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A STUDY OF THE ADVERSE SOIL CHEMICAL CONDITIONS IN THE LOWLAND RICE AREA OF WEST AFRICA: A PROJECT FOR COOPERATIVE RESEARCH, GRADUATE EDUCATION AND SCIENTIFIC EXCHANGE

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EXECUTIVE SUMMARY

Rice is a major staple of for a large segment of the West African population therefore concerted efforts are required to increase its yield through out the region. Rice consumed is produced mostly on upland sites where yields are often very low due to low fertility, decreased fallow periods, use of low yielding cultivars, inadequate technical know-how and unidentified toxicities. Rice production on hydromorphic and bottomland soil sites although high yielding often experience nutritional disorders attributed to Fe or Mn toxicities. Some of the plant factors limiting rice yield have been addressed by the West Africa Rice Development Association (WARDA) through its network of researchers in more than sixteen member nations. However, considerably more research dealing with identifying the many factors limiting rice yield is needed. WARDA has collaborated with many institutions and universities throughout the world to achieve some of its objectives. The Wetland Biogeochemistry Institute of Louisiana State University and WARDA jointly developed this project "*A study of the adverse soil chemical conditions in the lowland rice area of West Africa*" to investigate soil properties limiting in rice growth in regions of West Africa. For reasons beyond control, work was only carried out on soils from Liberia and Côte d'Ivoire.

Laboratory investigations of four bottomland soils of West Africa showed that the soils are sandy, moderately acid to acid, medium in organic matter and contained moderate to high levels of exchangeable cations. It was determined that these bottomland

soils could be suitable for bottomland rice production. The soils however contained large amounts of extractable Fe that could become toxic to rice under low soil pH and anaerobic conditions. Extractable Fe and Mn increased with reducing conditions and were significantly correlated with Eh, pH and length of flooding. Investigations of three agricultural soils of West Africa (Typic Tropaquult; Plinthic Paleudult; Typic Dystrepept) involving lime showed increased pH, effective cation exchange capacity (ECEC), extractable Ca, Mg, K and decreased extractable and percent Al saturation. Uptake of Fe, Mn and Al by rice plants decreased with increased soil pH. The application of 0.5 to 1.5g kg^{-1} of lime to soil prior to flooding significantly increased soil pH and thereby making the soil conditions suitable for sustained agricultural production.

Investigations of soil factors limiting rice production at Mbé in bottomland soils indicated that Fe and Mn toxicity accounted for the majority of the low yield at the site. Iron toxicity was also identified as a major factor in limiting rice production at Korhogo. Iron and Mn toxicities symptoms were observed on rice grown in hydromorphic soils at Mbé. Soil pH and redox potentials were variable among cultivars but there was no significant relationships between these factors and cultivars. In-situ extraction of extractable ions was demonstrated to be a promising approach for the speedy and reliable identification of suitable sites for growing both non-Fe-tolerant and Fe-tolerant cultivars. Significant differences were observed in the uptake of

nutrient ions among cultivars during tillering and booting stages. Combinations of NPKZn fertilizers decreased Fe uptake by two test rice cultivars and also affected the uptake of other ions by the test cultivars. Iron toxicity evaluation confirmed the uptake of Fe by the two rice cultivars. Lime amendments on upland soils did not significantly influence soil pH. However increased nutrient amendments decreased extractable Al availability and increased the uptake of some soil nutrients.

High yields were obtained from plant cultivars grown in highly reduced soils. Soil pH values varied in the rooting zones of the rice cultivars. High yielding and Fe-tolerant cultivars which could out yield present Fe-tolerant cultivars in Fe-toxic fields were identified.

The contributions of West Africa rice production to global methane budget were also estimated. Atmospheric methane emissions from the West Africa Rice Development Association (WARDA) rice fields in Côte d'Ivoire, West Africa, were measured during maximum tillering and booting/flowering stages in order to determine the magnitude of methane flux from rice cultivars at different locations and under various cultural practices. Gas collection chambers installed in field trials treated at 36 $kgha^{-1}$ with 200 kg of 10-18-18 of NPK fertilizer and N rates of 0, 30, 60, 90 $kgha^{-1}$ as urea nitrogen. Phosphorus (P) and potassium (K) for the second trial were applied at 50 $kgha^{-1}$ as triple superphosphate (TSP) and 80 $kgha^{-1}$ as potassium chloride (KCl), respectively. Most of the methane samples were collected in the

morning and late afternoon. Methane flux from flooded rice fields varied with growth stage and location. Methane fluxes determined at night were generally lower than daytime measurements. Urea nitrogen application increased methane flux five folds in three of the four rice cultivars studied. Lower methane fluxes were measured over plots lacking N and P applications. These results indicate that Côte d'Ivoire wetland rice soils contribute to global methane emission similar to other rice growing areas of the world. Additional research will be required to establish the magnitude and range of the fluxes.

The findings from these investigations have been submitted for publication or published in journals so that the information will become available to the scientists in the region. Locally trained staff are using knowledge gained from this study to assist farmers in selecting suitable cultivars and sites for rice production.

INTRODUCTION

Improved rice production in West Africa has been plagued with uncertainties including the availability of appropriate technologies, equipment, supplies and technical know-how. Despite these setbacks, many West African nations have made great strides towards increasing crop production necessary for feeding their ever increasing populations. Sixteen West African nations formed the West Africa Rice Development Association (WARDA) to address factors limiting rice production. WARDA has cooperated with many international organizations and universities for assistance in addressing some of the crucial problems associated with rice production under various settings. Though much has been accomplished, clearer understandings of problems such as low nutrient status and toxicities in many rice producing environments have not been adequately investigated.

Rice is produced on a continuum comprising of several contiguous ecosystems such as upland, hydromorphic, inland valleys and irrigated lowlands. Upland rice accounts for about 44% of West Africa's total rice production. It is grown on about 1.3 million ha (57% of the total area under rice), primarily in Côte d'Ivoire, Guinea, Liberia, Nigeria and Sierra Leone. Over 70% of the region's peasant farmers grow upland rice as a subsistence crop. Yields vary considerably from year to year, with averages ranging from 0.5 tha^{-1} to 8 tha^{-1}. Slightly higher yields are obtained in areas where soil, rainfall and management conditions are more favorable, particularly irrigated,

hydromorphic areas and lands bordering inland valleys (WARDA, Annual Report 1991, 1992).

The relocation of WARDA at Mbé, Côte d'Ivoire presented a new challenge to researchers. The need for thorough assessment of existing soil parameters controlling rice production at the site became apparent. In this regard, WARDA and the Wetland Biogeochemistry Institute (WBI), Louisiana State University (LSU) agreed to cooperate on research that could provide answers concerning limitations in rice production. The report that follows summarizes work that was done by these institutions under a project " *A study of the adverse soil chemical conditions in the lowland rice area of West Africa*" supported by the United States Agency for International Development (USAID) was conducted with the goal of increasing rice yields in West Africa.

PROJECT OBJECTIVES

Cognizant of the needs of the nations and the manner in which rice is produced in West Africa, this investigation embarked on several approaches to provide information and a better understanding for solving the production problems associated with soil toxicity and low fertility on lowland, hydromorphic and upland soils in the region. The research conducted evaluated methods and strategies for solving plant nutrition and soil toxicity problems limiting rice production in West Africa. The first objective addressed was laboratory characterization of soils to determine nutrient contents,

acidity/basicity levels, oxidation-reduction potential status and evaluated various amendments for overcoming growth limiting factors in these soils. Field evaluations of these soil parameters were also conducted to determine conditions governing production of rice cultivars grown in the region. Both laboratory and field experiments were conducted to evaluate some amelioration techniques to reduce toxicities due to Fe, Mn, and Al and other factors such as pH and oxidation and reduction potential limiting rice production. In addition, local participants were trained in procedures for measuring soil pH and oxidation-reduction determinations and to relate their findings to potential growth related problems.

GENERAL METHODOLOGIES

Soil characterization

Soils were characterized for mineralogy, nutrient levels, pH, cation exchange capacity, organic matter content, aluminum saturation, particles size fractions and oxidation reduction potential. Standard procedures in use by the Soil Testing Laboratory and Wetland Biogeochemistry Institute at Louisiana State University were followed for most analyses. Other procedures are described separately.

A. Soil mineralogy and nutrient content

X-ray diffraction

Thin clay films were prepared using Caldwell's modified

version (1978) of the method by Jackson (1958) and mineralogy was determined from x-ray diffraction patterns using CuKα radiation at 2θ d-spacing.

Soil pH and chemical analysis

The pH of dry soil samples were obtained from a 1:1 soil to water ratio and a pH meter. Soil suspension and field pH values were determined by inserting pH electrodes into soil suspensions or directly into moist soils in the field and taking readings after a minute of equilibration. The electrodes were calibrated using pH 4.0 and 7.0 buffers. Total elemental contents were determined by digesting samples with HNO_3. Soil phosphorus, soil organic matter and exchangeable cations and anions were measured using standard procedures at the LSU Soil Testing Laboratory. Iron and manganese were extracted with normal NaOAc adjusted to pH 5.0. All ions were measured using an Inductively coupled-Argon Plasma (ICAP) Spectrophotometer.

B: Oxidation reduction potential measurements

Controlled and uncontrolled oxidation reduction potential evaluations were conducted in an apparatus made by sealing two one-half inch 18-gauge pieces of platinum wire on opposite sides near the bottom of a large pyrex test tube. These platinum electrodes were checked in a quinhydrone solution to ensure that correct Eh readings were obtained: Buffer, pH 4 (218 ± 5 mV) buffer pH 7 (40.8 ± 5 mV).

Sixty grams of air dried soil samples were added to each of two test tubes and flooded with 120 ml deionized water and the samples kept at room temperature. Initial pH and Eh measurements were taken and subsequent readings were taken everyday for thirty days or until there were less than 5 mV change in Eh values. Measurements were made by connecting alligator clips attached to a Beckman Zeromatic pH meter to the ends of the Pt electrode on the test tubes. A salt bridge connected to a calomel half cell was inserted into each test tube at measuring time to complete the circuit. Deionized water was added as needed to maintain the same water level above the soil.

Subsamples of moist soils from the oxidized and reduced zones in each test tube were removed and extracted sequentially with water and N NH_4OAc, buffered at pH 5.0. Filtrates were analyzed for extractable Al, Fe, Mn, Mg, Ca, K, Na and P with an Inductively Coupled Argon Plasma Spectrophotometer.

Task I

Assessing and Identifying Growth Limiting Properties of West African Bottomland Rice Soils

Abstract

Laboratory investigations were conducted using four bottomland soils of West Africa to determine soil solution properties that may limit rice yields. The soils were analyzed for mineralogy, particle size distribution, acidity, organic matter, native nutrient levels, oxidation reduction (redox) potential patterns of soil columns and suspensions and extractable and water soluble ions. These investigations have documented that the soils are sandy, moderately acid to acid, medium in organic matter and contained moderate to high levels of exchangeable cations that could be suitable for bottomland rice production. These soils also contained large amounts of extractable Fe that could be toxic to rice at low soil pH under anaerobic conditions. Extractable Fe and Mn increased with reducing conditions and were significantly correlated with Eh, pH and length of flooding. These findings indicate that these properties are important contributors to the observed low rice productivity in many of the bottomland soils of West Africa.

Introduction

Rice, the major staple of West Africa, is grown on upland soils. As a result of low yields on these upland soils demand for rice is greater than the production. The reported low yield are

attributed to low yielding cultivars, shortened fallow periods, low inherent nutrient availability of soils and ever increasing populations. Seeking to obtain higher yields, many farmers have been compelled to grow rice in bottomland soils where yields are potentially greater. However, productivity on bottomland soils are also restricted because of the use of low yield rice cultivars, poor fertility and unknown toxicities. To address varietal shortcomings, the West African Rice Development Association (WARDA) introduced many improved rice cultivars. Nevertheless, potential yields have eluded the farmers despite concerted efforts to increase yield. The lack of success in obtaining rice yield expected is a result in part to inadequate guidelines for rice production practices and inherent soil limitations in the bottomland regions.

Flooding of soils introduces reducing conditions that can initiate chemical and physical changes that affect many chemical species. Under continuous flooding oxygen become depleted and obligate anaerobic organisms initiate the consumption of alternative sources as terminal electron acceptors (Dolle, 1969). The end products vary from low molecular weight organic acids to sulfides, carbon dioxide and complex humic materials (Gambrell, et al. 1991). Many of these end-products potentially can adversely affect plant growth. In addition nutrient imbalances, high levels of iron, manganese, sulfate and aluminum have been reported as some of the causes of low rice yields in many wetland soils (Ponnamperuma, 1965, Tanaka et al., 1966, Jugsujinda and Patrick, 1977, Ottow et al., 1982). Iron toxicity symptoms have

been reported at concentrations ranging from 20 to 400 $mgkg^{-1}$ with most symptoms occurring between 300 to 500 $mgkg^{-1}$ (IRRI, 1963, 1964, 1987).

Acidity and oxidation-potential status (Eh) are known to greatly affect the solubility of Mn in soils. Under acidic conditions Mn (IV) and Mn (III) oxides and hydroxides are reduced to the soluble manganous form. Manganese solubility in aerated soils is very pH dependent (Adams and Wear, 1957). Patrick and Turner (1968) observed an increase in water soluble Mn under reducing conditions.

To date, there have been inadequate and insufficient number of systematic studies carried out on soils in West Africa necessary for truly understanding the factors limiting rice yields. The soil solution chemistry are very critical to predicting and understanding crop yield production.

This study was undertaken to determine some of the bottomland soil properties limiting rice yields obtained by farmers in the West African region. To achieve this objective, four representative bottomland soils were selected. These soils have generally exhibited lower than expected rice yields, exhibited Fe toxicity symptoms and have been used to screen rice cultivars for tolerance to Fe toxicity. Soil oxidation-reduction potential (redox) patterns in columns and in suspensions, particle size distribution, extractable nutrients, water soluble Fe, Mn, and pH were determined.

Materials and methods

Four dominant bottomland soils from the rice producing regions of Liberia and Côte d'Ivoire were collected and analyzed at the Wetland Biogeochemistry Institute, LSU using procedures currently in use at the LSU Soil Test Laboratory. The determinations made included: a) mineralogy and particle size distribution; b) acidity: 1:1 soil to water paste and in 1:2 soil to calcium chloride suspension; c) organic matter; d) phosphorus; e) salts: f) cations (calcium, magnesium, sodium, potassium, aluminum; manganese, iron). All ions were analyzed using the Inductively Coupled Argon Plasma (ICAP) Spectrophotometer.

