52(0.05)	0.39(0.15)
2	0.70(0.003)	0.68(0.005)	0.46(0.08)	0.31(0.26)
3	0.60(0.02)	0.58(0.022)	0.38(0.16)	0.24(1.00)
4	0.60(0.02)	0.59(0.021)	0.41(0.13)	0.24(1.00)
5	0.65(0.01)	0.63(0.012)	0.44(0.09)	0.28(0.31)
6	0.64(0.01)	0.62(0.014)	0.44(0.09)	0.28(0.31)
7	0.64(0.01)	0.63(0.012)	0.45(0.09)	0.28(0.31)
8	0.61(0.01)	0.61(0.016)	0.42(0.12)	0.27(0.32)
9	0.61(0.01)	0.61(0.016)	0.43(0.11)	0.31(0.27)
10	0.63(0.01)	0.63(0.012)	0.44(0.09)	0.31(0.26)
11	0.57(0.03)	0.58(0.021)	0.40(0.15)	0.27(0.33)
12	0.58(0.02)	0.58(0.021)	0.42(0.12)	0.28(0.30)

with organic C ($r = 0.70$) and total N ($r = 0.68$) were obtained at 2 weeks of flooding although they remained significant throughout the 12-week period (Table 3).

The ammonium N released in the solution attained a dynamic equilibrium within about 2 weeks of flooding and this can be conveniently used for predicting the N supplying capacity of soils using short-term tests. These results are in accordance with the work done at the IRRI which indicated that almost all the mineralizable N in submerged soils were converted into ammonium within 2 weeks of submergence provided that the temperature was favourable (Ponnamperuma, 1972). The favourable temperature range is 25°C–35°C. It would appear from our results that under submergence of soils for longer periods of time, immobilization of N becomes increasingly important and this affects the prediction of N availability to wetland rice. For example, short-term incubation tests under waterlogged condition were found to be better than the longer-term incubation tests in predicting N availability to wetland rice (Sahrawat, 1983). In a recent study, Sahrawat (1998) found that the mineral N released in the soils under waterlogged incubation at 50°C in 2 days was significantly correlated with the mineral N released in 14 days at 30°C and mineral N released at 40°C in 7 days. The results indicated that short-term incubation test using incubation for 2 days at 50°C may be employed for assessing the potentially mineralizable N, especially in tropical soils.

For fitting the two models, the data on ammonium in solution for 12 weeks only were used because the results were not significantly affected by including data beyond 12 weeks.

The equations describing the changes of ammonium N in soil solution, based on the exponential model, are shown in Table 4. The fit to the model was highly significant for all soils, with the exception of soil 8, which gave a poor fit to the model. The fit to the model was also relatively poor for soil 13. The fitted curves for the 15 soils are shown in Fig. 2. Soil 8 also released the lowest amount of ammonium in solution throughout the period of study.

The fit to the model was also tested for the data on ammonium N in solution for shorter periods: at 4, 6 and 8 weeks of flooding. In general, the fit to the model was best described with the data collected at 4 weeks of flooding for all soils, with the exception of soil 13. There was a good agreement in the fit to the model run using the ammonium in soil solution data for 4, 6, 8 and 12 weeks with the exception of soil 8. While soil 8 showed a poor fit ($r = 0.16$) to the data for 12 weeks, the fit was excellent with the data for 4 weeks ($r = 0.98$), 6 weeks ($r = 0.96$) and 8 weeks ($r = 0.84$). The fit of the data for soil 13 to the model was poor whether the data used were for 4, 6, 8 or 12 weeks.

The equations describing the pattern of ammonium N in soil solution for the 15 soils, according to the linear log model, are shown in Table 5. The fit to the model was generally good with the exception of soils 8, 10 and 11. As in the case of the exponential model, there was in general, a good agreement in the fit

Table 4
Equations describing the kinetics of ammonium N released in solution based on the exponential growth model [$(A-Y)/A=e^{-ct}$] for 15 flooded West African soils during 12 weeks (probability levels p, in parentheses)

