Influence of flooding on electrochemical and chemical properties of West African soils

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Abstract

An understanding of the influence of flooding on electrochemical and chemical properties of soils provides insight needed in their management for rice production in West Africa. With this objective, the influence of flooding on electrochemical and chemical properties of 15 lowland soils from five rice producing countries in West Africa was studied. The soils were held under flooded conditions in greenhouse pots for 15 weeks. Soil pH and redox potential (Eh), and anoxic soil solutions drawn weekly were monitored for the changes with respect to major and micronutrients. The electrochemical properties of the soils and their solutions with time tended to stabilize in a narrow range. Soils widely differed in their capacities to release ammonium, P, K, Ca, Mg, Fe, Mn and Zn in soil solution and thus provided useful information regarding the potential deficiencies of plant nutrients, and also, for the occurrence of Fe toxicity to lowland rice. Measurements made on the soil solution phase of the soils provided information for predicting the dynamic relationships among Eh, pH and Fe(II). The soil solution EC was closely related to the solution concentrations of K, Ca and Mg. The soils differed in the pattern and in the amounts of Fe released in soil solution and this information may be helpful in devising a strategy for the management of Fe toxicity to lowland rice. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: electrochemical properties; pH; redox potential; soil solution; macro- and micronutrients; lowland rice; Fe toxicity

1. Introduction

Rice ranks among the six major food crops of West Africa. Over the last decade the demand for rice has been increasing steadily and this demand has been met mainly through increasing imports. To counter this trend, West Africa

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Rice Development Association (WARDA) has been engaged with national programs and other international agencies in the sub-region for promoting increased indigenous production of rice. Rice in West Africa is produced in most diverse environments, which may be broadly grouped into uplands, inland swamps, irrigated humid, irrigated Sahelian and mangrove swamp environments.

Apart from a lack of water control that leads to flooding and drought in the same growing cycle, soil nutrient status is a major constraint to rice production in the sub-region. Rice growing in an upland soil faces a harsher growing environment in terms of nutrient status than rice growing in an inland swamp which provides free water on the surface of soil, not only alleviating water shortage, also, increasing the availability of key nutrients and eliminating Al and Mn toxicities.

For better management of soil, fertilizer and water regime for maximizing rice production in lowland ecology, it is important to understand the unique properties of flooded soils. In West Africa, a large land area under inland valleys, suitable for rice cultivation, remains unexploited (Andriesse and Fresco, 1991). This paper is an attempt to fill the research gap by way of characterizing the influence of flooding on the electrochemical and chemical properties of diverse wetland rice soils from five rice producing countries in West Africa.

2. Materials and methods

2.1. Soils

Surface (0–15 cm) samples of rice growing soils were collected from 15 locations in five rice producing countries in West Africa. Information about the location, classification and physical and chemical characteristics of the soils is summarized in Table 1. Chemical properties of the 15 soils, relevant to the present study .are summarized in Table 2. For the soil analyses, pH was measured by a glass electrode using soil to water or KCl solution ratio of 1:2.5. Particle-size analysis was made using the pipette method (Gee and Bauder, 1986). Organic C was determined by the Walkley–Black method (Nelson and Sommers, 1982), and total N and ammonium and nitrate N were determined as described by Bremner (1965a,b). Total P was determined colorimetrically after digestion of soil samples with nitric and perchloric acids, and Olsen and Bray 1 extractable P were determined as described by Olsen and Sommers (1982). Cation exchange capacity (CEC) was determined as described by Chapman (1965) and extractable Fe, Mn and Zn were determined as described by Lindsay and Norvell (1978). Exchangeable bases and Al in soil samples were also determined (Jackson, 1967).

A wide variety of soils was represented. Soils 1–12 were located in the forest and savanna agroecological zones and have had a known history of causing Fe

toxicity to the lowland rice crop. Soils 13 and 14 were located in the forest–savanna transition zone, and soil 15 was located in the forest agroecological zone. Soil 13 was without much Fe toxicity. Soils 14 and 15 were upland soils and were included to provide further diversity in soil characteristics.

2.2. Determination of changes in electrochemical and chemical properties of flooded soils

The changes with time in electrochemical and chemical properties of the soils as affected by flooding were followed. Samples of 10 kg dry weight were kept submerged with distilled water in glazed pots fitted with a system at the base of each pot for collecting the soil solution under gravity. It consisted of rubber stoppers with sintered glass tubes passing through them, bent vertically downwards to allow the collection of soil solution. A layer of 3–5 cm standing water over the samples was maintained throughout the period of study. Permanently fitted in the pots were platinum electrodes connected to Cu wire and inserted 8 cm deep into the soil to allow for the measurement of soil redox potential (Eh) by a combined pH–Eh meter. Soil pH was also measured.

Soil solutions were collected under anoxic conditions from the flooded 15 soils at weekly intervals using 250 ml Erlenmeyer flasks fitted with glass tubes in rubber stoppers. The flasks were filled with N_2 gas. Soil solution was analysed for Fe(II) immediately using atomic absorption spectrophotometer. If immediate analysis was not possible, the soil solutions were acidified (pH 3) with dilute HCl and kept under refrigeration (4°C). Soil solutions were analysed for pH, Eh, and macro and micronutrient elements for 15 weeks.

3. Results and discussion

3.1. Chemical properties of the soils

The 15 soils studied had a wide range in initial pH (4.3–7.7), organic C (7.4–46.0 g kg^{-1}), total N (500–3300 mg N kg^{-1}) and extractable plant nutrients (Tables 1 and 2). Generally, they were acidic in reaction and had a net negative charge at the natural soil reaction as indicated by the fall in pH between water and KCl solution. Soils 1, 6 and 15 recorded high exchangeable Al (> 80 mg kg^{-1} soil) and, when in use for upland rice production, they may cause Al toxicity and P deficiency, as indeed has been observed in the case of soils 6 and 15. Most of the soils were low in DTPA extractable Zn. Results on extractable P showed wide differences according to the method of extraction, i.e., Bray 1 (0.03 N $NH_4F + 0.025$ N HCl) and Olsen (0.5 M $NaHCO_3$). It has been suggested that, for lowland rice soils, an extractant that specifically extracts Fe–P in the air-dry samples should be suitable for predicting availability of P to

Table 1
Physical and chemical properties of the soils used in the study

Soil no.	Location	Classification (FAO, 1988)	Texture	pH	Clay (g kg^{-1})	Org. C (g kg^{-1})	CEC (cmol kg^{-1})
1	Edozhighi, Nigeria 9°06′N 5°59′E	Dystric Gleysol	Silt loam	4.3	163	7.8	5.6
2	Ikot-Obong, Nigeria 5°01′N 7°56′E	Dystric Gleysol	Loamy sand	5.2	53	11.4	1.4
3	Ifaki-Ekiti, Nigeria 7°14′N5°8′E	Eutric Gleysol	Clay	7.7	510	46.0	30.0
4	Itoikin, Nigeria 6°36′N 3°32′E	Dystric Gleysol	Silt loam	4.9	215	9.8	6.5
5	Fumesua, Ghana 6°54′N 1°35′W	Gleyic Arenosol	Loamy sand	5.4	45	8.8	0.8
6	Kikam, Ghana 4°53′N 2°14′W	Dystric Gleysol	Clay loam	5.1	350	35.2	17.0
7	Kou valley, Burkina Faso 11°11′N 4°18′W	Dystric Gleysol	Silt loam	6.1	262	13.4	11.1
8	Karfiguela, Burkina Faso 10°36′N 4°45′W	Dystric Gleysol	Silt loam	5.6	308	9.2	14.5