The redox potential of replicated soil columns were determined using platinum and a calomel reference electrode connected to a pH meter with a millivolt scale. Two large test tubes with two 1 cm pieces of Pt attached on opposite sides at 2 cm from the bottom were filled with approximately 60 g of each soil and saturated with de-ionized water. A minimum of 2 cm water level was maintained above each column. The redox potential (Eh) and pH of each column was monitored for 34 days. The redox potential readings were adjusted for the Pt potential at pH 7 by adding 240±5 mV.

Replicated sets of suspensions containing 200 g samples of each soil were made with 1800 ml of de-ionized water in large erlenmeyer flasks. Oxygen was slowly bubbled through the suspensions and after an hour of equilibration the pH and Eh of

the suspension were measured using two Pt electrodes and a pH meter with a millivolt scale. Subsequent measurements were made daily for eight days. On each measuring day, twenty-five milliliter samples of each suspension were removed, shaken, centrifuged, filtered and the filtrate analyzed for Fe, Mn, Al, Mg, K, Ca, Na and P ions. Twenty-five milliliters of 1N NH_4OAc was added to the residue and treated as above. The above procedures were repeated while N_2 gas was bubbled through the suspensions. A two week data collection on Soil 2 for Eh and pH changes was done by installing nine Pt electrodes in a rice field showing leaf discoloration.

Results

Particle size and mineralogy

Particle size distribution in the various soils are shown in Table 1.1. The textural classes identified were clay loam, sandy clay loam and sandy loam. The sandy nature of many of the soils indicated that nutrient losses by leaching are likely. X-ray diffraction studies revealed that the soils were kaolinitic. Total and exchangeable Al amounts were very large. Restricted root development and drought susceptibility have been associated with soils high in Al (Foy, 1974). Traces of potassium feldspars but no interlayer clays minerals were found in these soils.

Soil parameters

The chemical characteristics of the soils used in this study are presented in Table 1.2. Data showed that the soils were

Table 1.1 Particle size distribution in selected bottomland rice soils of West Africa

Soil	Sand (%)	Silt (%)	Clay (%)	Textural class
1	43	25	32	Clay loam
2	47	26	27	Sandy clay loam
3	73	19	8	Sandy loam
4	70	12	18	Sandy loam

Table 1.2 Properties of selected bottomland rice soils of West Africa

Parameters	Soil			
	1	2	3	4
pH 1:1 H_2O	6.6	6.8	6.0	5.0
1:2 $CaCl_2$	5.8	5.5	5.4	4.2
O.M. (%)	2.6	2.1	1.6	2.5
Salts ($mgkg^{-1}$)	182	143	115	136
Ca "	1400	905	482	136
Mg "	461	301	128	23
K "	120	70	51	39
Na "	68	58	16	10
Al "	3.5	5.2	5.7	42
P "	60	51	47	60
Fe "	154	256	158	303
Mn "	29	34	9	13
Bases $meq(100g)^{-1}$	11.5	7.5	4.3	1.0

slightly acid to acid and low to medium in organic matter content. They varied in the levels of exchangeable bases. Soils with high levels of exchangeable bases generally had lower amounts of Al and Fe than those with low levels. The proportions of Fe to critical nutrients like Ca, K, Mg and P showed that Fe may dominate the exchange complex in many of these soils. Future studies will determine the relationships between these ratios and Fe-toxicity occurrences.

Columns

The soil pH ranges measured during the first two weeks of the study were as follows; Soil 1: 6.2-6.8, Soil 2: 6.0-6.4, Soil 3: 6.1-6.6, Soil 4: 5.0-5.6. Very little pH changes in soil pH were recorded during the rest of the study.

The redox potential patterns of the soil columns are shown in Fig. 1.1. The Eh values went from highly oxidized (+600 mV) to highly reduced (-242 mV). The rates varied among the soils sampled. The Eh values for Soils 1, 2 and 4 decreased to zero within 10 days of flooding. The slopes of the regression lines for the first phase of reduction were -119 mV, -62 mV and -82 mV per day, respectively. It took approximately 30 days for the Eh value of Soil 3 to reach zero. The slope of the regression line that described this trend was -12 mV per day. These differences may be related to the amounts of reducible components in each soil. The organic matter content rankings were: Soil 1> Soil 4> Soil 2> Soil 3. Soils containing low quantities of reducible components donot buffer a flooded system very well (Gambrell and

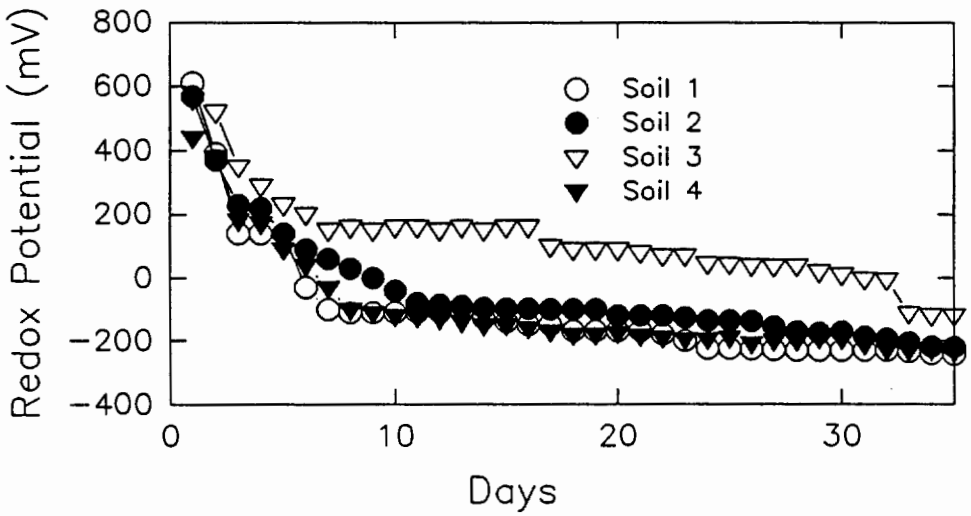

Fig. 1.1 Soil redox potential patterns in flooded columns of bottomland soils of West Africa

Patrick, 1978).

The soil redox relationships for the second phase of the reduction had slopes of -6 mV, -6 mV, -34 mV and -5 mV per day for Soils 1, 2, 3 and 4, respectively. All soils behaved alike except Soil 3. However, these patterns could not be linked to specific soil parameters.

Soil redox measurements could help wetland rice producers determine when certain critical and harmful chemical species were likely to be in the soil solution. It has been found that the order of reduction of redox-active chemical components is oxygen, nitrate-nitrogen, manganous-manganese, ferrous-iron, sulfate-sulfur and methane (Patrick, 1972; Harter and McLean, 1965; Bohn, 1971). The early reduction of three of these soils strongly suggested that many chemical species are likely to come into solution and in contact with young rice roots soon after transplanting and flooding rice fields. Nitrate reduction has been detected around 225 mV while manganous and ferrous species have generally appeared around 200 mV and 100 mV, respectively (Gambrell et al., 1991). Some essential chemical species could be removed from soil solution. Further research may help determine necessary seedling age and soil redox levels critical for successful transplant of rice in these soils.

Soil suspensions

Acidity patterns of the soil suspensions varied with oxygen levels (Fig. 1.2). During the oxidation phase, very little changes were observed in pH values. In most instances, the change

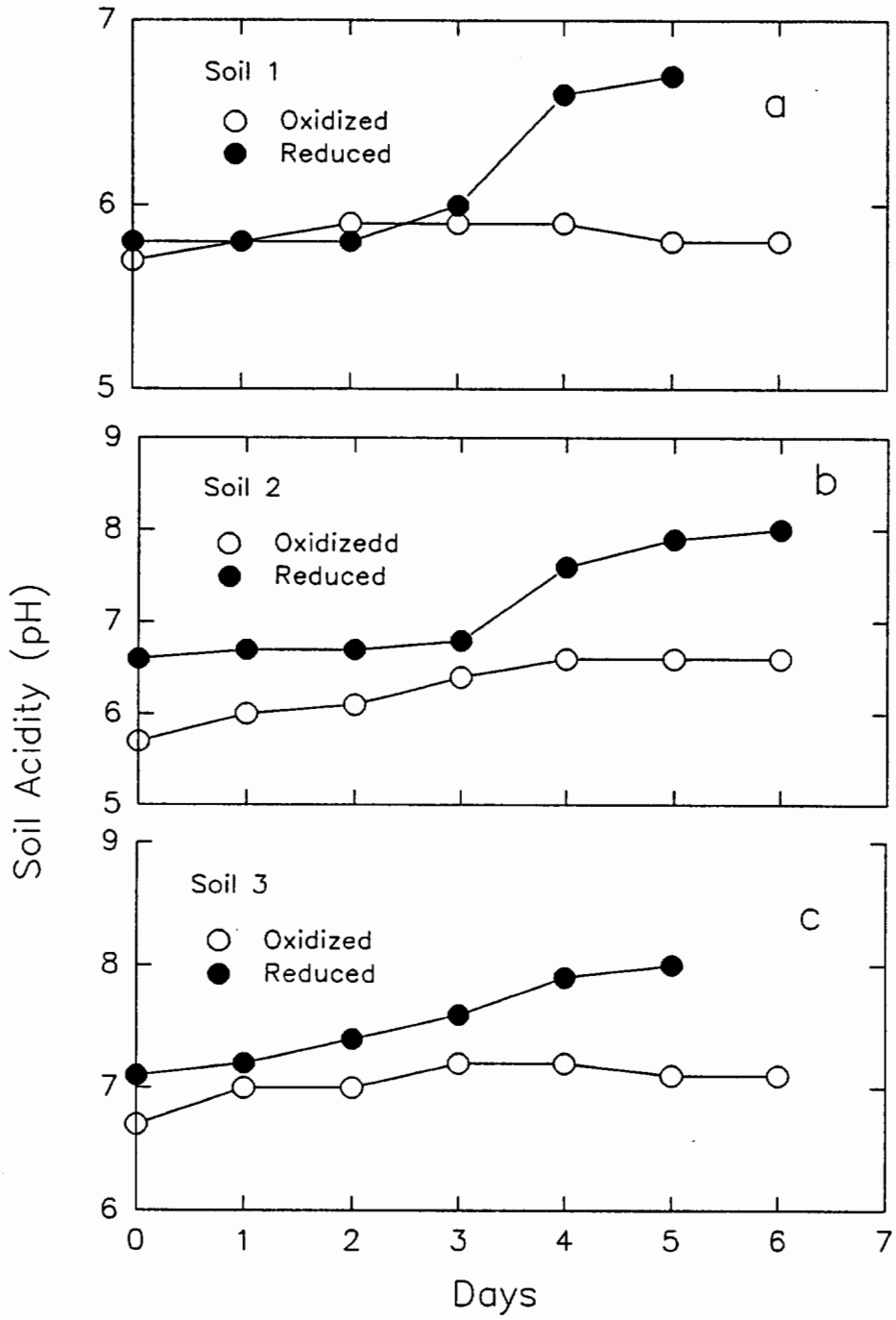

Fig. 1.2: Acidity patterns of oxidized and reduced suspensions of bottomland soils of West Africa

was less than one pH unit. However, with reduced oxygen levels, pH increased with length of flooding. These values were generally higher than those measured during the oxidation phase. The soil pH value ranges for the oxidation phase of the suspensions were Soil 1: 5.7-5.9; Soil 2: 5.7-6.6; soil 3: 6.7-7.1 and Soil 4: 5.0-5.4. The corresponding suspension pH values for the reduction phase were: 5.8-6.7; 6.6-8.0; 7.1-8.0; and 5.0-5.6, respectively.

As expected, oxidation of the suspensions increased in the Eh values of all the soils to about 600 mV. Very little differences were observed between the soils with time. This phase of the study demonstrated the effect of several days of air infiltration into inundated soils.

The introduction of N_2 gas into the soil suspensions enabled anaerobic microbes to decrease Eh of the soil suspensions with time as depicted in Fig. 1.3. The Eh values ranged from highly oxidized (600 mV) to strongly reduced (-300 mV). The order of the slopes of the regression lines describing the changes were -129 mV, -117 mV, -114 mV and -43 mV per day for Soils 1, 2, 3 and 4, respectively. The redox potential of Soils 1, 2 and 4 were significantly correlated with pH with correlation coefficients (r) of 0.93^{***}, 0.94^{***} and 0.91^{***}, respectively.

Soil pH values measured during this investigation were not in the normal ranges where large amounts of water soluble and extractable Fe and Mn are commonly observed. However, most of these soils had quantities of Fe and Mn that have been considered toxic to rice plants (IRRI, 1963, 1964, 1987). Rice plants

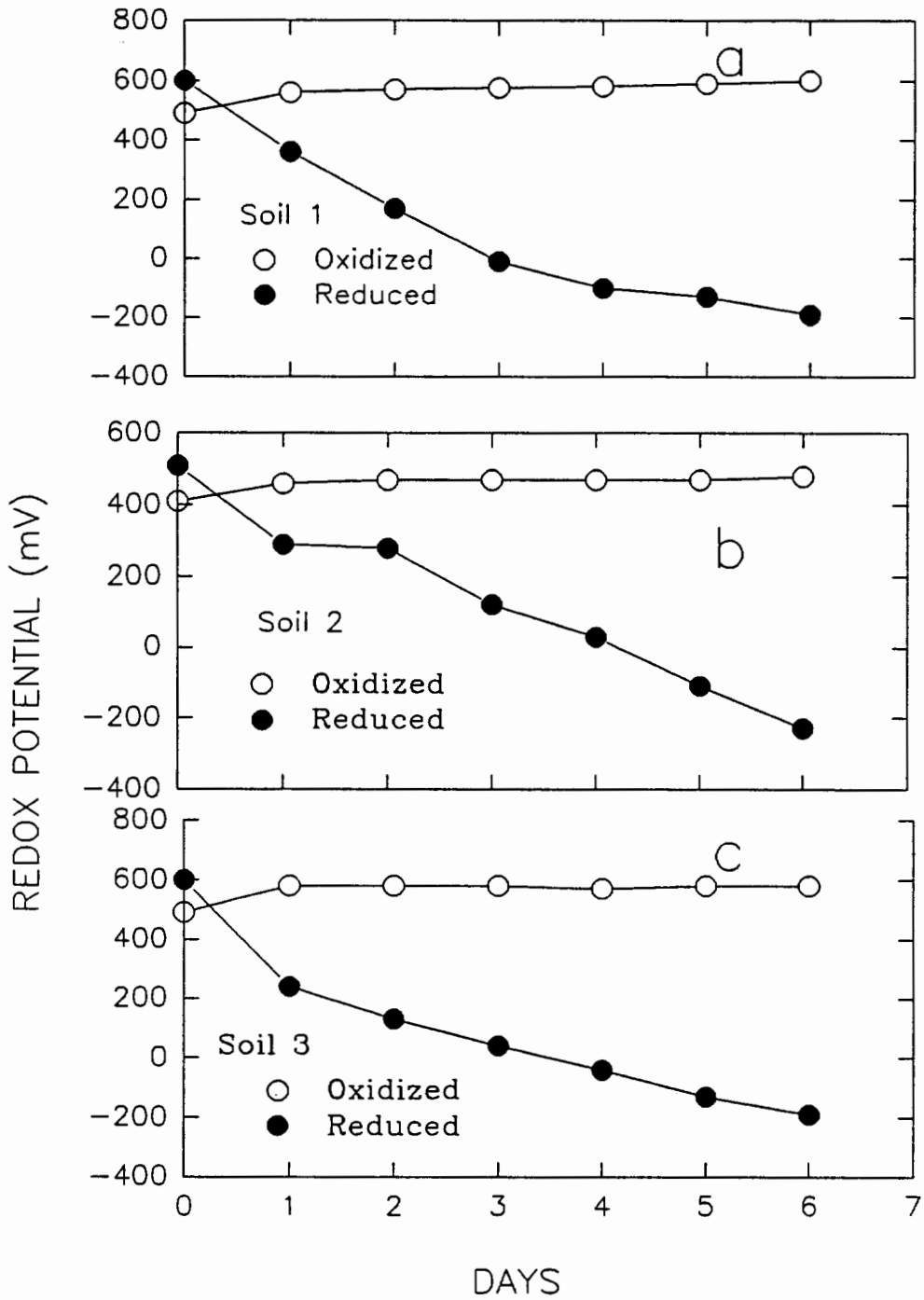

Fig. 1.3: Redox potential patterns of oxidized and reduced suspensions of bottomland soils of West Africa

growing in fields with similar pH values exhibited Fe toxicity symptoms.