Soil no.	Equation	r
1	$Y=3.62\,(1-e^{-0.16t})$	0.99 (<0.001)
2	$Y=2.33\,(1-e^{-0.94t})$	0.66 (0.002)
3	$Y=5.31\,(1-e^{-1.78t})$	0.64 (0.03)
4	$Y=8.32\,(1-e^{-0.24t})$	0.86 (<0.001)
5	$Y=2.53\,(1-e^{-0.50t})$	0.94 (<0.001)
6	$Y=4.49\,(1-e^{-0.83t})$	0.89 (<0.001)
7	$Y=4.33\,(1-e^{-0.13t})$	0.94 (<0.001)
8	$Y=0.32\,(1-e^{-0.14t})$	0.16 (0.61)
9	$Y=5.88\,(1-e^{-1.53t})$	0.78 (0.002)
10	$Y=7.60\,(1-e^{-1.28t})$	0.80 (0.002)
11	$Y=1.98\,(1-e^{-0.55t})$	0.52 (0.007)
12	$Y=2.79\,(1-e^{-0.73t})$	0.88 (<0.001)
13	$Y=2.29\,(1-e^{-20.34t})$	-0.41 (0.18)
14	$Y=1.90\,(1-e^{-0.29t})$	0.99 (<0.001)
15	$Y=3.55\,(1-e^{-0.21t})$	0.97 (<0.001)

to the linear log model when data for 4, 6, 8 or 12 weeks were used, with the exception of soils 10 and 11. Soils 10 ($r=0.17$) and 11 ($r=0.28$) showed poor fits to the model when the data for 12 weeks were used. The fit to the model was, however, greatly improved with the data for 4 weeks ($r=0.98$), 6 weeks ($r=0.83$) and 8 weeks ($r=0.78$) for soil 10. There was also an improvement in the fit to the model for soil 11 when data for 4 weeks ($r=0.42$), 6 weeks ($r=0.61$) and 8 weeks ($r=0.63$) were used compared to when the data for 12 weeks ($r=0.28$) were used. The fit of the data to the model for soil 8 was poor, and it was not improved with an additional run of the model using data for 4, 6 or 8 weeks.

It is important to note that the fit of the data to the exponential and linear log models peaked when data on ammonium in soil solution for 4 weeks was used indicating again that the short-term flooding of soils achieve a relatively stable trend in the release of ammonium in solution. Moreover, increase in the temperature can further shorten the time needed to reach such a steady state (e.g., see Sahrawat, 1998)

The fit of the data to the linear log model compared to the exponential model seemed less consistent in predicting the accumulation of ammonium N in soil solution. More importantly, the results of our study clearly support the conclusion drawn by Ponnamperuma (1965,1972) and Sahrawat (1983) that in the flooded soils low in organic matter, ammonium N accumulation in solution follows an asymptotic course described by the exponential model.