9	Korhogo, Ivory Coast 9°22′N 5°31′W	Dystric Gleysol	Silt loam	5.4	275	20.0	12.5
10	Kilissi, Rep. of Guinea 10°3′N 12°49′W	Dystric Gleysol	Sandy clay loam	5.6	220	25.2	12.7
11	Farannah, Rep. of Guinea 10°01′N 10°47′W	Dystric Gleysol	Silty clay loam	5.5	330	23.2	16.8
12	Kissidougou, Rep. of Guinea 9°48′N10°8′W	Dystric Gleysol	Silt	5.3	60	19.6	8.8
13	Bouake, Ivory Coast 7°42′N 5°00′W	Dystric Gleysol	Clay loam	6.1	318	23.0	8.7
14	Bouake, Ivory Coast 7°42′N 5°00′W	Eutric Leptosol	Sandy loam	6.3	88	7.4	2.0
15	Man, Ivory Coast 7°31′N 7°37′W	Ferric Acrisol	Loam	5.0	298	15.6	8.5

Table 2
Additional chemical characteristics of the 15 West African soils used in the study

Soil no.	Total		Bray1	Olsen	Extractable				Exchangeable		
	N (mg kg^{-1})	P (mg kg^{-1})	P (mg kg^{-1})	P (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})	Al (mg kg^{-1})	K (c mol kg^{-1})	Ca (c mol kg^{-1})	Mg (c mol kg^{-1})
1	750	162	8	20	339	19	1	85	0.10	0.80	0.23
2	600	80	8	10	63	1	1	30	0.06	0.36	0.06
3	3300	1125	3	104	178	66	40	5	0.17	14.80	3.04
4	900	163	8	14	178	10	1	40	0.07	0.88	0.33
5	700	89	12	11	112	4	1	10	0.04	0.66	0.11
6	2700	448	5	25	264	4	1	165	0.15	0.70	0.28
7	1100	176	2	11	295	5	1	5	0.11	1.84	0.12
8	800	248	1	14	340	74	2	20	0.13	1.78	1.08
9	1500	463	1	30	486	29	2	30	0.07	0.84	0.28
10	1800	545	5	50	485	33	1	50	0.04	0.96	0.17
11	1500	300	1	13	415	15	1	45	0.03	0.96	0.48
12	1200	500	4	11	236	3	1	30	0.04	0.64	0.35
13	1800	180	4	18	284	57	1	5	0.04	0.62	0.36
14	500	211	10	13	24	22	6	5	0.10	1.03	0.67
15	1200	234	6	10	166	3	1	85	0.08	0.88	0.44

wetland rice (Cholitikul and Tyner, 1971). Ekpete (1976) evaluated several chemical methods for assessing the available P status in 13 waterlogged soils (pH 4.2–6.1). He concluded that Olsen's method was better than all other methods because it better predicted the availability of P under waterlogged conditions from the analysis performed on air-dry samples.

Among the 15 soils under study, soil 3 was rather atypical as it was highest in organic C, total N, CEC and total and extractable P levels as compared with the rest of the soils. For the presentation of results, the soils were grouped into three groups on the basis of their organic C and clay contents. Soils 3, 6, 9, 10 and 13 were in one group and contained relatively high amounts of organic C and clay. Soils 1, 4, 7, 11, 12, 15 and 8 formed the second group and were generally low to moderate in organic C and silt loam in texture. The third group consisted of soils 2, 5 and 14 and they were low in organic C and loamy sand or sandy loam in texture.

3.2. Changes in the electrochemical properties

3.2.1. pH

Flooding of samples narrowed the soil and soil solution pH (Figs. 1 and 2). At the first week of flooding, the soil pH ranged between 5.6 (soil 1) and 7.4 and they were narrowed to range between 6.8 (soil 15) and 7.7 at the 15th week of flooding (Fig. 1). The soil solution pH ranged between 4.9 (soil 11) and 7.8 (soil 8) at the first week, and recorded a range of 5.6 (soil 2) to 8.2 (soil 13) at the 15th week of flooding (Fig. 2). The observed increase in soil and solution pH as a result of submergence into water is well known (Ponnamperuma, 1972) and attributed to the consumption of protons during reduction processes. However, Yu (1985) observed that the relationship between soil pH and soil reduction was not a simple one. He noted that upon submergence, production of acid radicals, especially COO^- and organic radicals may partly compensate for the pH-raising effect of reduction in acid soils or may cause lowering of pH in the case of alkaline soils.

The optimum pH, measured in soil solution, for rice is 6.6 at which microbial release of N, P and their availability is high. The supplies of micronutrient elements such as Cu, Zn and Mo are adequate and the concentrations of reduction products such as organic acids and Al, Mn and CO_2 are below toxic levels (Ponnamperuma, 1965).

3.2.2. Redox potential (Eh)

A wide range of 482 mV soil Eh was recorded at the first week of flooding with soil 12 recording an Eh of 476 mV and soil 3 of -6 mV. By 15th week, the range had drastically reduced to between 40 mV (soil 14) and -45 mV (soil 3) (Fig. 3). A similar trend was recorded in soil solution Eh. Soil 12 recorded 184 mV at the first week, while -20 mV was recorded for soil 2 (Fig. 4). By
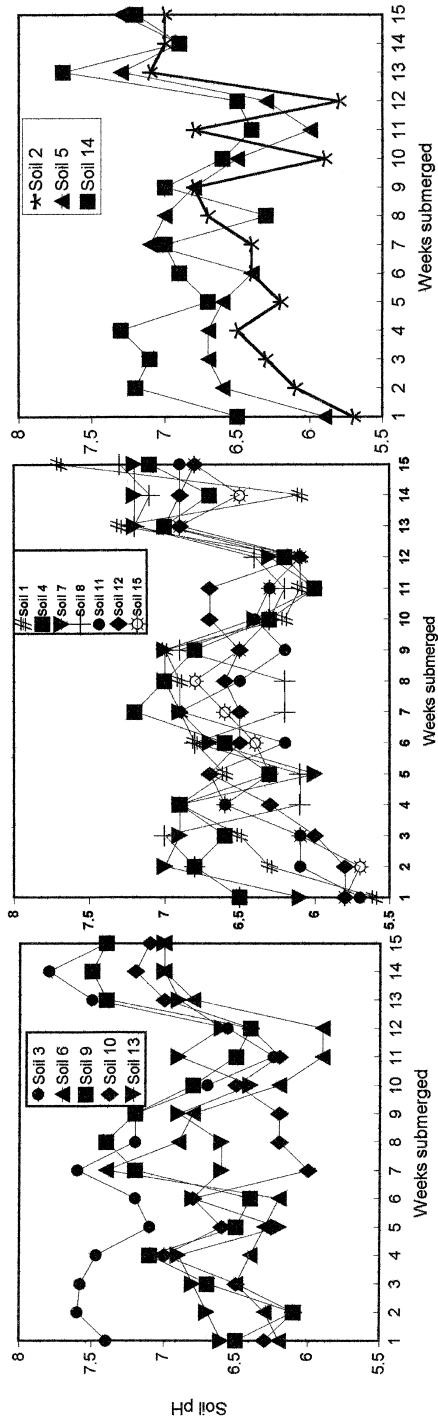
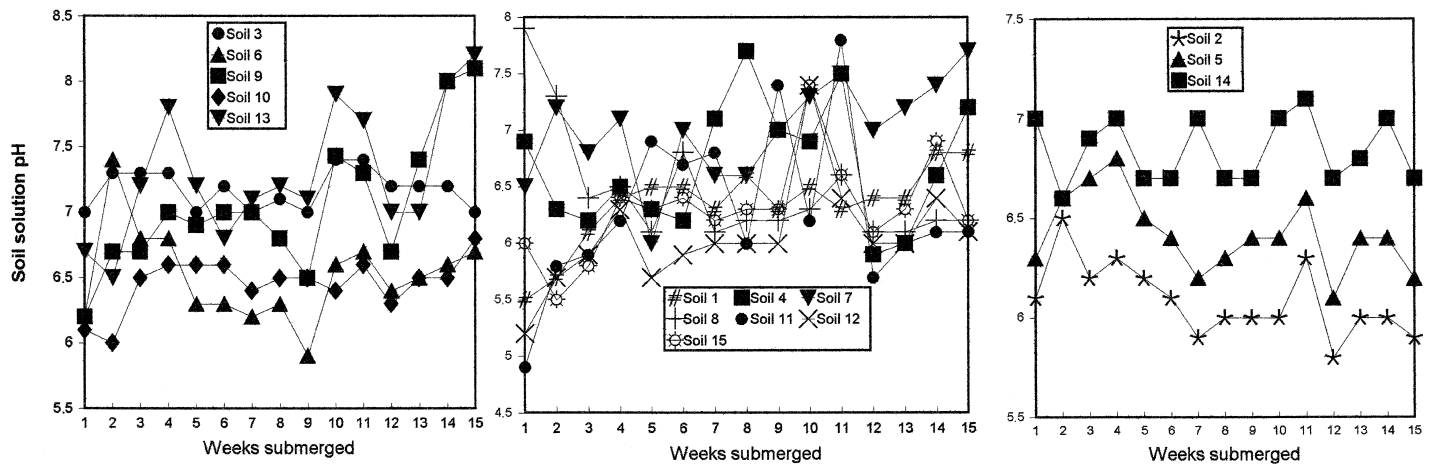Fig. 1. Changes in soil pH of 15 flooded West African soils.