The water soluble Fe concentrations of the suspensions increased with time of incubation (Fig. 1.4). Except for a slight drop in Mn levels for Soils 2 and 3 at the beginning of the measurements, Mn concentration also increased with time as shown in Fig. 1.5. Equilibration of the suspensions at specific oxidized and reduced Eh values caused significant changes ion concentrations. The dissolving of Fe containing compounds caused a slight increase in the quantity of water soluble Fe during the oxidation phase (Fig. 1.6a). The levels of two redox-active components (Fe, Mn) increased as redox potential decreased (Fig. 1.6b). These results indicate that the levels of Fe and Mn could become high enough to cause to affect young rice plants after 2 to 3 days of flooding or when the redox potential decreases drastically. Iron levels ranging from 20 to 400 $mgkg^{-1}$ have caused toxicity in rice plants under flooded conditions (IRRI, 1963, 1964).

The extractable Fe and Mn in Soil 4 varied with Eh. The concentration of Fe in suspension at 632 mV was 25.7 $mgkg^{-1}$ but this value increased to 160 $mgkg^{-1}$ when Eh reached -208 mV. Increases in Mn levels were also noted but not of similar magnitude. Mn increased from 4.0 $mgkg^{-1}$ at the highly oxidized level to 6.7 $mgkg^{-1}$ at the well reduced state.

Field measurements

The results of the measurements of pH and Eh in a rice field

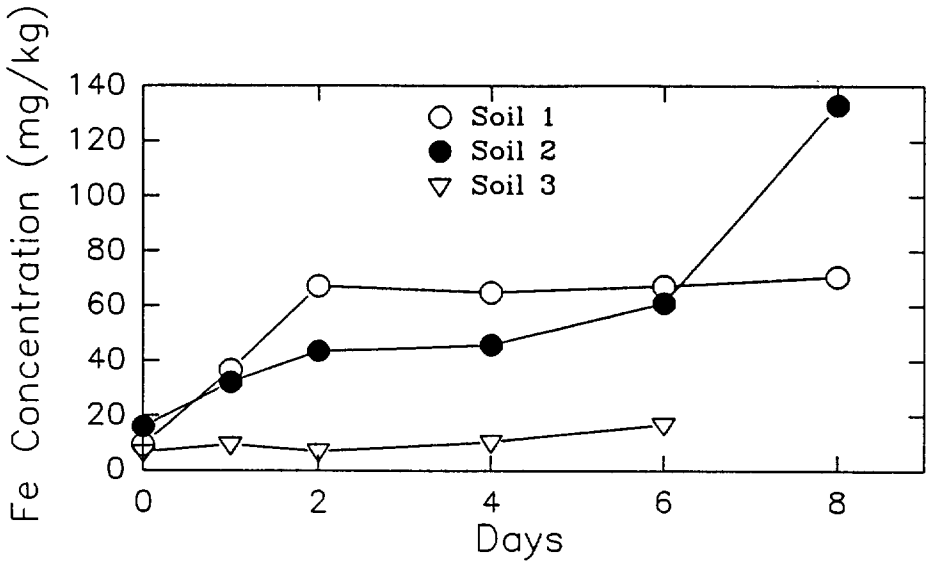

Fig. 1.4: The effects of incubation days on water soluble Fe in suspensions of three bottomland soils of West Africa.

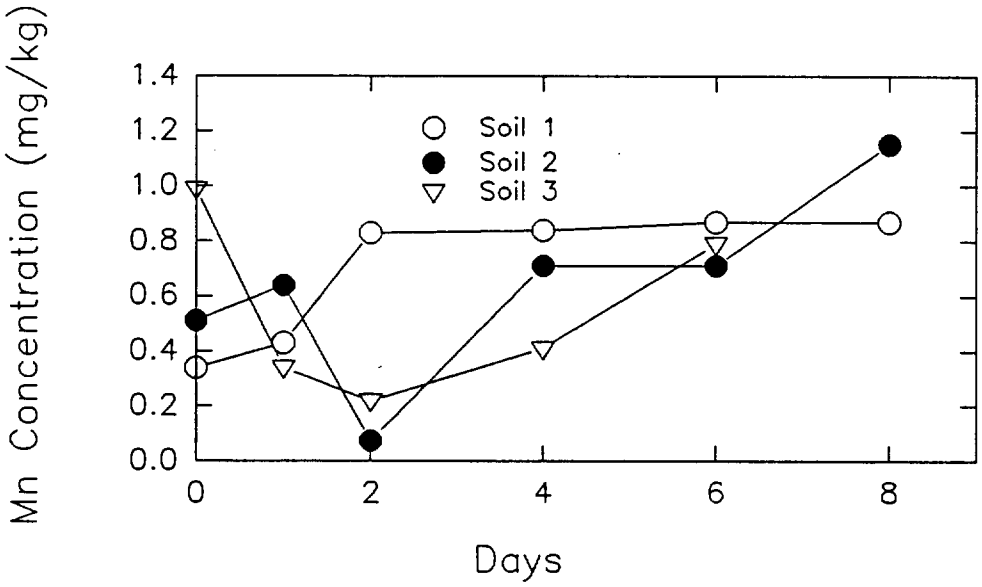

Fig. 1.5: The effects of incubation days on water soluble Mn in suspensions of three bottomland soils of West Africa

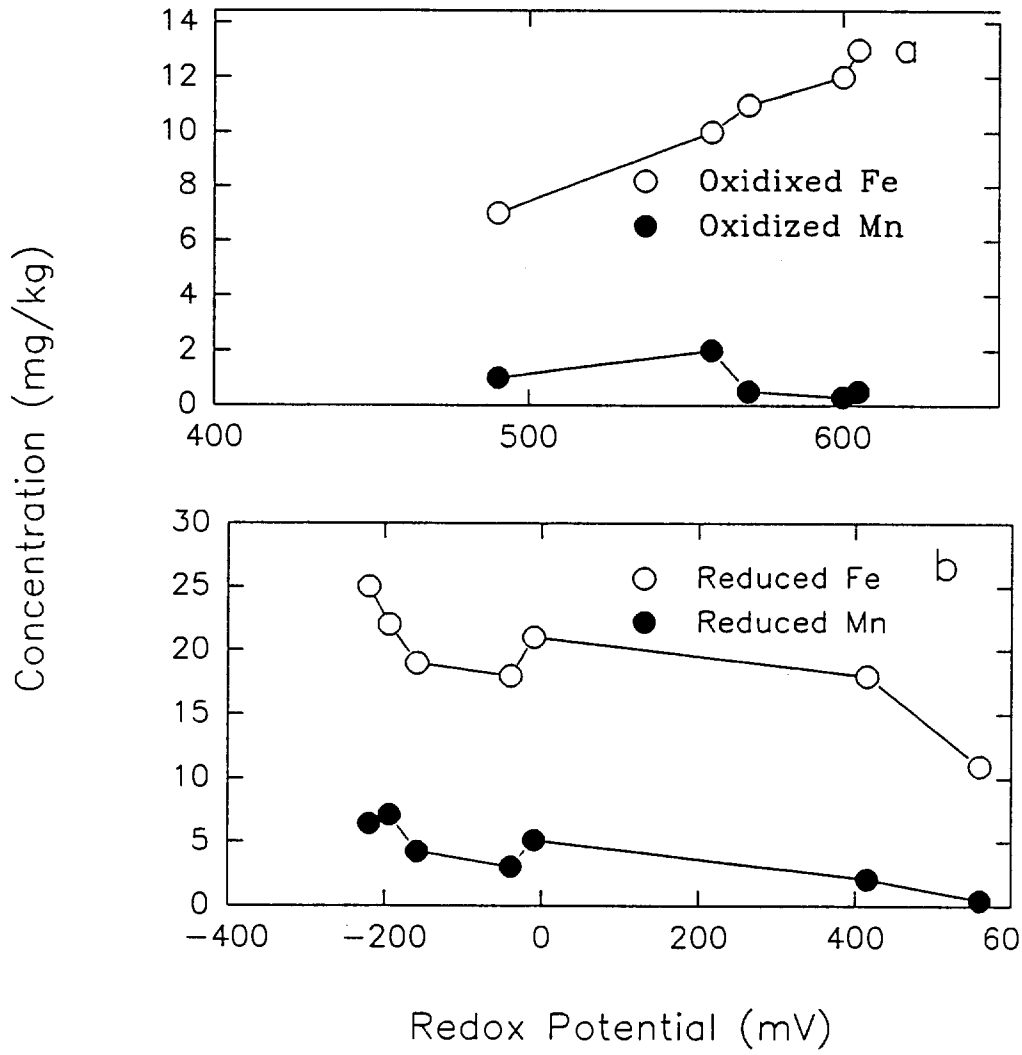

Fig 1.6 The effects of (a) oxidation and (b) reduction on water soluble Fe and Mn in bottomland soil suspensions

showing toxicity revealed that soil pH ranged from 4.6 to 6.3 with average pH value of 5.5. The Eh values ranged from 100 mV to -320 mV. These reducing conditions and the fact that Fe and Mn usually become more soluble at pH 5 and lower (Adams and Wear, 1957) strongly suggest that substantial quantities of these ions were likely in solution at the time of the study.

Conclusion

The study revealed that soil pH and redox potential relationships were very critical to the release of toxic levels of Fe and Mn. The slopes of the lines describing the decreases with time were closely related to the quantity of organic matter. The Fe and Mn determined from the soil suspensions were significantly correlated with Eh and time. Reducing conditions and pH were identified as important contributing factors in the release of very high levels of growth limiting components into the soil solution.

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TASK II

Liming and Flooding for Reduction in Aluminum Saturation in Rice Soils of West Africa

Abstract

Three agricultural soils of West Africa (Typic Tropaquult; Plinthic Paleudult; Typic Dystrepept) were limed at rates of 0, 0.5, 1.0, 2.0, 4, 12, 24 g kg^{-1}, flooded and incubated for 4, 6, 11 and 15 weeks to monitor changes in soil pH, cation exchange capacity, extractable Al, percent Al saturation and available nutrients. Liming increased pH, effective cation exchange capacity (ECEC), extractable Ca, Mg, K and decreased extractable and percent Al saturation. The uptake of potentially toxic Fe, Mn and Al by rice plants decreased with increase in soil pH resulting from lime application. Significant increase in soil pH with minimal lime addition in these acid soils was obtained as a result of flooding. Reduction of Fe and Mn oxides contributed to the increase in soil pH. The application of relatively low liming rates (0.5 to 1.5g kg^{-1} of soil) was effective under flooded soil condition for obtaining suitable soil pH conditions for sustaining agricultural production.

Introduction

Many soils in West Africa are very acid to moderately acid and have low nutrient holding capacity (Juo and Fox, 1977). Aluminum accounts for over 50% of the cation exchange capacity (CEC) of many of the soils (Pleysier et al., 1979). Aluminum

Table 2.1 Properties of experimental soils

Soil Properties	Ballam	Kollieta	Samukata
pH	4.7	5.2	4.1
O.M (%)	2.2	1.1	1.1
Clay (%)	18	10	
Extr. P($mgkg^{-1}$)	60	12	7
Exch. Al($mgkg^{-1}$)	65	76	111
Exch. Ca($mgkg^{-1}$)	148	49	52
Exch. K($mgkg^{-1}$)	38	44	16
Exch. Na($mgkg^{-1}$)	9	4	10
Exch. Fe($mgkg^{-1}$)	303	61	20
Exch. Mn($mgkg^{-1}$)	37	1	2
ECEC meq$(100g)^{-1}$	1.7	1.4	1.6
Al (%)	27	74	76

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Table 2.2 Effect of liming on selected extractable ions

Soil		Ca	Mg	K	Na	Fe	Mn	P
		mgkg^{-1}						
Lime rate(gkg^{-1})								
Ballam	0	105	25	30	10	871	13	6.7
	0.5	247	25	39	11	869	13	7.3
	1.0	265	23	30	13	782	11	6.5
	1.5	320	24	32	10	853	11	5.9
	2.0	340	24	30	10	847	11	6.3
Kollieta	0	27	12	34	3	493	1	1.5
	0.5	165	12	35	3	446	1	2.5
	1.0	278	11	34	4	375	1	2.2
	1.5	316	12	36	4	371	1	2.0
	2.0	343	12	36	5	389	1	2.2
Samukata	0	29	7	4	9	580	3	1.7
	0.5	177	7	6	8	552	3	1.7
	1.0	309	8	6	10	497	3	1.8
	1.5	379	8	10	10	445	3	1.9
	2.0	402	7	10	10	437	3	1.8

