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A FERTILITY INDEX FOR SUBMERGED RICE SOILS

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ABSTRACT

Soil fertility indices that consider the dynamic nature of submerged soils are needed for assessing the fertility status of wetlands. It is proposed that the soil solution electrical conductivity (EC) determined at 4 weeks after submergence can be used as an index of general fertility of wetland soils. This proposition is based on the finding that the soil solution EC provides a measure of the concentration of nutrient elements mobilized in solution. The results with 15 diverse West African rice soils showed that at 4 weeks after flooding, the soil solution EC was highly significantly correlated ($r = 0.927, n = 15$) to the total concentration of macro- and micronutrient elements released in solution. This period (4 weeks after flooding) coincided with the establishment of a dynamic equilibrium between pH and Eh (redox potential) for the 15 soils and the increase in pH was quantitatively ($R^2 = 0.84$) associated with the decrease in Eh. The soils had a wide range in solution EC and nutrient concentration in soil solution, indicating a range in the fertility status. The soil solution EC was significantly correlated to organic C and iron extracted by EDTA. It is suggested that soil solution EC at

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4 weeks after flooding can be used as an index of the fertility status of wetland soils not affected by salinity.

INTRODUCTION

Submerged soils are distinctly different from their upland counterparts and this distinctness is caused by the lack of oxygen. Submerging a soil in water cuts off the supply of oxygen and quickly the soil is exhausted of oxygen. This results in soil reduction and sets in motion a series of physical, chemical and biological processes that profoundly influence the quality of soil as a medium for the growth of crops such as wetland rice (1–3).

The fertility status of wetland soils is routinely assessed by analyzing soil samples in the air dry state for various nutrient elements. It is important, however, to note that submerged soils are distinct and that water plays an important role in the amelioration of soils as a result of flooding them under water by bringing the pH in the neutral range. This greatly influences the release and availability of plant nutrients (1,2). Moreover, the solution phase of submerged soils serves as a dynamic reservoir of plant nutrients and plays an unique and important role in the mineral nutrition of the rice plant (4).

Developing indices of soil fertility is an important component of research for soil fertility management and plant nutrition (5) and this paper is an attempt towards developing a soil fertility index for wetland rice. The importance of such research cannot be overemphasized in view of the growing importance of rice as a food and the opportunity for exploiting a large area under inland valleys in West Africa, although ideally suited for wetland rice cultivation, remains largely unexploited (6).

In this context, the role of organic matter and reducible iron in regulating the dynamics of soil fertility in wetland rice is of crucial importance (2,7). Organic matter is the source of energy for the anaerobes operating in the submerged soils (1) and iron-related processes dominate in submerged soils due to iron reduction and this influence far exceeds the total amounts of other redox elements by a factor of 10 or more (8). For example, in a recent study of diverse soils from West Africa, Narteh and Sahrawat (3) demonstrated that under flooded conditions, the changes in soil solution pH corresponded to changes in solution Eh and at 4 weeks after flooding of the soils, a dynamic stability in the Eh–pH relationships ($R^2 = 0.84$) was recorded.

MATERIALS AND METHODS

Soils

The soils used in this study were surface (0–0.15 m) samples collected shortly before the study, from 15 rice growing locations in five West African

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countries. Background information about the soils such as location, classification and physical and chemical properties were described in an earlier paper (3). Soil characteristics relevant to this study are given in Table 1. For the analysis reported in Table 1, pH was measured by a glass electrode using a soil to water ratio of 1:2.5. Organic C was determined using the Walkley and Black method (9). Extractable iron was determined using ammonium oxalate (Amox–Fe) (10) and EDTA (EDTA–Fe) (11).