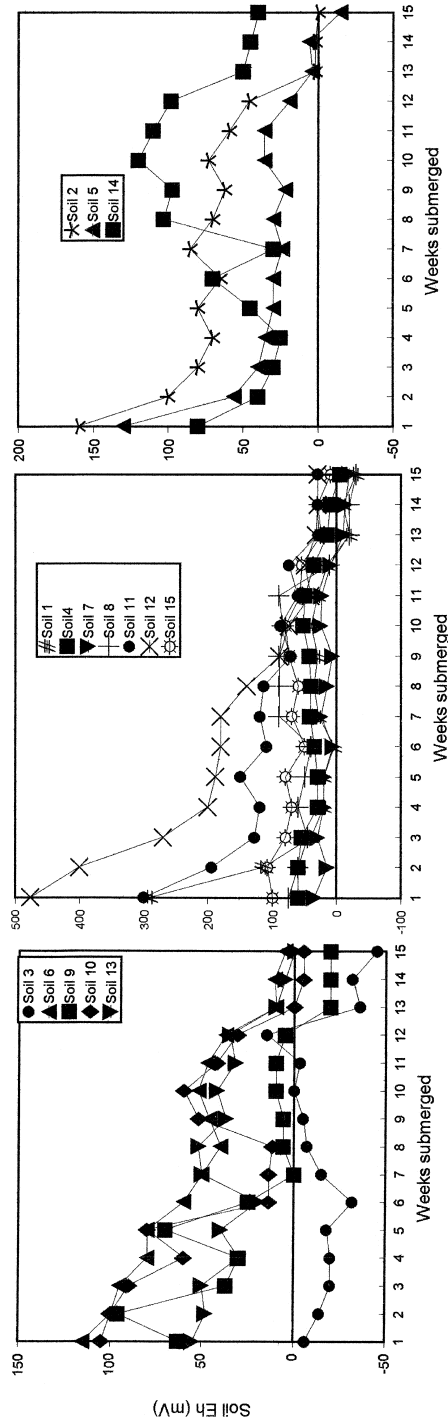Fig. 2. Changes in solution pH of 15 flooded West African soils.

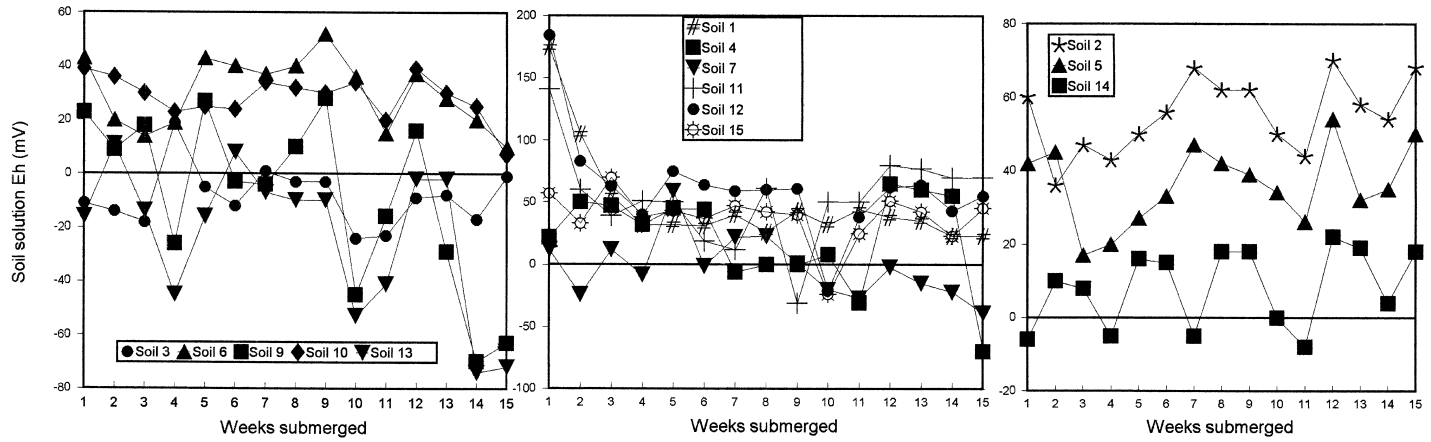Fig. 3. Changes in soil Eh of 15 flooded West African soils.

Fig. 4. Changes in solution Eh of 15 flooded West African soils.

15th week, a still narrower range was observed in the soil solution Eh. The kinetics of soil solution Eh were more chaotic than the soil phase. Generally, the soil and soil solution Eh decreased in all soils. The differences in the trends are dependent on organic matter content of the soils and the amounts of reducible Fe and Mn (Ponnamperuma, 1972).

3.2.3. pH–Eh relationship

The relationship between Eh or pE (pE = Eh/0.059) and pH for soils 3 and 12, for soil and solution phases, which recorded the highest and lowest Eh during 15 weeks of submergence were described by the following regression equations:

Flooded soils

$$\text{Soil 3: soil pE} = 2.5 - 0.37 \text{ soil pH} \quad (r = -0.642; \ p < 0.012) \qquad (1)$$

$$\text{Soil 12: soil pE} = 33.0 - 4.70 \text{ soil pH} \quad (r = -0.735; \ p < 0.002) \qquad (2)$$

Soil solution phase

$$\text{Soil 3: solution pE} = 5.20 - 0.76 \text{ solution pH} \quad (r = -0.817; \ p < 0.001) \qquad (3)$$

$$\text{Soil 12: solution pE} = 9.40 - 1.20 \text{ solution pH}$$
$$\times (r = -0.992; \ p < 0.001) \qquad (4)$$

Our results are in accord with those reported for the studies carried out in the Philippines by Ponnamperuma (1965) who contended that soil solution measurements are thermodynamically more meaningful because they are potentials of a homogenous phase in equilibrium with the solid and gaseous phases of the soil. On the other hand, there is poor reproducibility in Eh between two electrodes on the same soil. Our results corroborate his conclusions in that platinum electrode measurements indicate localized potentials.

Our results also showed that the changes in soil solution pH generally corresponded to changes in solution Eh. The stability in the changes in the Eh–pH relationships was recorded at the 4th week after submergence, and is presented in Fig. 5, was described by the following equation:

$$\Delta \text{Eh} = -16 - 48 \, \Delta \text{pH}; \qquad R^2 = 0.84 \qquad (p < 0.001) \qquad (5)$$

These relationships could allow for the calculation of the changes in pH as long as the changes in Eh are known or vice versa.