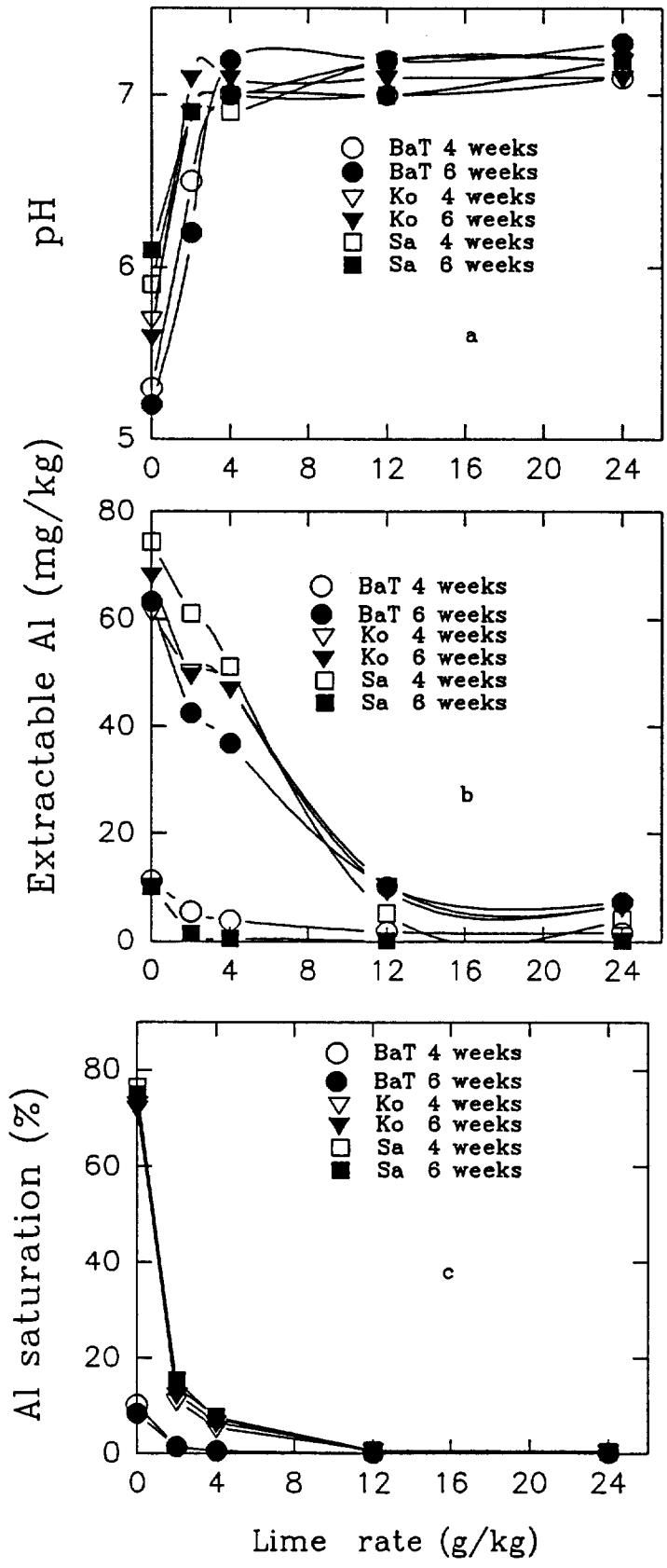

Fig. 2.1: Effects of liming on (a) pH, (b) extractable Al and (c) percent Al saturation in three three soils of West Africa

Ponnamperuma et al. (1966) reported that soil pH approached neutrality when air dried soils with acidity in the range of 4.5-6.0 were flooded for 6 weeks. Similar results were obtained by Mahapatra (1968); Yamane (1974); Halder and Mandal (1987). The formation of ferrous Fe and CO_2 in flooded soils under reduced conditions were said to be responsible for the increase in soil pH (Ponnamperuma, 1966). Increased soil pH could lead to increased availability and mobility of some plant nutrients as well as increased mineralization of N (Ono, 1991).

The effect of lime ($CaCO_3$) applications on extractable Al contents of the three tropical soils (Typic Tropaquult, Plinthic Paleudult and Typic Dystrepept) are presented graphically in Fig.2.1b and Fig. 2.1c. Less Al was extracted from the Ballam sample, as the lime rate increased. Both extractable and percent Al showed decreases with rates. The Kollieta sample also showed similar behavior. However, an exception was noted for the 4 g kg^{-1} rate which showed no significant difference between the values at the 0.05 probability level. The amount of Al extracted from the 2 and 4 g kg^{-1} treated soils were smaller than those extracted from the unlimed soils. The Al values found for the 6 week incubation period, though smaller than the unlimed soil values, were not significantly different from those reported for the 4 week incubation period at the 0.05 probability level. Statistical test at the 0.05 probability level revealed that the percent Al saturation values determined for the limed Kollieta soil were significantly different from those found for the unlimed soils.

The pattern of the extractable Al from the Samukata sample, showed that the 6 week incubation values were slightly higher for the 0, 2 and 4 g kg^{-1} lime rates. Further increase in lime rate reversed this trend. The decreases in extractable Al and percent Al saturation were all nonlinear. The results indicated that the lime rates were significantly different at the selected probability level and were effective in causing changes in extractable and percent Al saturation. The addition of 2 g kg^{-1} of lime caused more than 50% reduction in Al saturation. The lime probably precipitated inorganic Al and increased organic complexing of Al as noted by Curtin and Smillie (1983; 1986). The difference between the extractable Al values for the 4 and 6 week incubation periods were not statistically significant.

Liming had varying effects on the extractable cations in the soils but the difference between the four and six week incubation periods were not significant at the 0.05 probability level. The extractable Ca, K and Mg generally increased for all soils as the lime rate increased for both incubation periods (Figs. 2.2a-2.2d). More Ca ions were extracted from the soils than K and Mg ions. The extractable Na did not show any consistent trend thus it was not graphically presented here. Lime governs cation and anion retention in soils (Coleman and Thomas, 1976) and thus the availability of most plant nutrients (Jackson, 1967). The increasing concentration of cations in solution suggested increasing solubility of soil minerals with increasing lime rate.

The ECEC increased with increasing lime addition up to the

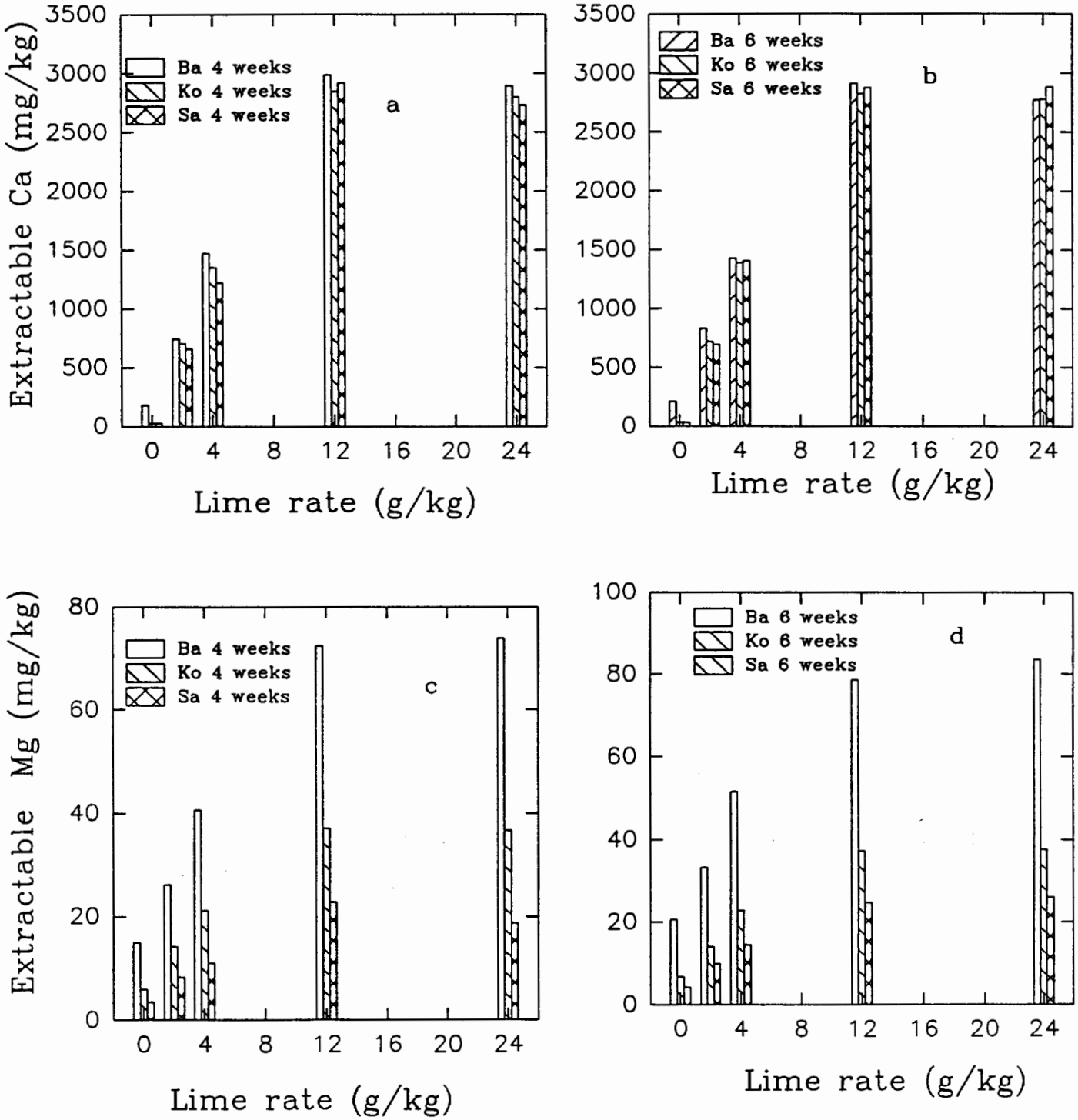

Fig. 2.2a–d: Effects of increased lime rates on ion concentrations in three soils of West Africa

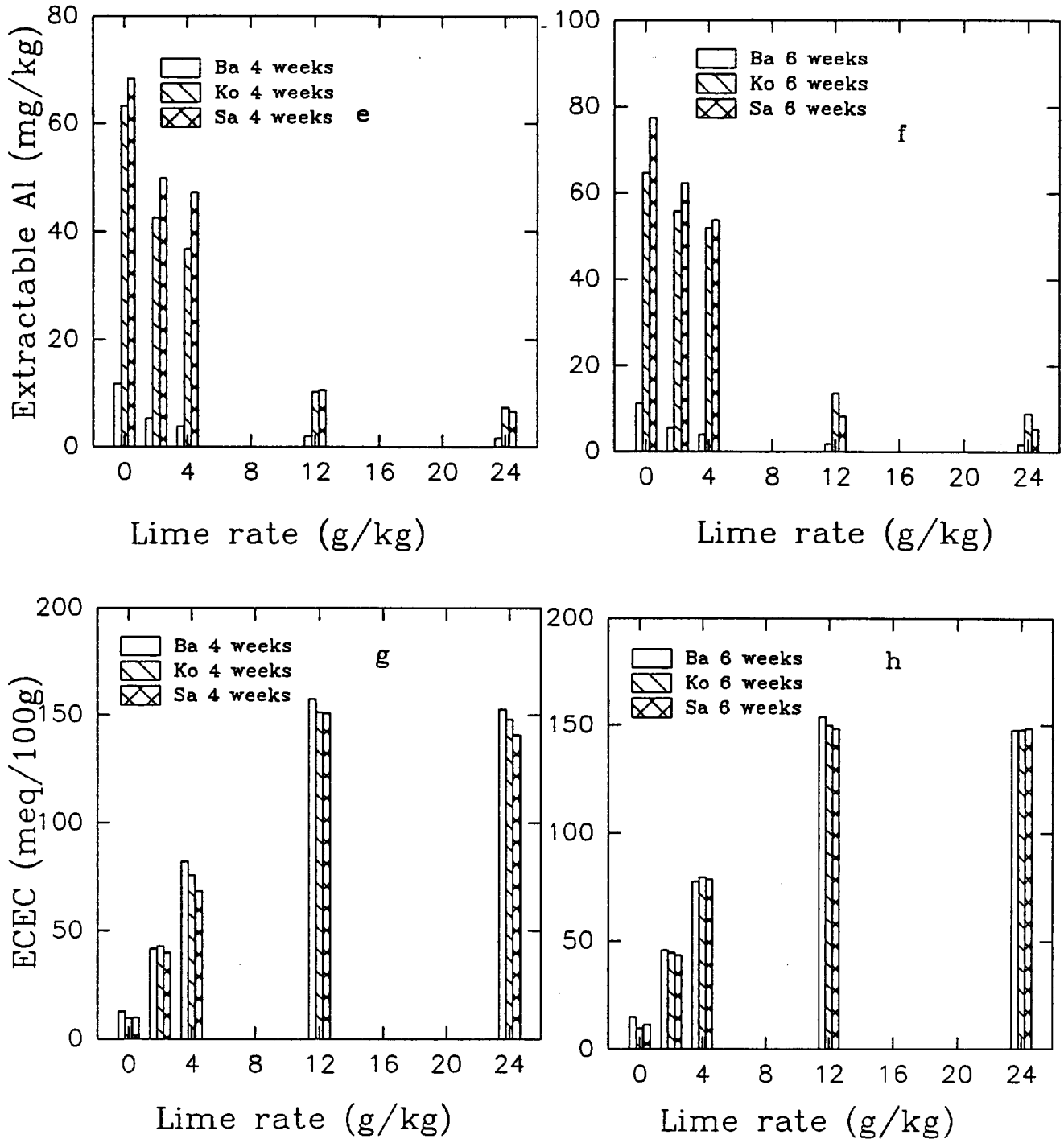

Fig. 2.2e–h: Effects of liming and length of flooding on extractable Al and effective cation exchange capacity in three soils of West Africa

12 g kg^{-1} rate (Figs. 2.2f and Fig 2.2h). Here as in other cases, the difference between the 4 and 6 week incubation periods was not significant at the 0.05 probability level. It is very likely that increased ECEC enhanced the retention of Al in these soils. It could therefore be assumed that liming these soils for crop production would augment nutrient retention. Liming probably caused Al to react with hydroxyl ions to give Al precipitates.

Increased liming generally increased pH, ECEC, nutrient cations and decreased percent Al saturation. Liming and flooding decreased the amounts of exchangeable aluminum ions in comparison to original soil levels.

Incubation of limed soils

The application of reduced rates of $CaCO_3$ promoted changes in several soil properties. The pH of the Ballam soil sample increased towards neutrality with the application of 1.5 g kg^{-1} of lime. At this treatment level, the Al saturation of the bottomland soil was reduced to less than 50% of the unlimed soil value. The ECEC increased from 1.9 meq$(100g)^{-1}$ to 4.8 meq$(100g)^{-1}$. The Ca ion concentration increased with liming but very little if any changes occurred in the concentrations of other nutrient ions (Table 2.3). There was an increase in extractable Fe as a result of flooding and liming. Increased Fe concentrations are known to present problems for crops grown under flooded conditions (IRRI, 1987; Tanaka and Yoshida, 1970; Ponnamperuma, 1965).