Determining EC and Amounts of Nutrient Elements Released in Soil Solution

Soils (10 kg) were kept submerged in distilled water in glazed pots, fitted with a system at the base of each pot for collecting soil solution under gravity. The system consisted of a rubber stopper with a sintered glass tube passing through it and bent vertically downwards to allow collection of soil solution under gravity flow (3). A layer of 3–5 cm of standing water over the soil surface was maintained throughout 15 weeks of study. Samples of soil solution were collected under anoxic conditions from the submerged soils held in pots, at weekly intervals, using 250-mL Erlenmeyer flasks fitted with glass tubes in rubber stoppers designed to allow for the displacement of air by nitrogen gas. The flasks were filled with nitrogen gas. Soil solution was analyzed for Fe(II) immediately using atomic absorption spectrophotometer. If immediate analysis was not possible, the solutions were acidified to pH 3 with dilute hydrochloric acid. Soil solution were analyzed for pH, EC, and macro- and micronutrient elements (3). Soil solution EC was measured using a conductivity meter. The total concentration of nutrients in soil solution was computed by adding the concentration of various nutrient elements (ammonium-N, phosphate-P, potassium, calcium, magnesium, iron, manganese and zinc).

RESULTS AND DISCUSSION

The soils used had a range in pH, texture, organic C and iron extracted by EDTA (EDTA–Fe) and ammonium oxalate (Amox–Fe). At 4 weeks after flooding, the soils had a range in soil solution EC and total concentration of water soluble macro- and micronutrients which included ammonium, phosphorus, potassium, calcium, magnesium, iron, zinc, and manganese (Table 1).

When soils are submerged under water, the suite of cations and anions held in the exchange complex are released in solution, resulting in an increase in the EC of soil solution. The EC of soil solution stabilizes after a few weeks of

Table 1. Physical and Chemical Properties and Soil Solution EC and Total Concentration of Nutrient Elements in Solution Determined at 4 Weeks After Flooding of the Soils Used

						Soil Solution at 4 Weeks	
Soil No.	Texture	pH	Organic C ($g\,kg^{-1}$)	EDTA–Fe ($mg\,kg^{-1}$)	Amox–Fe ($mg\,kg^{-1}$)	EC ($mS\,cm^{-1}$)	Conc. of Nutrients ($mg\,L^{-1}$)
1	Silt loam	4.3	7.8	600	3,175	0.36	126
2	Loamy sand	5.2	11.4	150	1,187	0.25	111
3	Clay	7.7	46.0	2,200	11,412	1.90	352
4	Silt loam	4.9	9.8	550	3,400	0.13	65
5	Loamy sand	5.4	8.8	350	3,562	0.50	180
6	Clay loam	5.1	35.2	325	1,100	0.72	263
7	Silt loam	6.1	13.4	575	3,052	0.53	125
8	Silt loam	5.6	9.2	800	6,750	0.12	43
9	Silt loam	5.4	20.0	1,275	10,737	0.77	180
10	Sandy clay loam	5.6	25.2	1,375	9,812	0.92	197
11	Silty clay loam	5.5	23.2	800	5,837	0.20	59
12	Silt	5.3	19.6	450	1,562	0.30	98
13	Clay loam	6.1	23.0	150	1,875	1.10	229
14	Sandy loam	6.3	7.4	125	925	0.83	173
15	Loam	5.0	15.6	125	1,525	0.60	134

flooding depending on the soil characteristics, especially organic matter content, texture and the amount of redox elements (1,3,4).

Our results showed that for the 15 soils studied, the soil solution EC was correlated to the concentration of nutrient elements in solution, and the correlation coefficient between solution EC and concentration of nutrients was highest ($r = 0.927, n = 15$) at 4 weeks after flooding (Fig. 1). The correlation coefficients were lower at 2 weeks ($r = 0.226$) and 6 weeks ($r = 0.883$). These results suggest that solution EC at 4 weeks after flooding can provide a meaningful measure of the concentration of water soluble nutrient elements and thus can be used as a possible index for assessing the fertility status of submerged soils. The relationship between the solution EC and concentration of nutrient elements at 4 weeks after flooding was represented by the following equation:

$$\text{Solution EC}\,(\text{m Scm}^{-1}) = -0.191 + 0.0055\,\text{Nutrient conc. in solution}\,(\text{mg L}^{-1})\; r = 0.927 \qquad (1)$$

Support for the conclusion that a dynamic equilibrium is attained at 4 weeks after flooding the soils was provided by Narteh and Sahrawat (3) who demonstrated that the changes in soil solution pH generally corresponded to changes in solution Eh and the dynamic stability in the Eh–pH relationships was