3.2.4. Electrical conductivity (EC)

The changes in solution EC of the 15 soils are shown in Fig. 6. After 1 week of flooding, the EC ranged from 0.11 mS cm^{-1} (soil 5) to 2.07 mS cm^{-1} (soil 3). There were no appreciable changes with time in the EC trends.
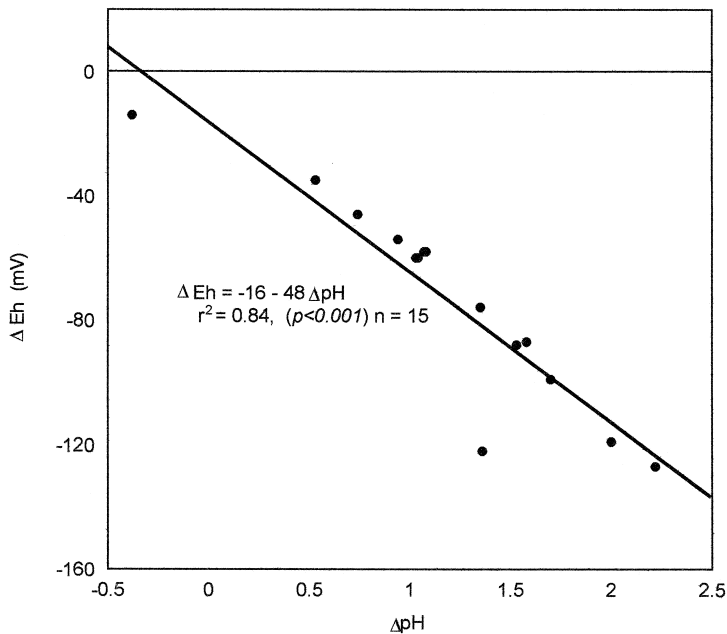
Fig. 5. Relationship between change in solution pH and change in solution Eh of 15 flooded West African soils at 4 weeks of flooding.

Considering all the 15 soils at the 4th week of flooding, it was found that the soil solution EC was correlated with the concentrations of the basic cations, namely, Ca, Mg and K rather than with Fe, Mn or Zn (Table 3). The importance of Ca in contributing to the soil solution EC was clearly evident (Fig. 7). At 4th week of flooding, the mean EC value of soil solution was highly significantly correlated with the mean total concentration of Ca, Mg and K in the soil solution ($r = 0.91$) (Fig. 8). These results are in accord with the results reported for the flooded Asian soils (Ponnamperuma, 1965). In most samples, the concentrations of cations, especially of Ca, in soil solution fell sharply by the 8th week, indicating another phase of dynamic equilibrium. It was shown that the relationship, as indicated by coefficients of correlation, between soil solution EC and K concentration in soil solution improved over that observed at the 4th week of flooding, and also over those of Ca and Mg (Figs. 9 and 10).

The close relationship observed between soil solution EC and the concentration of basic cations in the flooded soils is therefore, very important, and has a direct influence in the use of fertilizers and amendments for rice production in the lowland swamp ecology in West Africa. Rice soils in the submerged state mobilize large concentrations of Fe and Mn into soil solution which displace cations such as Ca, Mg and K from the soil exchange complex, increasing their concentration in the soil solution. A slight increase in the concentration of water-soluble K brought about by cation exchange may be important in the
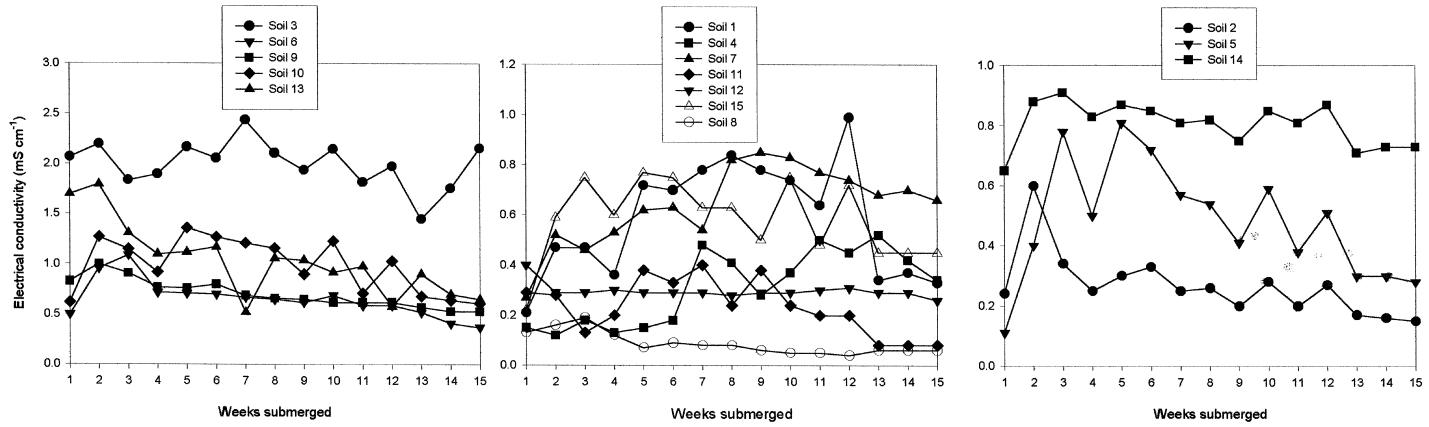
Fig. 6. Changes in solution electrical conductivity (EC) of 15 flooded West African soils.

Table 3
Correlations between the soil solution EC of 15 flooded West African soils and the concentration of important nutrient elements at 4 weeks of flooding

Nutrient element	Correlation coefficient (r)
K	0.85 ($p < 0.001$)
Ca	0.86 ($p < 0.001$)
Mg	0.84 ($p < 0.001$)
Total K + Ca + Mg	0.91 ($p < 0.001$)
Mean K + Ca + Mg	0.91 ($p < 0.001$)
Ammonium N	0.62 ($p < 0.001$)
Mn	0.12 ($p < 1.00$)
Fe(II)	−0.16 ($p < 1.00$)
Zn	−0.35 ($p < 0.20$)

Probability levels of significance (p) are shown in the parentheses.

nutrition of rice plant, although loss of Ca and Mg displaced from the soil exchange complex may lead to soil acidification (Brinkman, 1970).

3.3. Changes in chemical properties

3.3.1. Changes in the concentration of ammonium N in soil solution

The production of ammonium is the key process for the N nutrition of lowland rice because the N mineralization process stops at ammonium production in the submerged rice soils.

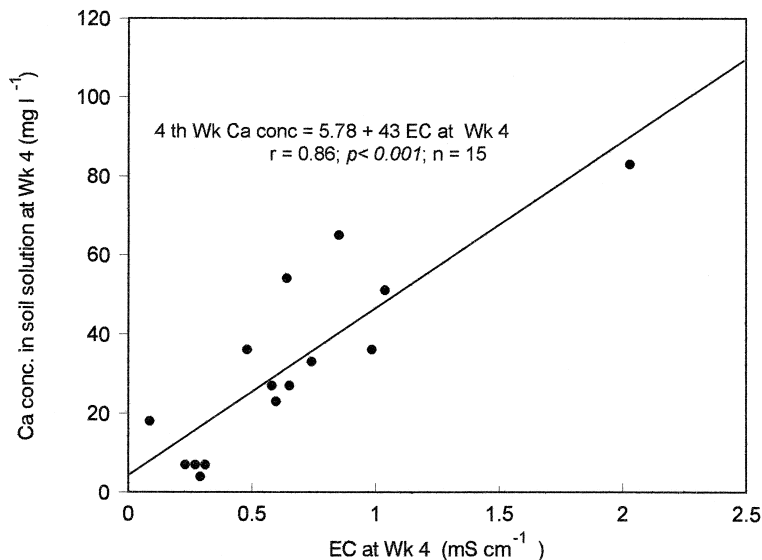4 th Wk Ca conc = 5.78 + 43 EC at Wk 4
r = 0.86; p< 0.001; n = 15