An illustration of acidity trends produced in the three

Table 2.3 Effects of lime and rice plants on selected upland soil parameters

Soil	Extractable ions								
	Ca	Mg	K	Na	Al	Fe	Mn	P	ECEC
	mgkg^{-1}								meq(100g)$^{-1}$
Kollieta unlimed	49	13	44	4	76	16	1	9	1.4
Lime rate (gkg$_{-1}$)									
0	68	21	27	41	69	676	9	1	1.5
0.5	277	20	13	36	69	774	8	2	2.5
1.0	344	15	42	40	7	392	6	0	2.2
1.5	512	16	36	39	7	378	7	0	3.0
2.0	567	14	31	41	5	323	6	0	3.3
Samukata unlimed	52	10	16	10	111	20	2	16	1.6
Lime rate (gkg^{-1})									
0	78	15	43	41	76	978	14	2	1.6
0.5	250	13	39	41	72	718	8	1	2.3
1.0	261	8	12	22	5	309	4	1	1.6
1.5	461	11	2	30	5	301	7	1	2.6
2.0	563	8	5	24	4	276	7	1	3.1

soils is given in Fig. 2.3. The pH levels of the Kollieta and Samukata soils increased with liming but did not reach neutrality. At the 1.5 g kg^{-1} treatment level, the percent Al was reduced to well below 50% of the original values while the ECEC increased two to three times the original values in both soils (Table 2.1). The Ca ion levels in both soils increased with liming. There were sharp reductions in percent Al saturation with the first increment of lime. Additional lime resulted in gradual declines in percent Al saturation (Fig. 2.1).

The affects of liming on the concentrations of other cations in solution are depicted in Table 2.3. The concentrations of Mg, K, and Na did not vary significantly from that of the unlimed soils. However, Fe concentrations were several times the values measured in the original soils. Increased Fe concentration with liming was likely due to the reduction of Fe oxides and solubilization of organic complexes similar to trends noted by Curtin and Smillie (1983). The extractable Mn and P were lower than the original soil values but did not change much with increasing treatment rate (Table 2.2). These findings suggest that liming could be beneficial through increased sorption sites, removable of exchangeable Mn and Al ions from the soil solution and reduced toxicity for upland crops. Weaver and Bloom (1977) observed that one of the factors limiting crop production on highly weathered soils of the humid tropics is toxic levels of Al that result from dissolution of soil minerals under acidic conditions. Curtin and Smillie (1986) reported that the addition

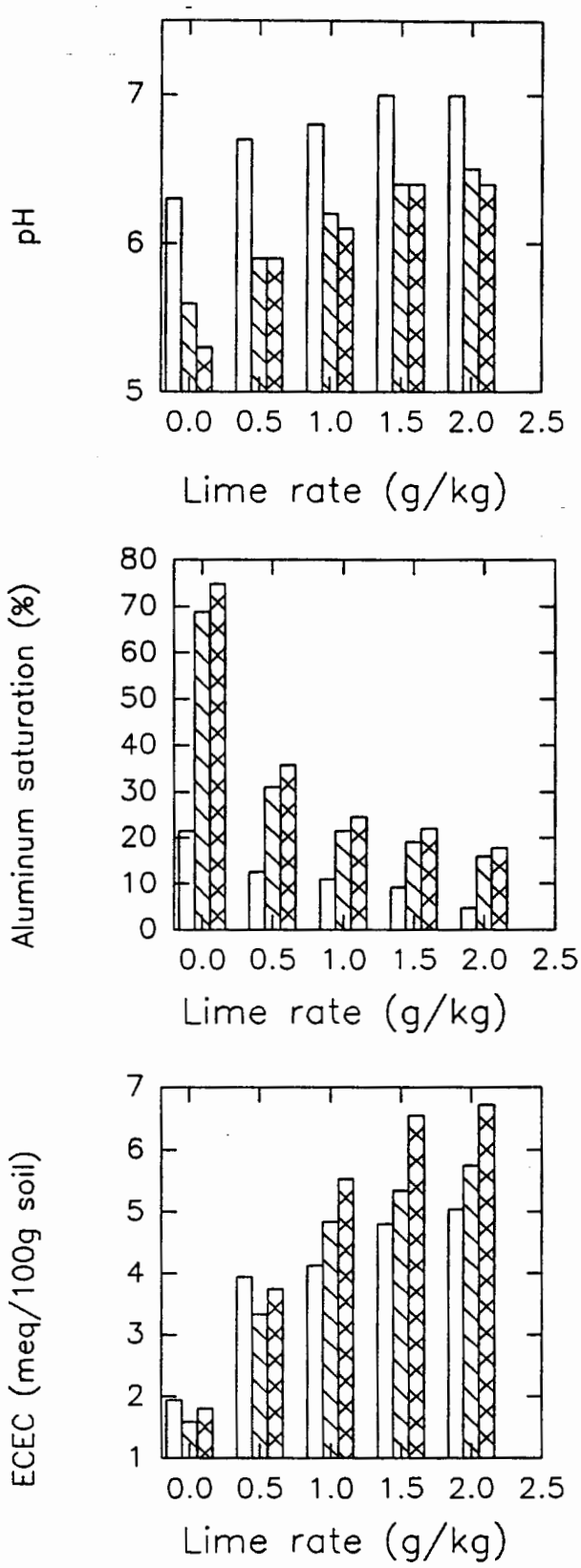

Fig. 2.3: Effect of liming on (a) acidity, (b) extractable Al and (c) ECEC of three soils of West Africa.

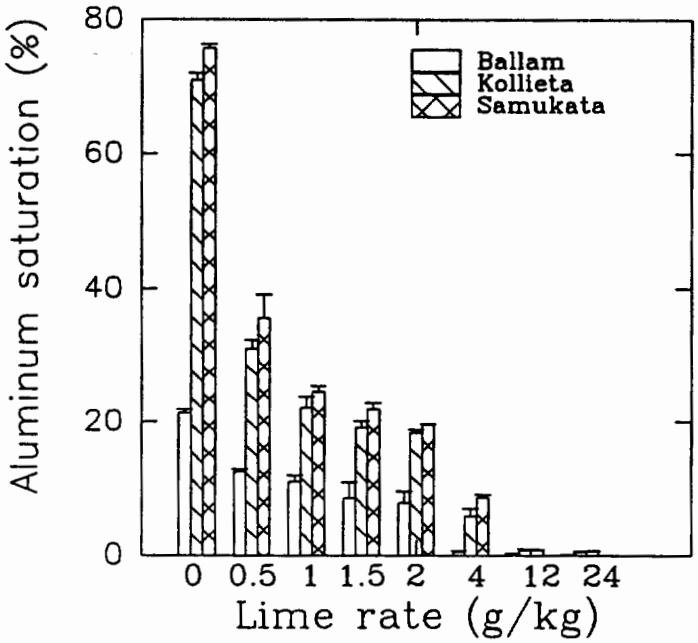

Fig. 2.4: Effect of lime on percent Al ssturation in three soils from West Africa

of lime resulted in increased adsorption sites and reduced Mn in solution. These authors also suggested that liming could lead to decreased solubility of Al as a result of slow crystallization of Al precipitate.

The results of the 4 week incubation with increasing lime rates (Fig. 2.4) provide essential information for determining the rate needed to obtain the desired reduction in Al saturation. The information indicated that about 2 g kg^{-1} would be needed to cause more than 50% reduction in Al saturation in the Ballam soil. The same amount of reduction would require about 0.5 g kg^{-1} for the Kollieta and Samukata soils. If it were desired that Al saturation of these soils be reduced to about 20%, about 1.5 g kg^{-1} could be used. Such low rates of lime could easily be purchased by farmers. Furthermore, the rates mentioned above would also produce increases in pH, ECEC and available cations as has been shown earlier.

Liming and plant growth Effects

Liming, flooding and incubating the soils for extended periods reduced acidity in all soils. The presence of rice decreased soil pH but the values were still higher than those observed after 4 weeks of incubation. The reduction in pH could be due to the production of low molecular weight acids and humic materials under anaerobic conditions (Gambrell et al., 1991). Rice roots can conduct O_2 to the rooting zone via the aerenchyma (Reddy et al. 1989). The presence of O_2 in the reduced zone

affect the biogeochemical processes such as the oxidation of reduced Fe, Mn, S, N compounds (Ponnamperuma, 1972; Engler and Patrick, 1975; Chen et al., 1980). Therefore, the increased acidity could have been caused by biogeochemical processes.

The data on the root and stem lengths, plant dry matter weight, culm and leaf blade discoloration did not reveal significant differences between the lime treatments. Visual observation did reveal thicker root mass as lime rate increased. Stem lengths increased over that of the unlimed soil with a maximum 5 cm difference between the first and last treatment. Treatment had very little impact on dry matter weight. Samples treated with lime did have slightly larger values than the unlimed treatments. Visual scoring of the plants using the Standard Evaluation System for Rice (IRRI, 1988) revealed that plants grown in the unlimed soil had over 50% discoloration. The level of discoloration decreased to less than 30% as lime rate increased.

The extractable iron levels (Table 2.3) from limed soil decreased as lime rate increased but these levels (>200 mg kg^{-1}) were well above toxic levels. Iron toxicity symptoms were observed when soil solutions contained 300-500 mg kg^{-1} (Trolldenier, 1977). However, soils containing between 20 and 40 mg kg^{-1} have also manifested Fe toxicity symptoms as a result of low levels of other nutrients (van Breemen, 1978). Considering that the amount of Fe reported only represented that which was left after the plants had removed some, it could be safely

assumed that the soils did have adequate amounts of Fe to have produced toxicity and discolorations in the leaves.

Concentration of extractable cations in the limed and flooded soils (Table 2.3) were greater than the extractable ions in soils without incubation. The quantity of K found in the Samukata soil was higher for the zero treatment in comparison to the amount found in Kollieta soil at the same treatment rate. The extractable K generally decreased as lime rate increased for the Samukata soil. The ECEC increased as Ca concentration increased with rate (Table 2.4). This trend was similar to those observed in earlier studies. The increased cation adsorption sites could have been responsible for the observed reduction in K (Bartlett and McIntosh, 1969). The quantity of P ions were much lower in the limed and flooded soils than non-incubated soils. The trend shown by P indicated precipitation of Al was likely a mechanism for the reduction in percent Al saturation. Alva et al. (1986) observed a significant decrease in total and monomeric Al as P/Al ratio increased. Increased anaerobic conditions may have lead to the dissolution of minerals that contain P and other anions. The increased surface charge could therefore remove Al and other cations from solution.

Liming effects on pH and tissue ion levels

The concentrations of Al, Mn and Fe and percent Al saturation in the rice tissues removed from the Samukata soil generally showed decreasing trends with increasing lime rate (Table 2.4).

Table 2.4 Effect of liming on ion concentrations in rice tissues

Soil	Selected tissue ions							
	Ca	Mg	Al	Fe	Mn	P	Zn	Alsat'n
	mgkg^{-1}							%
Kollieta								
Lime rate (gkg^{-1})								
0	3858	3197	1253	2771	1830	1500	63	11.44
0.5	4393	3051	1193	1512	1603	1269	38	10.71
1.0	5119	2699	705	956	1233	1455	38	6.41
1.5	6054	2987	811	1365	1740	1502	33	7.08
2.0	6243	2795	1124	1493	1477	1619	29	9.35
Samukata								
Lime rate (gkg^{-1})								
0	4855	3397	1420	1619	2170	1643	53	11.14
0.5	5102	2734	950	1027	1919	1323	36	9.19
1.0	3854	1971	543	841	1494	926	23	7.29
1.5	6810	2909	607	798	1696	1295	25	4.95
2.0	5190	2498	498	761	1365	1139	28	5.08

Similar consistent decrease in percent Al saturation was not observed in the Kollieta soil. The effect of Al on rice production could be detrimental only if the field remains flooded for a lengthy period. Although upland rice is not constantly flooded, the conversion of many fields to irrigated paddies could present unhealthy growing environments involving Al as rice has slight tolerance for Al (Foy et al., 1978). The phytotoxicity of Al is dependent on the concentration or activity of predominantly toxic Al monomers in solution rather than the concentration of total Al (Alva et al., 1986). Alva and Sumner (1989, Blamey et al., 1983) found that a concentration of 40 μM Al was extremely toxic to soybean. Threshold limits of 20 mg kg^{-1} Al have been seen for some rice cultivars while some crops are known to grow at much higher concentration levels (Foy et al., (1978). The cultivar used did not show any toxicity symptom at the Al concentrations in the tissues.

The initial goal of quantifying the level at which liming substantially decreases Al concentration and increases pH in these tropical soils was realized. The effect of liming on pH after 4, 11 and 15 week incubation periods showed that soil pH was maintained at a level where Al concentration was not high in the soil solution to affect rice production. Liming did not induce deficiencies of P and /or micronutrient (Munns, 1965) as the rice tissues had nearly normal levels of nutrients.

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Conclusions

Results from this study indicated that liming and flooding of some West African soils can lead to increased pH, improved extractability of most nutrient ions, increased adsorption sites through increased ECEC. Liming resulted in decreased percent Al saturation, Fe and Mn in most soils. Similar decreases in Fe, Mn and Al uptake by rice plant were observed. The use of low lime rates (0.5 to 1.5 g kg^{-1}) were quite effective in promoting these changes in many soil parameters and could therefore make lime use more profitable for low income West African farmers. The study further indicated that liming also led to improved nutrient availability and was therefore very effective in producing desirable changes in soil properties.

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TASK III

Soil Acidity, Redox Potential, Iron Toxicity, and Extractable Ion Assessments in Rice Soils of Côte d'Ivoire, West Africa

Abstract Investigations of bottomland soils from Mbé and Korhogo indicated that both Fe and Mn may be responsible for limiting rice yield at Mbé while Fe toxicity could be a major factor in limiting rice production at Korhogo. Rice grown in hydromorphic soils at Mbé showed both Fe and Mn symptoms. Results from studies with several cultivars indicated variability in pH and Eh levels but no clear relationship between these factors and cultivars. In-situ extraction and quantification of extractable ions was determined to be a promising novel approach for the speedy and reliable identification of suitable soil sites for growing both non-Fe-tolerant and Fe-tolerant cultivars. Significant differences were observed in the uptake of nutrient ions among cultivars during tillering and booting stages. Combinations of NPKZn fertilizers decreased Fe uptake by the two test rice cultivars and also affected the uptake of other ions the test cultivars. Iron toxicity scores confirmed the uptake of Fe by the two rice cultivars. Lime amendments on upland soils did not significantly influence soil pH. Nutrient additions decreased the Al availability and increased the uptake of some soil nutrients.