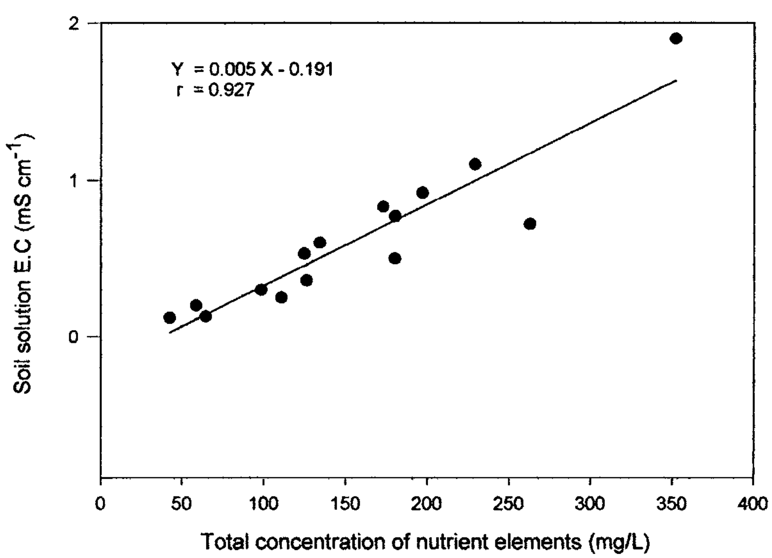

Figure 1. Relationship between soil solution EC at 4 weeks after flooding and total concentration of macro- and micronutrient elements in solution for 15 West African soils.

recorded at 4 week after submergence, and was described by the following equation:

$$\Delta \text{Eh} = -16 - 48\Delta \text{pH} \quad R^2 = 0.84\,(n = 15, p < 0.001) \qquad (2)$$

It was also shown that at 4 weeks after flooding of the soils, the solution EC was highly significantly correlated with the concentrations of basic cations, potassium, calcium and magnesium and ammonium but not with iron, zinc, or manganese (3).

The solution EC of the 15 soils at 4 weeks after submerging was significantly correlated to organic C ($r = 0.73$) and EDTA–Fe ($r = 0.57$), but was not significantly correlated to Amox–Fe ($r = 0.46$) (Table 2). It has been suggested that EDTA and ammonium oxalate solutions extract the fractions of iron which are easily reducible (12,13) and are used as indices for the activity of the iron oxides or poorly crystalline iron oxides in soils (10,11).

Based on the concentration of nutrient elements in solution at 4 weeks after flooding, the 15 soils tested can be categorized into three groups: (i) soils (soil no. 3, 6, and 13) having more than 200 mg L^{-1} nutrient concentration in solution; (ii) soils (soil no. 1, 2, 5, 7, 9, 10, 14, and 15) having nutrient concentration ranging from 100 to 200 mg L^{-1}; and (iii) soils (soil no. 4, 8, 11, and 12) having nutrient concentration less than 100 mg L^{-1}. Results on the association of solution concentration of nutrient elements and solution EC with organic C and EDTA–Fe are summarized in Table 3.

Our results show that there is association of organic C and fraction of the easily reducible iron with the concentration of nutrients mobilized in soil solution and solution EC of submerged soils (Table 3). Results also showed that soils with high organic C and high EDTA–Fe had relatively high solution EC and concentration of macro- and micro-nutrient elements in solution. On the other hand, soils with low content of organic C and reducible iron had lower EC and lower concentration of nutrient elements in soil solution (Table 3).