Fig. 7. Relationship between Ca concentration in soil solution and the solution EC of 15 flooded West African soils at 4 weeks of flooding.
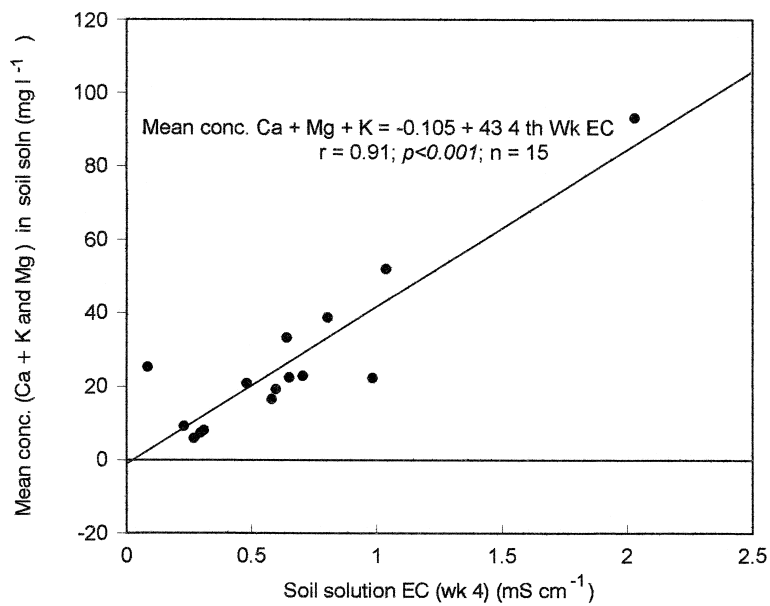
Fig. 8. Relationship between mean total concentration of Ca, Mg and K in soil solution and the solution EC of 15 flooded West African soils at 4 weeks of flooding.

The changes in the concentration of ammonium in soil solution of the 15 soils are shown in Fig. 11, indicated that the soils had a wide range in the amounts of ammonium N mobilized in soil solution. Based on the mean ammonium values
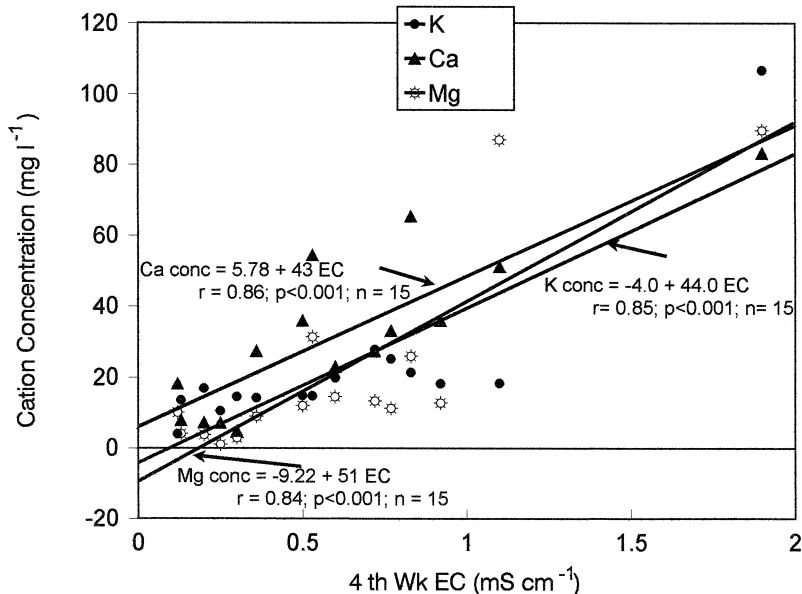

Fig. 9. Relationships between K, Ca and Mg concentration in soil solution and the solution EC of 15 flooded West African soils at 4 weeks of flooding.
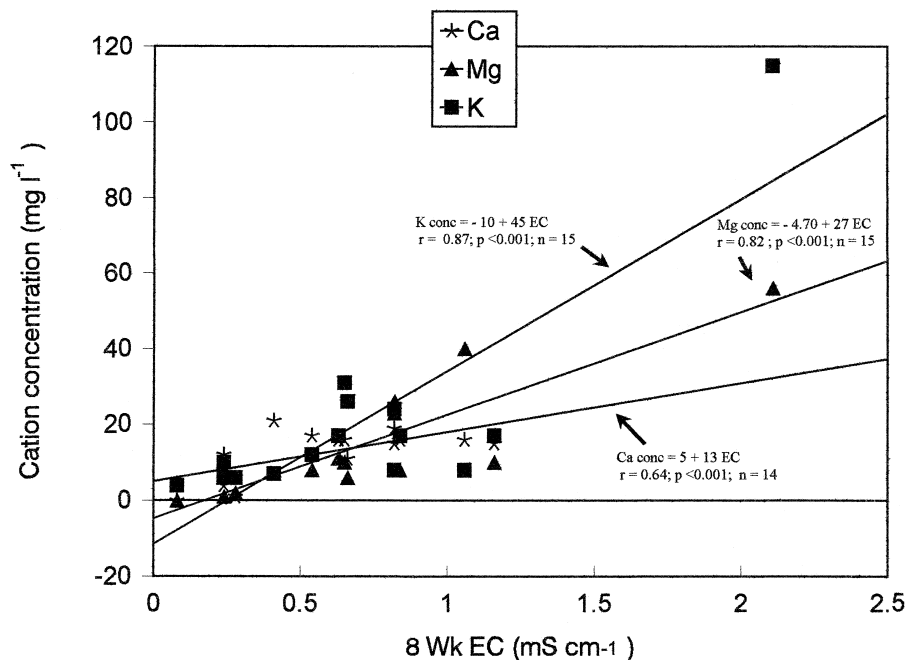
Fig. 10. Relationships between K, Ca and Mg concentration in soil solution and the solution EC of 15 flooded West African soils at 8 weeks of flooding.

released during 15 weeks of flooding, soil 10 released the highest ammonium, with a mean value of 74 mg N l^{-1} and soil 8 the least, with a mean value of 3 mg N l^{-1} and clearly reflected the extent of variability in the soils examined with respect to their capacity to mobilize ammonium.

Based on the kinetics of ammonium release in the soils they can be grouped into three classes:

(i) The soils (soils 3, 6, 9 and 10) that released greater than 50 mg N l^{-1} for most of the 15 weeks they were submerged may be considered best with respect to N supply and thus may need only modest application of fertilizer N;

(ii) The soils (soils 1, 2, 4, 5, 7, 11, 12, 14 and 15) that mobilized ammonium between 15 and 50 mg N l^{-1} on weekly basis are deficient in N and rice growing on them should greatly respond to added fertilizer N;

(iii) The soils (soil 8 and 13) that released less than 15 mg ammonium N l^{-1}, are considered acutely deficient in N supply and may need fertilizer N at both planting and as top dressing.

These results clearly establish that different soils may greatly differ in their capacity to release ammonium and thus may need different amounts of external N to achieve a target yield of rice (for a review see Sahrawat, 1983). Our earlier results with these soils also showed that they differ widely in their capacities to release ammonium during anaerobic incubation. Soil characteristics controlling
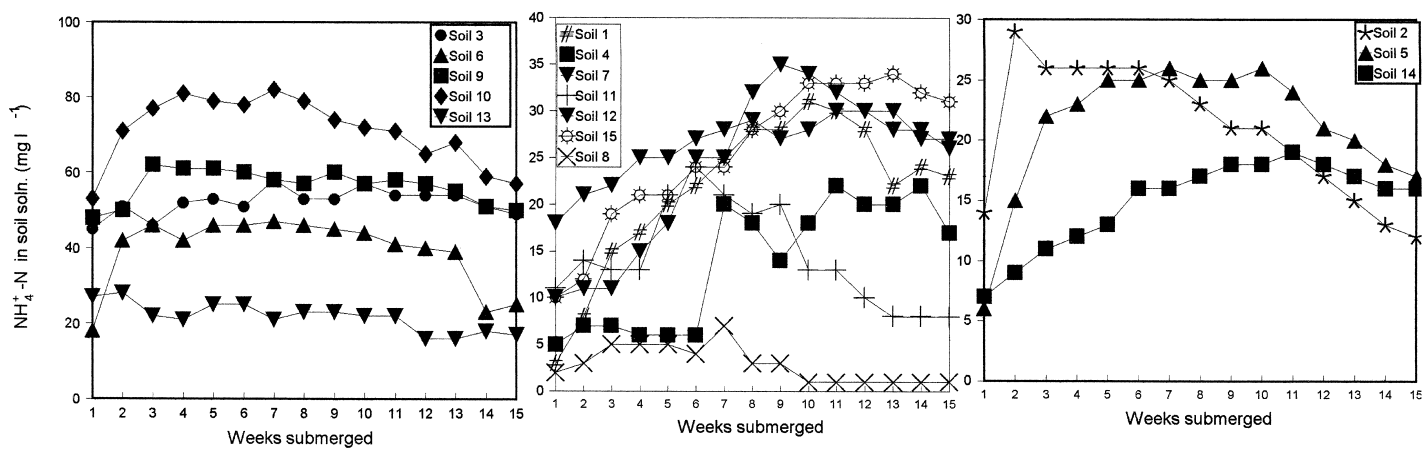
Fig. 11. Changes in the concentration of ammonium N in solution of 15 flooded West African soils.