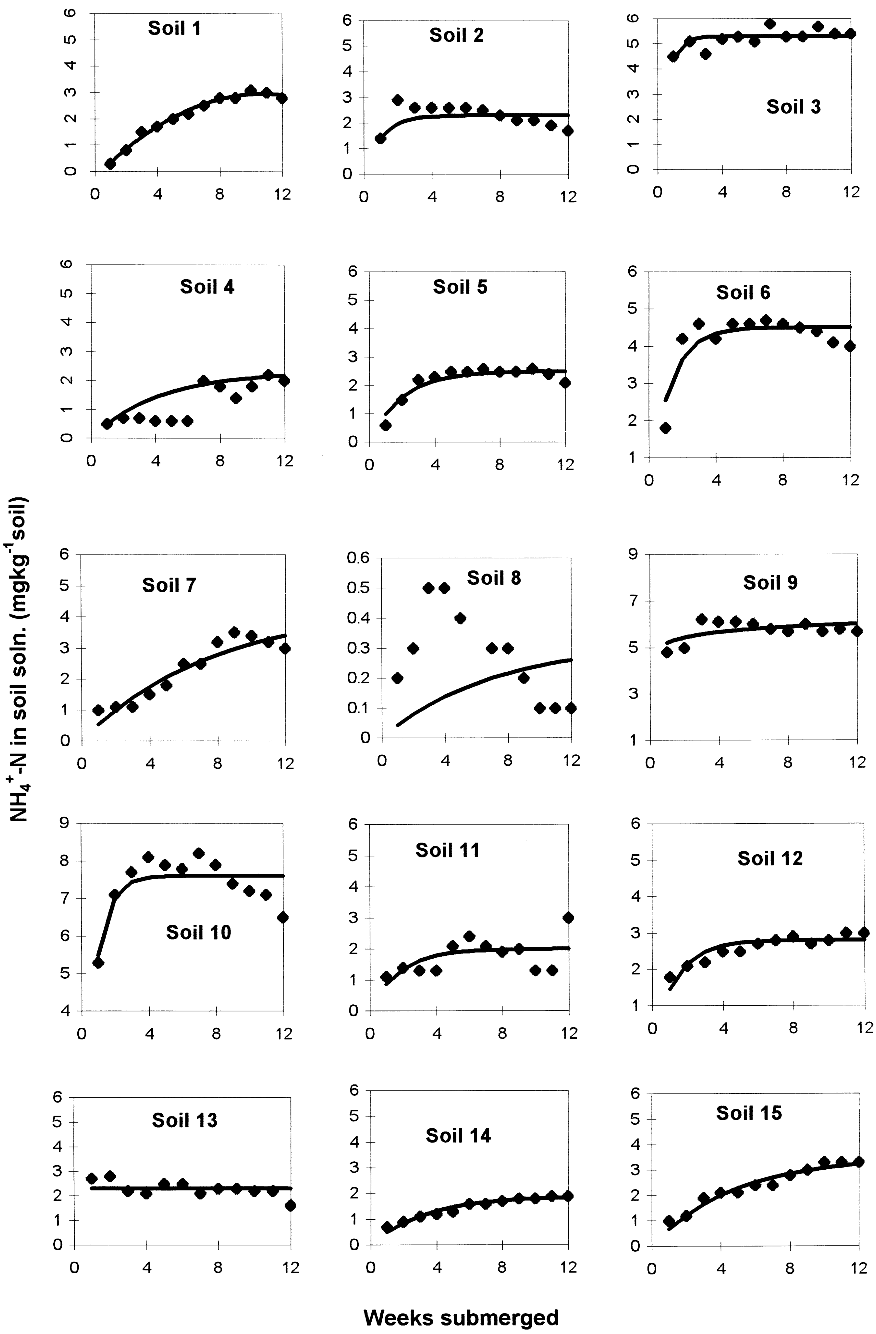

Fig. 2. Kinetics of ammonium N in solution of 15 flooded West African soils. The data were fitted to the exponential model. For details of fitted equations and correlation coefficients (r) see Table 4.

Table 5
Equations describing the kinetics of ammonium N released in solution based on the linear log model ($Y = a + b \log t$) for 15 flooded West African soils during 12 weeks (probability levels, p in parentheses)

Soil no.	Equation	r
1	$Y = 0.17 + 1.17 \log t$	0.97 (< 0.001)
2	$Y = 1.82 + 0.22 \log t$	0.62 (0.003)
3	$Y = 4.57 + 0.39 \log t$	0.62 (0.003)
4	$Y = 0.07 + 0.72 \log t$	0.61 (0.003)
5	$Y = 1.12 + 0.65 \log t$	0.69 (0.003)
6	$Y = 3.09 + 0.66 \log t$	0.42 (0.03)
7	$Y = 0.39 + 1.16 \log t$	0.82 (< 0.001)
8	$Y = 0.43 - 0.07 \log t$	0.08 (0.37)
9	$Y = 5.20 + 0.33 \log t$	0.33 (0.05)
10	$Y = 6.61 + 0.44 \log t$	0.17 (0.18)
11	$Y = 1.09 + 0.41 \log t$	0.28 (0.07)
12	$Y = 1.77 + 0.49 \log t$	0.95 (< 0.001)
13	$Y = 2.77 - 0.29 \log t$	0.47 (0.014)
14	$Y = 0.59 + 0.58 \log t$	0.96 (< 0.001)
15	$Y = 0.72 + 1.00 \log t$	0.94 (< 0.001)

Based on the release of ammonium release in soil solution, the 15 soils examined can be divided into the following three groups.

(i) The soils that released greater than 5 mg N kg soil^{-1} for most of the 15 weeks they were submerged (soils 3, 6, 9 and 10), may be considered relatively fertile with respect to N and thus may need modest application of fertilizer N.

(ii) The soils that mobilized ammonium in solution between 1.5 and 5 mg N kg^{-1} on weekly basis, may be considered deficient in N supply and the rice growing on them should greatly respond to added fertilizer N. Eight soils (soils 1, 2, 4, 5, 7, 11, 14 and 15) out of the 15 examined fall into this category.

(iii) The soils that released less than 1.5 mg N kg^{-1} (soils 8 and 13), may be considered acutely deficient in the N supply. For these two soils, the release of ammonium N in solution showed a rather poor fit to the exponential growth model.

In summary, the results of our study indicate that the West African studied soils differed widely in their capacity to mobilize ammonium in solution and the release of ammonium was well-described by an exponential model.

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