Introduction

Rice, a major staple for many of the inhabitants of West Africa, is grown on a continuum consisting of bottomland, hydromorphic and upland soils. Each of these environments possesses its own growth controlling characteristics. Bottomland and hydromorphic soils are increasingly being used for rice production. These ecosystems can under oxidation-reduction changes depending on water content. Facultative and anaerobic organisms are active in aerobic soils and use oxygen as terminal electron acceptors and produce by-products such as carbon dioxide, nitrate, sulfate and residual humic materials (Gambrell et al., 1991). Oxygen depletion resulting from flooding of rice fields causes obligate organisms in anaerobic soils to use other terminal electron acceptors (Doelle, 1969) such as nitrate, manganic manganese, ferric iron, sulfates which produce low molecular weight organic acids, complex humic materials, carbon dioxide, methane, ammonium, amine and hydrogen sulfide as end products (Reddy and Patrick, 1975, Gambrell et al. 1991). Some of the end products may enhance or hinder rice production.

Soil acidity affects the availability of essential nutrients. Aluminum toxicity occurs mainly in acid soils with pH less than 5. Flooding Ultisols and Oxisols which contain mainly Al causes increases in pH and lead to P fixation by Al. Van Mensvoort et al. (1985) reported that critical concentration for Al toxicity are 4.5 to 5.0 for seedlings and 3.4 to 4.0 for older plants. Manganese toxicity has been associated with increasing pH. Iron toxicity in rice is generally associated with low pH and

nutrient imbalances. This phenomenon, described as a purplish-brown discoloration of the leaf blades, depressed growth and tillering, scanty, short, coarse and stained brown or reddish root system (IRRI, 1963), occurs in many flooded rice fields in West Africa. The actual Fe concentration have been known to range from 20 mg/L to 400 mg/L and to vary with cultivar and growth stage (IRRI, 1964).

Oxidation reduction potential (redox) values range from +700 to -400 mV and involving several chemical species. Soil systems are well oxidized if they have redox potential values above 400 mV and strongly reduced if redox potential values go below -200 mV. Oxygen depletion occurs in the range of 340 to 320 mV. Patrick (1960) observed nitrate reduction at 338 mV in Crowley silt loam soil with pH of 5.1. Manganic manganese (Mn^{+3}) is reduced next to soluble manganous ion (Mn^{+2}) when redox potential decreases to 200 mV. Ferric iron (Fe^{+3}) reduces to ferrous iron (Fe^{+2}) when the redox potential decreases to 120 mV (Bohn, 1971). Sulfate (SO_4^{2-}) reduction to sulfide (H_2S) has been observed around -150 mV and methane production occurs around -250 mV.

End products exert different effects on rice plants. Investigation of the occurrences of some these processes are essential to understanding growth parameters in rice soils of West Africa. Extensive research activities on many of these processes and ions have been done by several prominent investigators in many parts of the world (Ponnamperuma, 1965; Tanaka et al. 1966; Jugsujinda and Patrick, 1977; IRRI, 1963,

1964; Ottow et al. 1982; Van Mensvoort et al., 1985). Very scanty, if any, information is available on rice soils of West Africa. To fill the voids, field investigations were conducted in Côte d'Ivoire on redox potential trends, Fe toxicity, soil acidity and nutrient status in rice growing ecosystems.

Scope and methodology

Visits were made to several research sites and farmer fields where observations were made and water, soil and plant samples collected for analyses. Field soil pH and water soluble iron determinations were made. In addition pH and Eh levels were monitored for two growing seasons on selected trials. Five cultivars out of twelve cultivars that were being tested by WARDA scientist for tolerance to Fe toxicity were also evaluated. The responses of two cultivars Suakoko 8 (Fe-tolerant) and Bouaké 189 (Fe-susceptible) were evaluated using combinations of nitrogen, phosphorus, potassium and zinc amendments. Extraction and other procedures were similar to those described earlier.

Results and discussions

Soil acidity profiles shown in Table 3.1 indicate a pH range of 5.2 to 7.2 for the hydromorphic soils. The average pH values of hydromorphic soils increased at times during study but maintained to an average around 6.4 after two years of monitoring during tillering to booting stages (Table 3.2). The perplexing fact is that some rice cultivars showed Fe toxicity symptoms under such pH values. It is clear that acidity alone could not

Table 3.1 Acidity profiles of non-Fe-toxic and Fe-toxic bottomland soils of Côte d'Ivoire, West Africa

Site	Non-Fe-toxic	Fe-toxic
1	7.8	5.5
2	7.3	5.4
3	8.9	5.5
4	7.4	6.3
5	7.2	5.7
6	7.3	5.3
7	7.9	6.6
8	7.1	4.4
9	6.8	5.3
10	7.6	4.6
Mean	7.5	4.9

Table 3.2 Acidity profiles in hydromorphic rice fields of Côte d'Ivoire, West Africa

	Days				
Electrode	1	5	10	21	Average
	pH				
1	6.3	5.7	6.6	5.3	6.0
2	5.5	5.2	6.0	5.5	5.5
3	5.7	5.5	5.9	5.2	5.5
4	6.0	5.8	6.2	5.3	5.8
5	5.4	4.9	5.4	6.3	5.5
6	5.8	5.8	5.8	5.7	5.8
7	7.6	7.2	7.4	6.2	7.1
8	5.8	5.7	6.4	7.0	6.2
9	7.1	7.3	7.6	7.5	7.3
10	6.0	6.0	6.4	6.7	6.3
11	6.6	6.6	7.5	6.6	6.8
12	6.9	6.9	7.5	6.3	6.9
13	7.3	7.4	7.6	6.9	7.3
14	6.3	6.6	6.4	6.8	6.5
15	7.3	7.5	7.5	6.8	7.3
16	6.8	7.4	7.4	6.3	6.9
Average	6.4	6.3	6.7	6.2	6.4

account for the Fe toxicity at this site.

The soil redox potential profiles (Table 3.3) clearly indicate that some site had highly reducing conditions that could have encouraged the release of Fe and Mn into solution. The average field redox potential decreased with time at this hydromorphic site as shown in Fig. 3.1 when the readings were corrected for the Pt electrode potential.

Iron, Mn and Al distributions in several soil profiles at two sites (Mbé and Korhogo) in Côte d'Ivoire provided valuable information. The results (Fig. 3.2) showed that Fe levels at the two sites very significantly different at the 0.05 probability level. Extractable Fe and Al values were higher at Korhogo than at Mbé. However, the reverse of this trend was true for Mn at Mbé. The means of the extractable Al and Mn were significantly different at the 0.05 probability level.

Investigation of wet and dry soil core samples revealed significantly higher levels of Fe at all depths in wet soil samples (Fig. 3.3). Similar results were not observed for Al and Mn. Extractable Mn levels varied greatly among sites. These findings suggest that using dry bottomland soil samples to determine extractable ions could underestimate the values. Rapid site selection for growing non-Fe-tolerant and tolerant cultivars could be achieved by collecting and immediately placing moist soil samples into extracting solution in the field.

Investigations conducted on two sandy loam upland sites produced the data given in Table 3.3. The organic matter content

Table 3.3 Redox potential profiles in hydromorphic rice soils of Côte d'Ivoire, West Africa

Electrode	Days 1	5	10	21	Average
	Redox Potential (mV)				
1	6	-98	-137	-298	-132
2	84	25	60	-152	4
3	177	164	162	-120	96
4	64	112	168	145	122
5	193	204	203	203	201
6	144	151	112	-106	75
7	97	90	-266	-242	-80
8	156	143	169	-91	94
9	91	257	75	82	126
10	348	319	309	114	272
11	8	2	-27	146	32
12	22	-49	-36	-232	-74
13	236	12	87	-59	69
14	146	140	19	10	78
15	305	333	350	-151	209
16	138	-46	14	-213	-27
Average	138	110	79	-60	67

Table 3.4 Soil characteristics and nutrient ion levels in upland soils of Côte d'Ivoire, West Africa

Parameter	Low Input	High Input
O.M (%)	3.7	4.2
pH	4.9	5.2
LR	5.7	5.8
P ($mgkg^{-1}$)	27	35
Na ($mgkg^{-1}$)	5	4
K ($mgkg^{-1}$)	63	79
Ca ($mgkg^{-1}$)	524	566
Mg ($mgkg^{-1}$)	59	64
Cu ($mgkg^{-1}$)	0.68	0.80
Fe ($mgkg^{-1}$)	59	67
Mn ($mgkg^{-1}$)	10	15
Zn ($mgkg^{-1}$)	0.7	0.7
Al ($mgkg^{-1}$)	65	59
Al (%)	18	16
BS $meq(100g)^{-1}$	3.4	3.6

LR= lime requirement

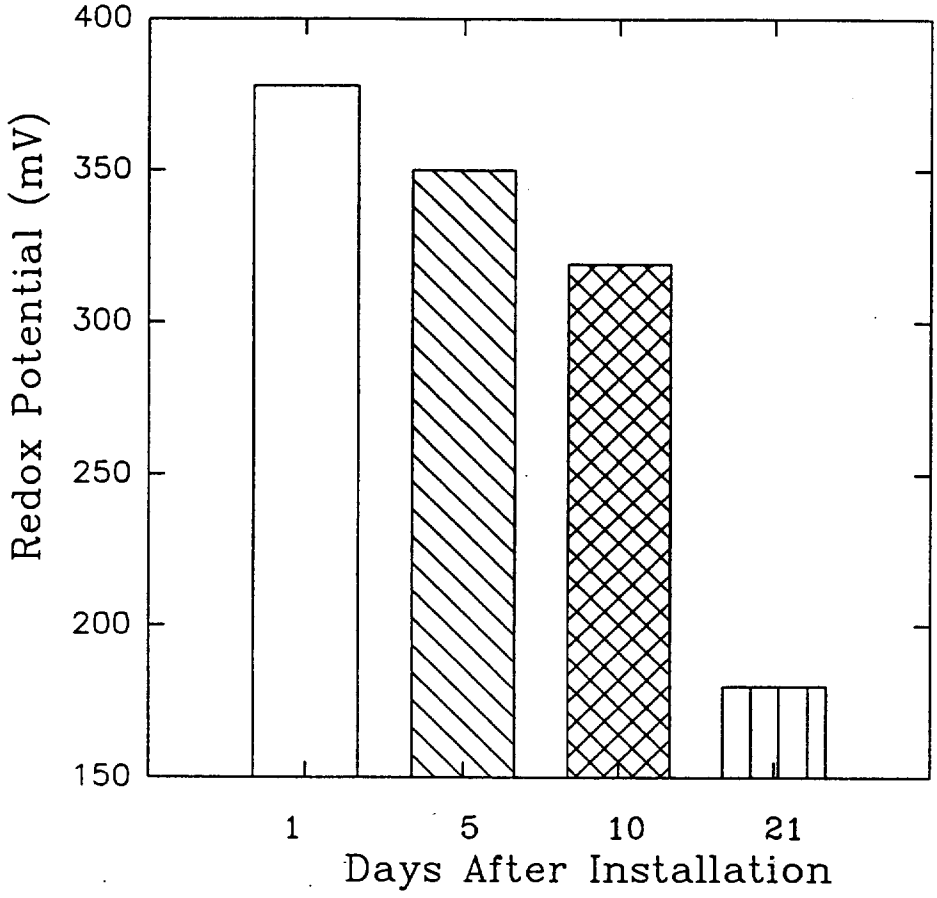

Fig. 3.1: Soil redox potential trends in hydromorphic rice fields of Côte d'Ivoire, West Africa

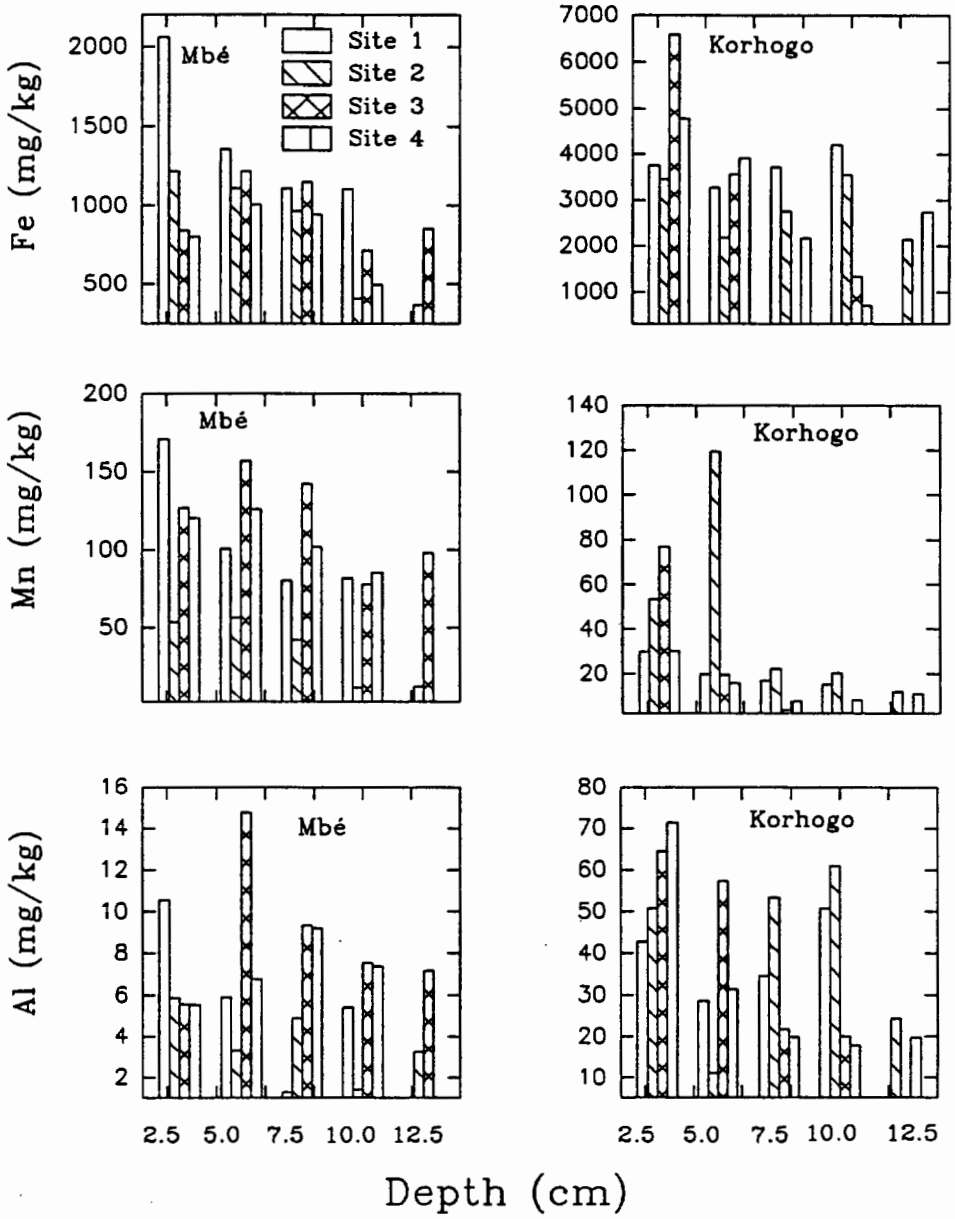

Fig. 3.2: Extractable Fe, Mn and Al distributions by depth at two research locations in Côte d'Ivoire, West Africa