N supplying capacity and N management strategy considering N supplying capacity of the soils for wetland rice production were discussed (Narteh and Sahrawat, 1997).

3.3.2. Changes in the concentration of P in soil solution

The increased availability of P as a result of flooding is of great benefit to lowland rice. It has been shown that Fe–P is the most important source of P to wetland rice and this is the fraction of P which is greatly influenced by water regime (Ponnamperuma, 1965).

The soils examined mobilized low amounts of P in soil solution during the 15 weeks under submerged conditions (Fig. 12), and the highest concentration of P in soil solution (0.63 mg P l^{-1}) was recorded by soil 8 and 9. It was further observed that the soil solution P showed three peaks: (i) soils 4 and 6 mobilized > 0.2 mg P l^{-1} during the first three weeks of flooding, (ii) all soils, except soils 10 and 15 mobilized > 0.25 mg P l^{-1} between 5 and 7 weeks, and (iii) soils 2, 5, 8, 9 and 15 mobilized P in soil solution between 0.30 and 0.63 mg l^{-1} at 8 weeks of flooding.

The initial increase in soil solution P in submerged soils is attributed largely to the reduction of ferric phosphate to the more soluble ferrous phosphate and, to a lesser extent, to displacement of phosphate by the organic anions from ferric and aluminum phosphates. The subsequent decline in soluble P is caused by resorption of phosphate on sorption surfaces such as clay and hydroxides and an increase in pH (Ponnamperuma, 1965).

3.3.3. Changes in the concentration of K in soil solution

At the first week of flooding, the concentration of K in soil solution ranged from 8 (soil 7) to 98 (soil 3) mg K l^{-1} and these values ranged between 6 (soil 8) and 110 mg K l^{-1} at 15 weeks of flooding (Fig. 13). All soils with the exception of soil 3 recorded values of K concentrations in soil solution less than 25 mg K l^{-1} indicating a need for K application from external sources in these soils. The requirement for K is further enhanced in soils that mobilize large amounts of Fe in soil solution (Sahrawat et al., 1996).