Table 2. Correlation Coefficients of Soil Solution EC at 4 Weeks After Flooding with Organic C, Iron Extracted by EDTA (EDTA–Fe), and Ammonium Oxalate (Amox–Fe) for 15 West African Soils

Parameters Correlated	Correlation Coefficient (r)
EC and organic C	0.73
EC and EDTA–Fe	0.57
EC and Amox–Fe	0.46

Table 3. Distribution of 15 West African Soils According to the Concentration of Nutrient Elements in Soil Solution at 4 Weeks After Flooding, and the Associated Solution EC, Organic C, and EDTA–Fe

Conc. of Nutrients in Solution (mg L^{-1})	Soil Solution EC (mS cm^{-1})	No. of Soils	Organic C (g kg^{-1})	EDTA–Fe (mg kg^{-1})
>200	0.72–1.92	3	23.0–46.0	150–2200
100–200	0.25–0.92	8	7.4–35.2	125–1375
<100	0.12–0.30	4	9.2–23.2	450–800

Clearly, a closer association was observed between solution EC or the concentration of nutrients in soil solution with organic C than with reducible iron extracted by EDTA and ammonium oxalate. The iron redox is just one of the redox systems which regulate soil reduction and the release of nutrients into solution. Moreover, the degree to which Eh of a soil solution will be poised at a given redox couple, e.g., Fe(III)/Fe(II), will depend on the availability of the electron acceptors and the C supply to bacteria. The application of organic matter to lowland rice culture is needed to maintain wetland soils in a fertile state so that they can mobilize plant nutrients into soil solution under submerged conditions. Nevertheless, it is important to note that the pH and Eh-mediated release of nutrients, their sorption and desorption and chemical kinetics in submerged soils are more influenced by reducible iron than any other mineral redox systems (1,2,8).

The results of this study suggest that the soil solution EC determined at 4 weeks after flooding can be used as an index of fertility for wetland soils not affected by salinity.

REFERENCES

1. Ponnamperuma, F.N. The Chemistry of Submerged Soils. Adv. Agron. **1972**, *24*, 29–96.
2. Sahrawat, K.L. Flooding Soil: A Great Equalizer of Diversity in Soil Chemical Fertility. Oryza **1998**, *35*, 300–305.
3. Narteh, L.T.; Sahrawat, K.L. Influence of Flooding on Electrochemical and Chemical Properties of West African Soils. Geoderma **1999**, *87*, 179–207.
4. Ponnamperuma, F.N. Dynamic Aspects of Flooded Soils and the Nutrition of the Rice Plant. In *The Mineral Nutrition of the Rice Plant*; International Rice Research Institute, Ed.; Johns Hopkins University Press: Baltimore, MD, 1965; 295–382.

5. Sahrawat, K.L. Nitrogen Availability Indexes for Submerged Rice Soils. Adv. Agron. **1983**, *36*, 415–451.
6. Andriesse, W.; Fresco, L.O. A Characterization of Rice-Growing Environments in West Africa. Agric. Ecosyst. Environ. **1991**, *33*, 377–395.
7. Sahrawat, K.L.; Narteh, L.T. Organic Matter and Reducible Iron Control of Ammonium Production in Submerged Soils. Commun. Soil Sci. Plant Anal. **2001**, *32*, 1543–1550.
8. Patrick, W.H., Jr.; Reddy, C.N. Chemical Changes in Rice Soils. In *Rice and Soils*; International Rice Research Institute: Manila, Philippines, 1978; 361–379.
9. Nelson, D.W.; Sommers, L.E. Total Carbon, Organic Carbon, and Organic Matter. In *Methods of Soil Analysis, Part 2*; Page, A.L., Miller, R.H., Keeney, D.R., Eds.; American Society of Agronomy: Madison, WI, 1982; Agron. No. 9, 539–579.
10. Schwertmann, U. Use of Oxalate for Iron Extraction from Soils. Can. J. Soil Sci. **1973**, *53*, 244–246.
11. Borggaard, O.K. Selective Extraction of Amorphous Iron Oxides by EDTA from a Danish Sandy Loam. J. Soil Sci. **1979**, *30*, 727–734.
12. Munch, J.C.; Ottow, J.C.W. Preferential Reduction of Amorphous to Crystalline Iron Oxides by Bacterial Activity. Soil Sci. **1980**, *129*, 15–21.
13. Wahid, P.A.; Kamalam, N.V. Reductive Dissolution of Crystalline and Amorphous Fe(III) Oxides by Microorganisms in Submerged Soil. Biol. Fertil. Soils **1993**, *15*, 144–148.