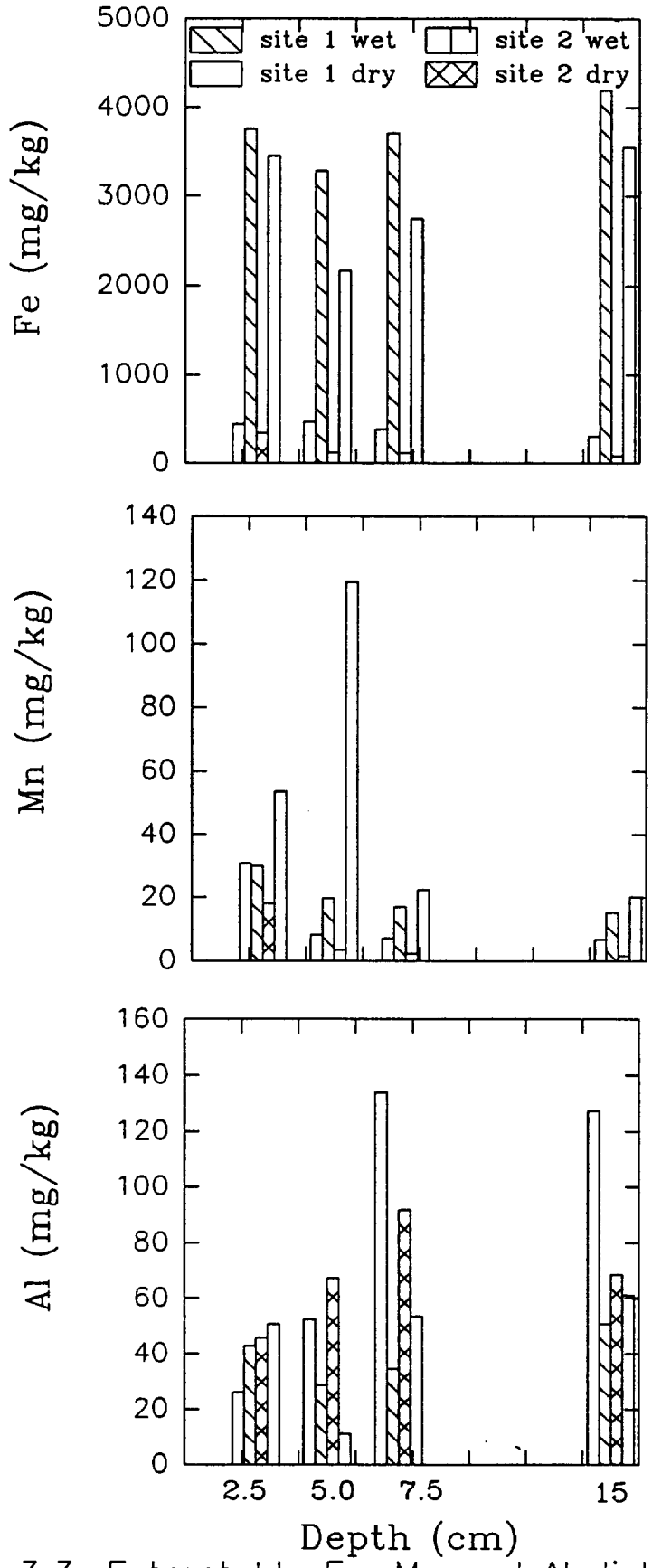

Fig. 3.3: Extractable Fe, Mn and Al distributions by depth in wet and dry rice soils at Korhogo, Côte d'Ivoire, West Africa

ranged from 3 to 4 percent. The addition of one ton to lime did not significantly in pH. Augmenting the soil with fertilizer improved the levels of some nutrients and slightly decreased the percent Al saturation.

Iron and Mn assessment in varietal trial

Responses of 5 rice cultivars to Fe toxicity investigated on bottomland soils indicated significant differences in the uptake of Fe and Mn (Fig. 3.4 a&b). The proportion of Fe to Mn in the leaves at tillering ranged from 0.29 to 0.67. These results suggest that Mn uptake may be a major factor in limiting rice growth.

Iron uptake varied with cultivar and plant part. Roots retained more Fe and Mn than at booting. Fe to Mn ratio ranged from 0.33 to 0.63 in the leaves and 0.46 to 0.84 in the roots. Iron uptake by a Fe-tolerant cultivar was generally higher for both leaves and roots since this cultivar is capable of adapting to the adverse environments in the rooting zone.

NPKZn interaction trial

Results of a study with two rice cultivars Bouaké 189 (Fe-toxicity susceptible) and Suakoko 8 (Fe-toxicity tolerant) involving combinations of nitrogen, phosphate, potassium and zinc amendments indicated that most of the Fe as well as other ion were retained by Bouaké 189 roots. Significant differences were not observed between treatments and cultivar but fertilizer

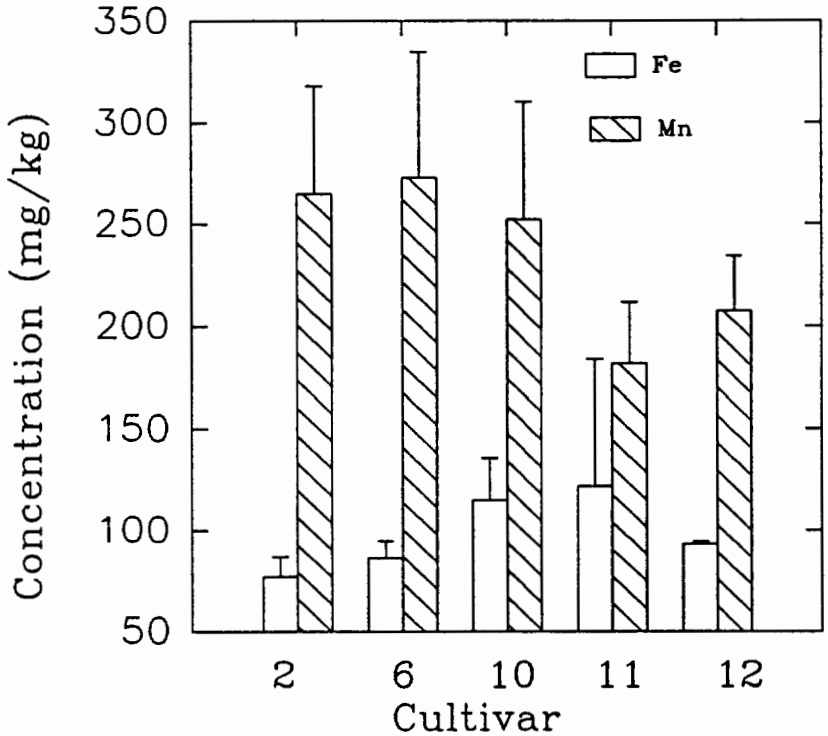

Fig. 3.4a: Uptake of Fe and Mn by rice cultivars during tillering stage at Mbé, Côte d'Ivoire, West Africa.

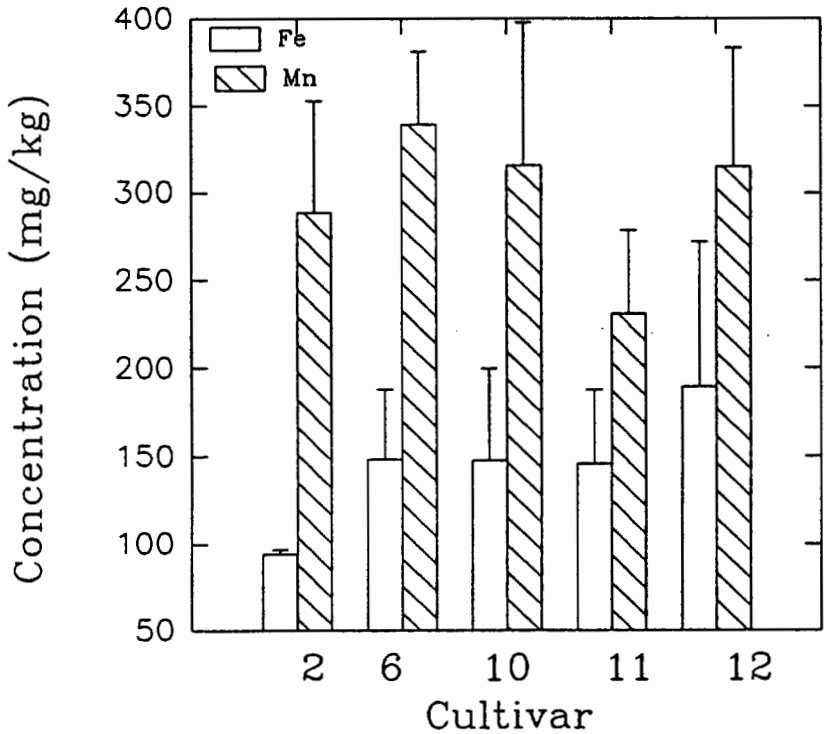

Fig. 3.4b: Uptake of Fe and Mn by rice cultivars during booting stage at Mbé, Côte d'Ivoire, West Africa.

addition decreased Fe uptake by Bouaké 189 as compared with Suakoko 8 (Fig. 3.5a).

The complete amendment (NPKZn treatment 5) was very effective in reducing the uptake of Fe, Mn and Al since a T-test revealed significant differences between the means of the two cultivars. The ratios of Fe/Mn for Bouaké 189 ranged from 2.4 to 3.5 while the values for Suakoko 8 ranged from 1.3 to 2.4. Iron toxicity scores for Bouaké 189 averaged around 4 (mild toxicity) while similar values for Suakoko 8 averaged about 1 (no visible symptoms). The concentrations of extractable ions from soils in which the two cultivars were grown are presented in Fig. 3.5b. The ease of extraction was dependent on type of ion and cultivar.

Conclusions

Results from studies on bottomland soils at Mbé indicated the likelihood of both Fe and Mn growth related problems while Fe toxicity occurrence could be a major factor in rice production at Korhogo. Rice grown in hydromorphic soils showed both Fe and Mn symptoms. Results from studies with several cultivars indicated variability in soil pH and Eh levels but no clear relationship between these factors and cultivars. In-situ extraction of extractable was observed as a promising approach to speedy and reliable identification of suitable sites for growing both non-Fe-tolerant and Fe-tolerant cultivars. Significant differences in the uptake of nutrient ions were observed among cultivars during tillering and booting stages. The use of NPKZn combinations

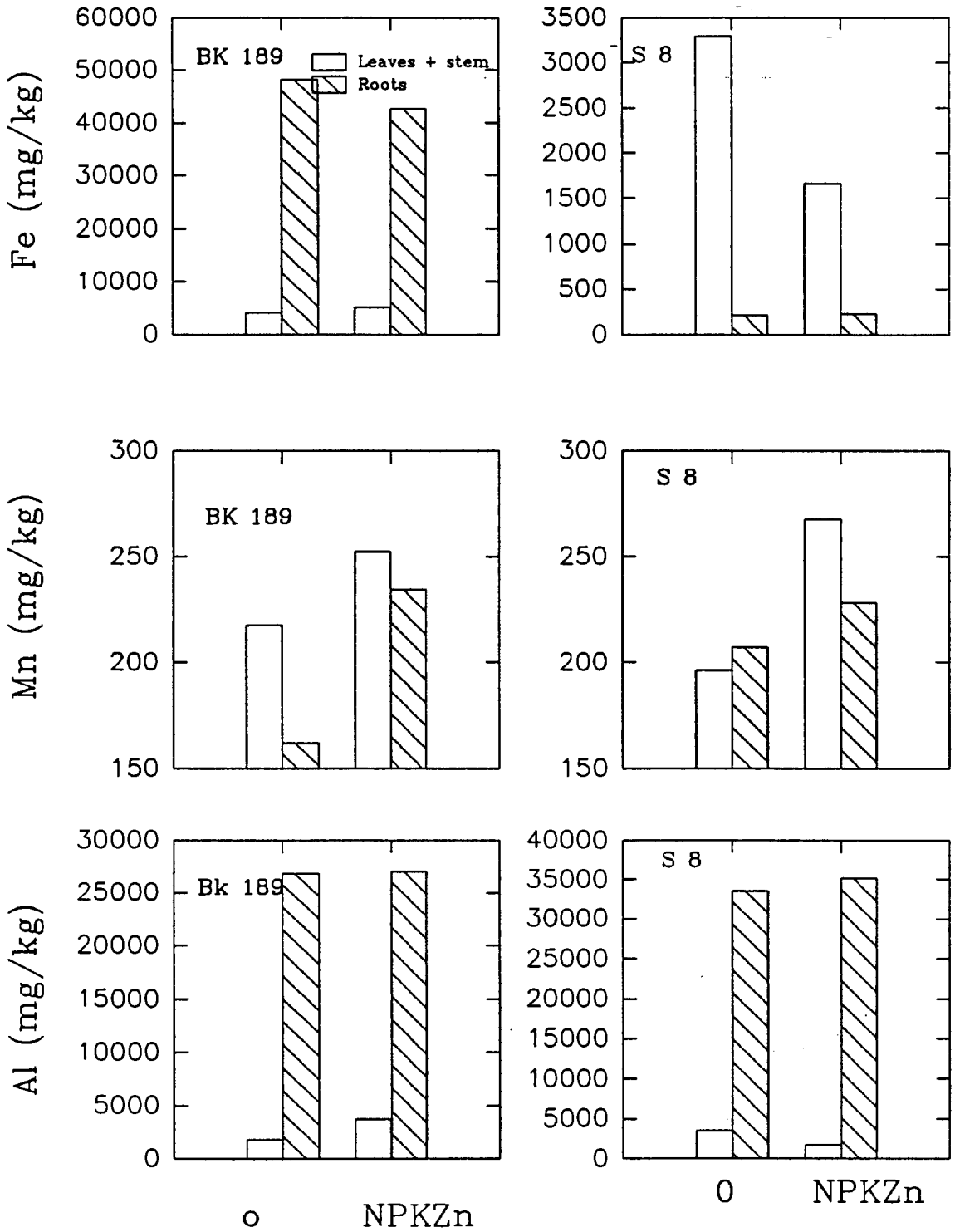

Figure 3.5a: Distribution of nutrient ions in rice plant parts following zero and NPKZn applications at Korhogo