3.3.4. Changes in the concentration of Ca and Mg in soil solution

Changes in the concentrations of Ca and Mg in the soil solution of 15 soils are shown in Figs. 14 and 15. At the first week of flooding, the concentration of Ca in soil solution ranged between a trace (soils 4, 6 and 8) and > 500 mg Ca l^{-1} (soil 3). By the 15th week of flooding, the Ca concentration in solution was greatly reduced and ranged between a trace (soils 8 and 11) and 16 mg Ca l^{-1} (Fig. 14). In general, the kinetics of Ca in solution reached a peak by the 4th week and then the concentration fell. The decrease in the concentration of Ca in soil solution might have been caused by loss of CO_2 and the reversion of soluble bicarbonate to insoluble carbonate. The highest variability in Ca concentrations in soil solution occurred at the 4th week of flooding.
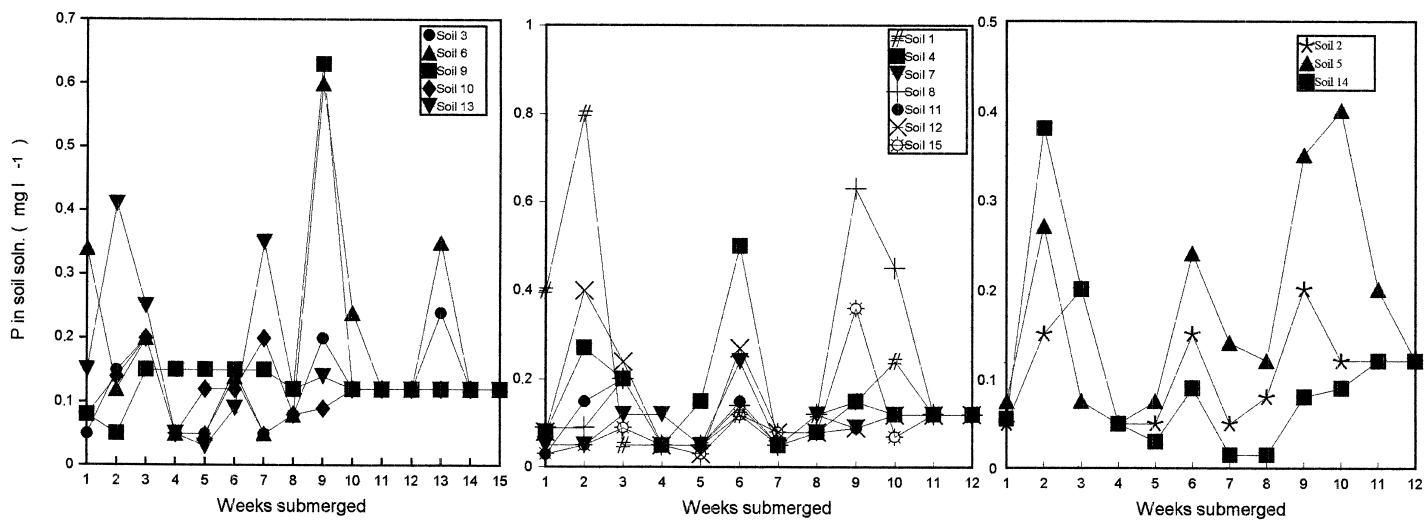
Fig. 12. Changes in the concentration of P in solution of 15 flooded West African soils.
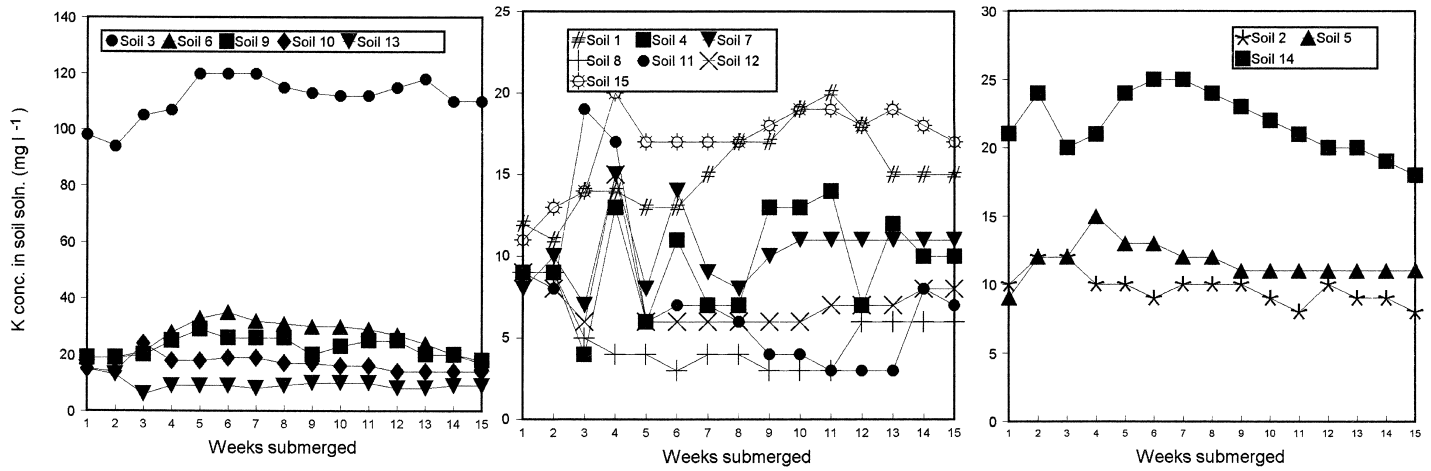
Fig. 13. Changes in the concentration of K in solution of 15 flooded West African soils.
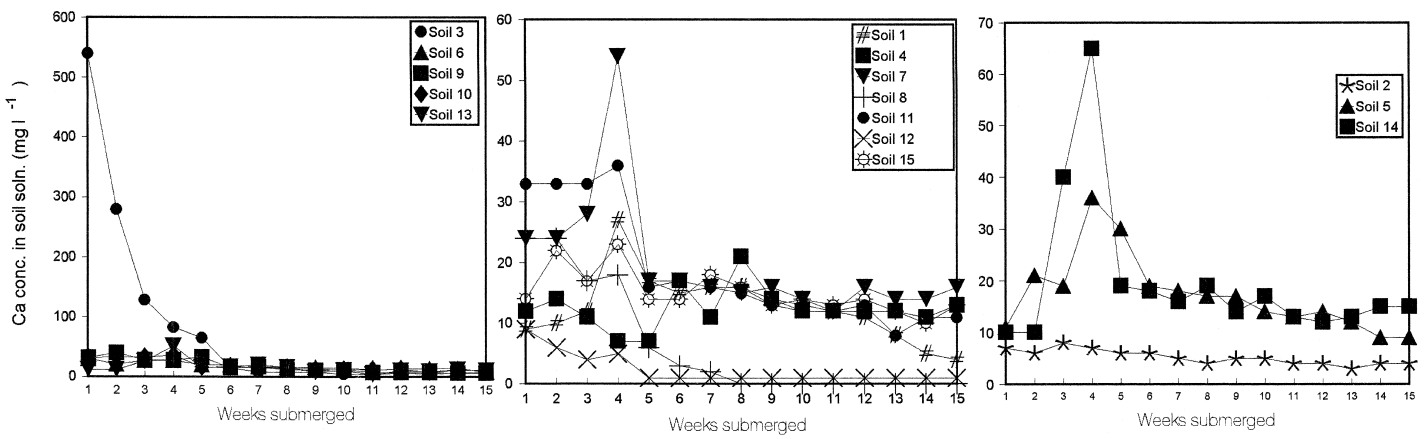
Fig. 14. Changes in the concentration of Ca in solution of 15 flooded West African soils.
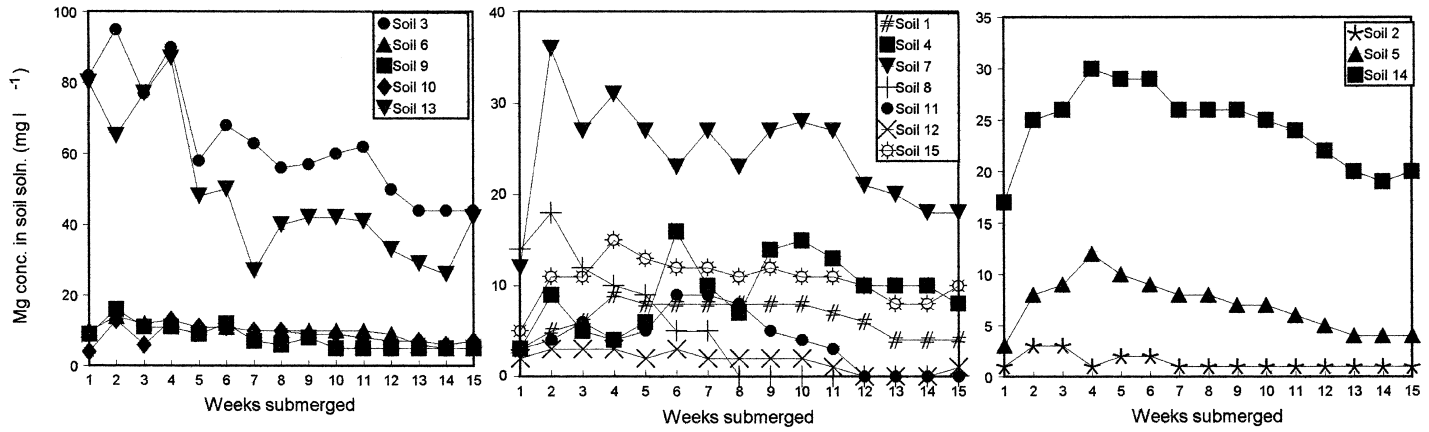
Fig. 15. Changes in the concentration of Mg in solution of 15 flooded West African soils.

At the first week of flooding of the soils, the concentration of Mg in soil solution ranged between a trace (soil 5) and 77 (soil 3) mg Mg l^{-1}, and by the 15th week the concentration ranged between a trace (soils 8 and 12) and 46 mg Mg l^{-1} (soil 3) (Fig. 15).

Assuming that Ca or Mg concentration of > 25 mg l^{-1} is critical for meeting the nutritional requirements of the rice plant, less than half of those examined (soils 3, 7, 9, 10, 13 and 14) met that requirement. Perhaps, more importantly, these soils may show an induced deficiency of these nutrients in iron-toxic soils or soils that mobilize excess Fe (> 40 mg Fe l^{-1} in solution) (Sahrawat et al., 1996).

3.3.5. Changes in the concentration of Fe(II) in soil solution

The soils exhibited a wide range in the concentration of Fe(II) mobilized in solution under flooded conditions over the 15 weeks period (Fig. 16). Concentrations of Fe ranged from 1 (soil 7) to 58 (soil 6) mg Fe l^{-1}. Based on the pattern of Fe(II) mobilized in soil solution, the 15 soils examined can be grouped into three classes:

(i) Soils (5, 6 and 13) that released > 50 mg Fe l^{-1} in soil solution and where the release of Fe peaked during the first 4 weeks of flooding. Delaying the transplanting of rice seedlings to 4 weeks after flooding (also termed presubmergence) on these soils may be a useful strategy for reducing iron toxicity to wetland rice;

(ii) Soils (1, 4, 9 and 10) that maintained a steady release of Fe in soil solution and released Fe in the range of 30–50 mg l^{-1} weekly during the 15 weeks. The Fe toxicity of rice on these soils may be difficult to manage because there will always be too much Fe in solution throughout the active growth period of the rice crop, provided the soil–plant conditions pertaining to Eh and pH promote the reduction of Fe;

(iii) Soils in which the amount of Fe(II) in soil solution was mostly < 30 mg l^{-1}. This group included upland, non Fe-toxic soils (soils 14 and 15) and other lowland swamp soils (soils 2, 7, 8, 11 and 12).

Organic matter acts as an electron donor in the reduction of Fe and high content of organic matter enhances the release of Fe(II) from Fe oxides (Ponnamperuma, 1972).

The equations which described the relationships between Eh, pH and the release of Fe(II) in soil solution were also evaluated considering all soils at 2, 4 and 6 weeks of flooding. They were as follows:

At week 2

$$Eh = 263 - 4.60 \log Fe(II) - 36 \, pH; \qquad R^2 = 0.49 \tag{6}$$

At week 4

$$Eh = 409 - 4.09 \log Fe(II) - 59 \, pH; \qquad R^2 = 0.99 \tag{7}$$
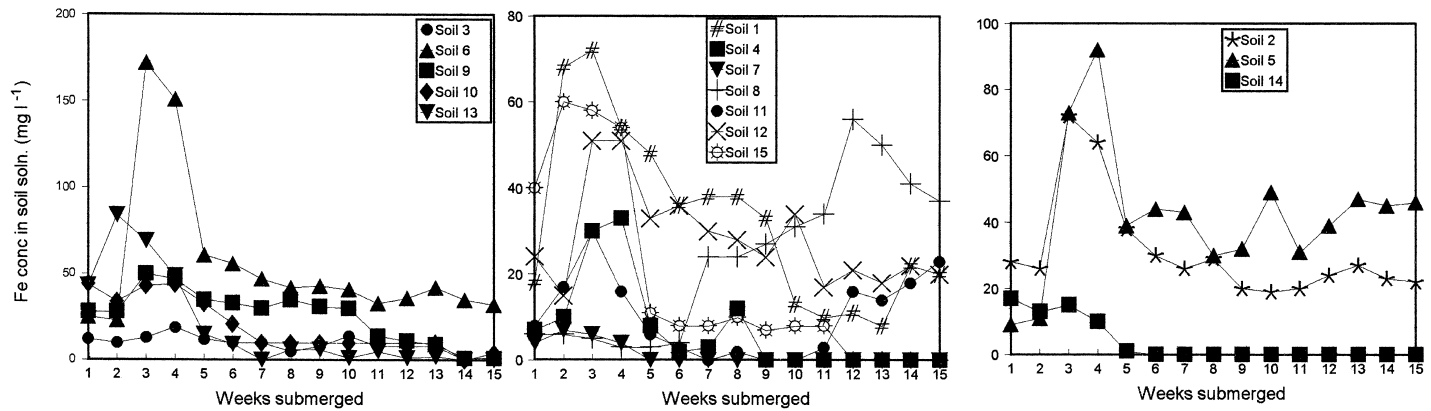
Fig. 16. Changes in the concentration of Fe(II) in solution of 15 flooded West African soils.

At week 6

$$Eh = 400 - 5.77 \log Fe(II) - 56 \, pH; \qquad R^2 = 0.71 \qquad\qquad (8)$$

These equations showed that by 4th week of flooding maximum variability in the Eh–pH–Fe(II) relationship was predicted, and the variability accounted for was lower at 6 and 2 weeks of flooding when the soils were in a phase of dynamic equilibrium. A considerable narrowing down in the range of the electrochemical properties of soils was observed as a result of their flooding under water. The pE + pH values of the anoxic water at 4th and 6th week of flooding when soil reduction was considered relatively stable (Table 4) support the finding that the soils were in a dynamic equilibrium. The recorded range in the values of pE + pH of 6.10 to 7.84 indicated that these values fall in the range of pE + pH required for the reduction of Mn and Fe oxides (Gotoh and Patrick, 1974; Genon et al., 1994).

Ponnamperuma et al. (1967) reported that the increase in the concentration of water soluble Fe(II) in flooded soils was caused by the reduction of ferric hydroxides and was described by the following equation:

$$Eh \,(mV) = 103 - 60 \log Fe(II) - 180 \, pH; \qquad r = -0.599 \qquad (n = 31) \qquad\qquad (9)$$

The equations describing the relationships among Eh, pH and Fe(II) in soil solution for the West African soils differ from those reported by Ponnamperuma (1965). In our study, higher values for coefficient of correlation were achieved

Table 4
Soil solution pH, pE and pH + pE of 15 flooded West African soils at 4 and 6 weeks of flooding

Soil no.	At 4 weeks			At 6 weeks		
	pE	pH	(pE + pH)	pE	pH	(pE + pH)
1	0.54	6.43	6.97	0.52	6.48	7.00
2	0.72	6.28	7.00	0.95	6.06	7.01
3	−0.32	7.31	6.99	−0.20	7.18	6.98
4	0.54	6.50	7.04	0.74	6.23	6.97
5	0.33	6.75	7.08	0.56	6.43	6.99
6	0.32	6.67	6.99	0.68	6.31	6.99
7	0.13	7.12	7.25	−0.016	6.99	6.97
8	0.52	6.50	7.02	1.00	6.84	7.84
9	0.44	7.44	7.88	−0.05	7.04	6.99
10	0.39	6.60	6.99	0.41	6.59	6.18
11	0.86	6.07	6.93	0.32	6.67	6.99
12	0.68	6.32	7.00	1.08	5.92	7.00
13	−0.76	7.76	7.00	−1.08	6.83	6.91
14	−0.08	7.03	6.99	0.25	6.74	6.99
15	0.64	6.35	6.99	0.63	6.37	7.00

Table 5
The range, mean and standard error (SE) of Mn concentration (mg l^{-1}) in solution of 15 flooded West African soils determined over 12 weeks

Soil no.	Range	Mean	SE
1	0–5	2.0	0.35
2	0–1	0.20	0.07
3	0–4	0.70	0.40
4	0–2	0.80	0.20
5	0–3	1.50	0.25
6	0–2	0.60	0.14
7	0–9	2.25	0.80
8	0–5	1.10	0.46
9	0–4	1.50	0.45
10	0–7	2.85	0.58
11	0–1	0.30	0.14
12	0–1	0.15	0.09
13	0–13	2.50	1.44
14	0–14	7.0	3.02
15	0–2	1.50	0.20

for predicting the Eh–pH–Fe(II) relationships, especially at 4 and 6 weeks of flooding the soils when the Eh values were in the range conducive for Fe reduction.

Table 6
The range, mean and standard error (SE) of Zn concentration (mg l^{-1}) in solution of 15 flooded West African soils determined over 5 weeks

Soil no.	Range	Mean	SE
1	0.0–0.50	0.23	0.09
2	0.0–0.30	0.13	0.05
3	0.0–0.22	0.08	0.04
4	0.0–0.36	0.10	0.06
5	0.0–0.20	0.10	0.04
6	0.0–0.43	0.16	0.07
7	0.0–0.40	0.15	0.07
8	0.0–0.44	0.09	0.09
9	0.0–0.70	0.34	0.14
10	0.0–0.35	0.10	0.70
11	0.0–0.60	0.22	0.12
12	0.0–0.40	0.20	0.07
13	0.0–0.23	0.10	0.04
14	0.0–0.20	0.10	0.04
15	0.0–0.20	0.10	0.04

3.3.6. Changes in the concentration of Mn and Zn in soil solution

The concentrations of Mn and Zn in soil solution for the 15 soils were low (Tables 5 and 6). The low concentrations of Zn and Mn in soil solution indicate a potential deficiency of these plant nutrients and, perhaps more importantly, the deficiencies of Zn and Mn to lowland rice may be further aggravated on Fe-toxic soils (Sahrawat et al., 1996).

4. Conclusions

Overall, our study showed that flooding affects electrochemical and chemical processes which, in turn, affect soil fertility in a dynamic manner. The main electrochemical changes that affect soil fertility include a decrease in redox potential or Eh and changes in soil and solution pH. These changes are mainly controlled by organic matter and reducible-Fe contents of soils. The chemical changes influenced by flooding include the release of macro- and micronutrients which depend on soil characteristics, especially texture, organic matter and reducible Fe.

In general, all the 15 soils, with the exception of soil 3, were reduced only in the healthy range. Soil 3 was highly reduced and can cause problems to lowland rice through the production of reduction products. It was observed that soils benefitted to varying degrees in terms of release of plant nutrients and stabilization of pH in the narrower neutral range. Soils 3, 6, 7, 9, 10, 11, 12 and 13 which were relatively high in both organic C and extractable Fe (related to reducible Fe), were generally more reduced and benefitted more. The rest of the soils were low in extractable Fe (soils 2, 5 and 14), organic C (soils 1, 2, 4, 5 and 8) or both, and were relatively less reduced and, in turn, released lower amounts of plant nutrients as a result of flooding. Certainly, flooding soil is a great equalizer of soil chemical diversity and this process is driven mainly by organic matter and the reducible iron status of the soils.

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