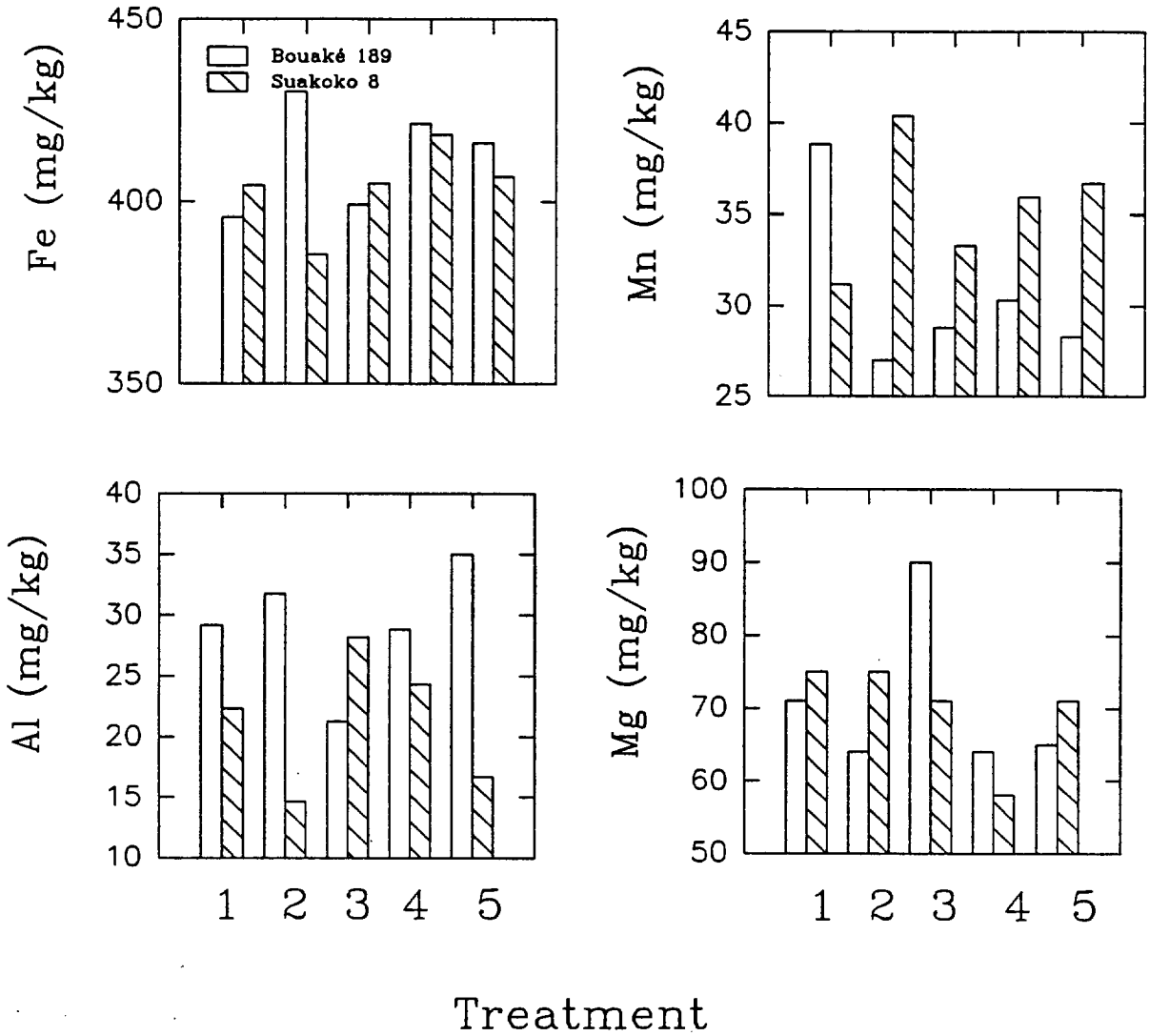

Fig. 3.5b: Effects of NPKZn treatments on extractable ions from soils in which Fe susceptible (Bouaké 189) and Fe tolerant (Suakoko 8) rice cultivars were grown

decreased Fe uptake by two rice cultivars and also affected the uptake of other ions. Iron toxicity scores confirmed the uptake of Fe by the two rice cultivars. The evaluation of lime amendments to upland soils did not show significant influence on pH. Nutrient additions decreased the availability of Al and increased the uptake of some soil nutrients.

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TASK IV

Evaluation of varietal productivity under reducing soil conditions in Côte d'Ivoire, West Africa

Abstract Plant cultivars produced high yields despite highly reducing conditions and varying soil pH values in their rooting zones. Potentially high yielding and Fe-tolerant cultivars were found that could be grown in potentially toxic fields.

Introduction

Rice productivity is highly depended on its ability to supply oxygen under flooded conditions in addition to available nutrients. Oxygen diffusion through water-filled pores is estimated to be about one-ten thousandth of the rated found in aerated soils (Howler and Bouldin, 1971, Reddy et al., 1980). Flooded rice plants obtain O_2 through the aerenchyma from the foliar parts (Armstrong, 1971, Luxmoore et al. 1970). The diffusion of O_2 enables rice roots to oxidize the area around the root tips thereby protecting the plant against reduced substances like Fe^{+2}, Mn^{+2} and H_2S which can sometimes reach phytotoxic concentrations under submerged conditions (Flessa and Fisher (1992). The oxidizing power of the rice roots are often indicated by the presence of reddish brown ferric oxides/hydroxides around the roots. Measurements of redox potential have shown that rice roots can increase the redox potential in reduced soils (Reddy and Patrick, 1986).

Changes in soil redox potential may indicate the presence of O_2 but the true measure of this change is the plant's ability to give acceptable yield despite reducing conditions. The purpose of this research was to investigate Eh changes in rice fields growing a large number of cultivars and to determine which cultivars were capable of supplying adequate O_2 to maintain good yields despite highly reduced conditions.

Method and scope

Twenty five platinum electrodes were installed at 15 cm depths in a field containing 50 lowland rice cultivars that were being evaluated for tolerance to Fe toxicity. Redox potential and pH values were monitored regularly for sixty days beginning at 30 days after transplanting. Iron toxicity were scored using a scale of 0 to 9 (IRRI, 1988). Zero represents lack of visual discoloration on the leaves and 9 indicates severe toxicity symptoms. Soil samples were collected, dried and shipped to the Wetland Biogeochemistry Institute, LSU for analysis. The field received uniform rates of 90 60 40 NPK kg/ha^{-1}. The nitrogen was applied in three splits.

Results and discussion:

Results from the analysis of samples taken from the research site found that the soil was a fine sandy loam containing 3-4% organic matter, 4340 $mgkg^{-1}$ Fe, 23 $mgkg^{-1}$ Mn, 14 $mgkg^{-1}$ Mg, 110 $mgkg^{-1}$ Ca, 6 $mgkg^{-1}$ P, 51 $mgkg^{-1}$ Al and 32 $mgkg^{-1}$ Na. The site contained

about two hundred times more Fe than Mn.

The pH ranges, Fe toxicity scores, plant height and yields are presented in Table 4. The soil pH values generally ranged between 5 and 6.6. Though the ranged seems large in some cases, the daily changes were gradual over the 60 day monitoring period. The appearance of discolorations and Fe toxicity scores indicated that Fe had indeed been present in the soil solution. The average Fe toxicity scores ranged from 2 to 7. The two check cultivars CK 30 (4) and Suakoko 8 (10) had average scores of 3 thus indicating mild symptoms. No direct relationships were observed between soil pH, Fe toxicity and plant height.

The average Eh values in the rooting zones of twenty of the cultivars (Fig. 4.1) ranged from reduced to highly reduced. Oxygen depletion is known to occur in the range of 340 mV to 320 mV. The Eh values observed under these rice cultivars indicate the high degree of reduction. Some cultivars were much better at maintaining Eh than the check cultivars Ck 30 (4) and Suakoko 8. These values were well below the critical O_2 depletion limit often observed in flooded soils. The growth, survival and the eventual yields the plants produced were therefore mostly dependent on the O_2 supplying powers of the cultivars.

In the first comparison it was found that all but 4 of the cultivars were significantly different from Ck 30. In comparison two, ten of the cultivars (4, 6, 8, 16, 18, 32, 34, 44, 46, 48) had significantly different Eh levels from Suakoko 8. Twenty five of the 50 cultivars investigated are graphically presented in

Table 4 Soil and plant properties measured in under lowland rice cultivars in Côte d'Ivoire, West Africa

Variety	pH range	Fe Score	Height (cm)	Yield $kgha^{-1}$
2 BW 295-5	5.6-6.6	4	84	4425
4 CK 30	5.2-6.3	3	112	4049
6 IR 13540-56-3-2-1	5.8-6.4	4	81	4329
8 TOX 85A-C2-455-2	5.8-6.2	2	100	4980
10 SUAKOKO 8	5.2-6.6	3	129	3636
12 TOX 3084-136-1-3-1-2	6.0-6.5	4	103	4449
14 TOX 3100-32-2-1-3-5	5.9-6.5	4	99	4102
16 TOX 3109-73-4-1-3	5.6-6.5	4	100	4360
18 TOX 3109-73-4-5-4-1	5.9-6.6	3	87	4193
22 TOX 3118-47-1-2-3-1	5.0-6.9	2	91	3937
24 TOX 3226-5-2-2-3	6.2-6.7	3	101	3695
26 TOX 3233-46-3-3-1-1	5.8-6.7	5	84	3593
28 TOX 3402-7-1-3-2	5.2-6.6	5	89	3120
32 TOX 3562-8-2-1-2	5.8-6.4	4	91	3926
34 TOX 3716-15-1-1	5.7-6.5	2	110	4088
36 TOX 4136-5-2-1	5.3-6.4	5	94	4058
38 RTN 16-2-1-1-1	5.5-6.7	3	106	3130
42 WAR 1 (ROK 22)	5.6-6.6	6	111	3318
44 WAR 77-3-2-2	5.4-6.6	7	114	3461
46 WAR 100-2-11-1	5.9-7.0	4	79	3127
48 WAR 102-1-3-1	5.5-6.5	4	83	3369

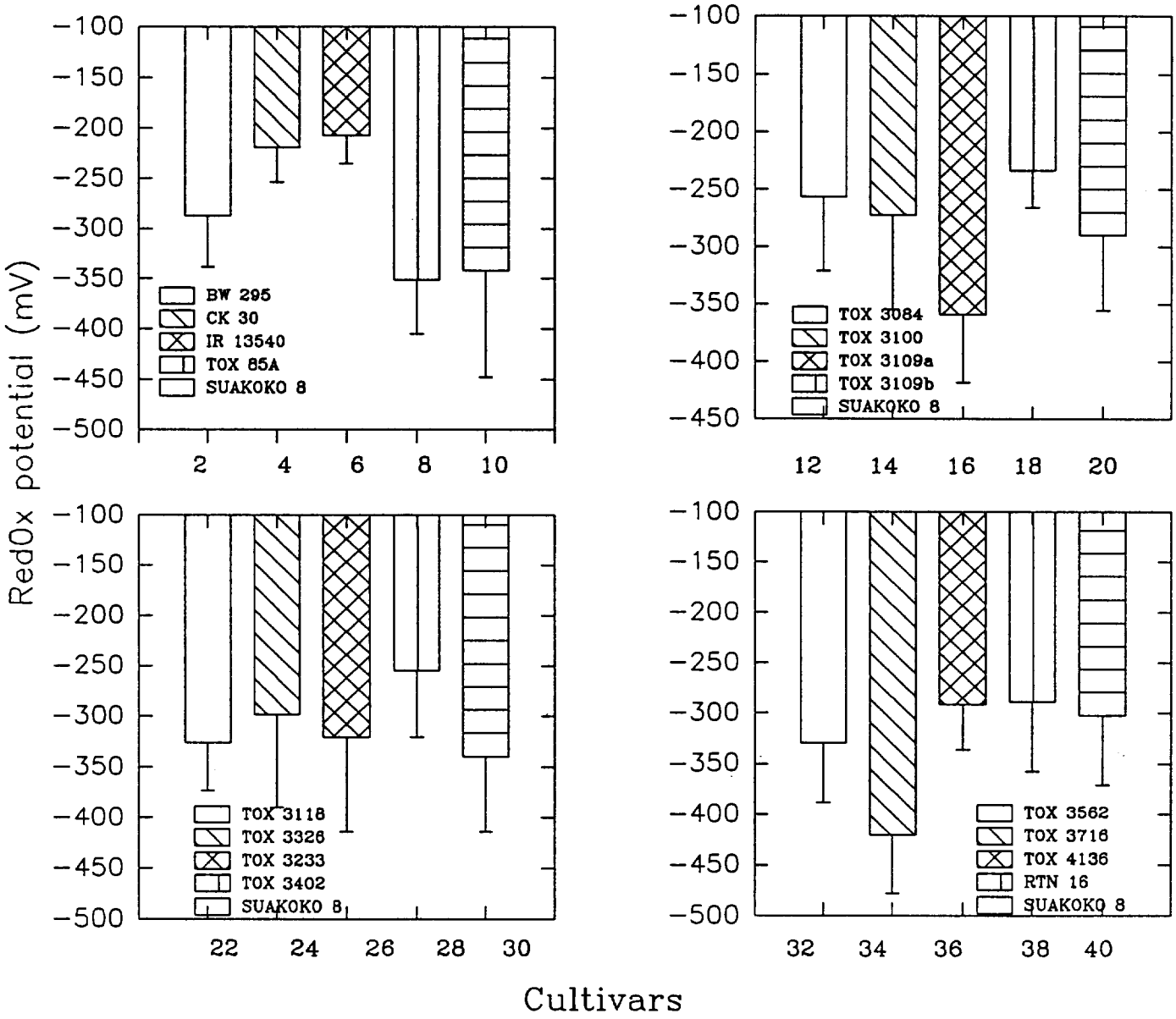

Fig 4.1 Soil redox potential patterns under rice cultivars at Korhogo, Côte d'Ivoire, West Africa

Fig. 4.2. It was found that 7 (44%) of the 16 cultivars that were significantly different from CK 30 and Suakoko 8 had higher yields values. Although there were no consistent trend between soil Eh and yields, ten cultivars produced yields above 4 tons per hectare. The highest yield was obtained from TOX 85A-C2-455-2.

The observation presented here could aid researchers in deciding which cultivars could be safely propagated depending on the reduction tendency. It could help farmers to avoid planting cultivars that are not quite adaptable to reduced Fe-toxic environments.

Conclusions

Soil pH under rice cultivars varied from moderate acid to acid. Some plant cultivars gave high yields despite highly reducing conditions and varying pH values in their rooting zones. Potentially high yielding and Fe-tolerant cultivars were found that could be used at potentially Fe-toxic sites.

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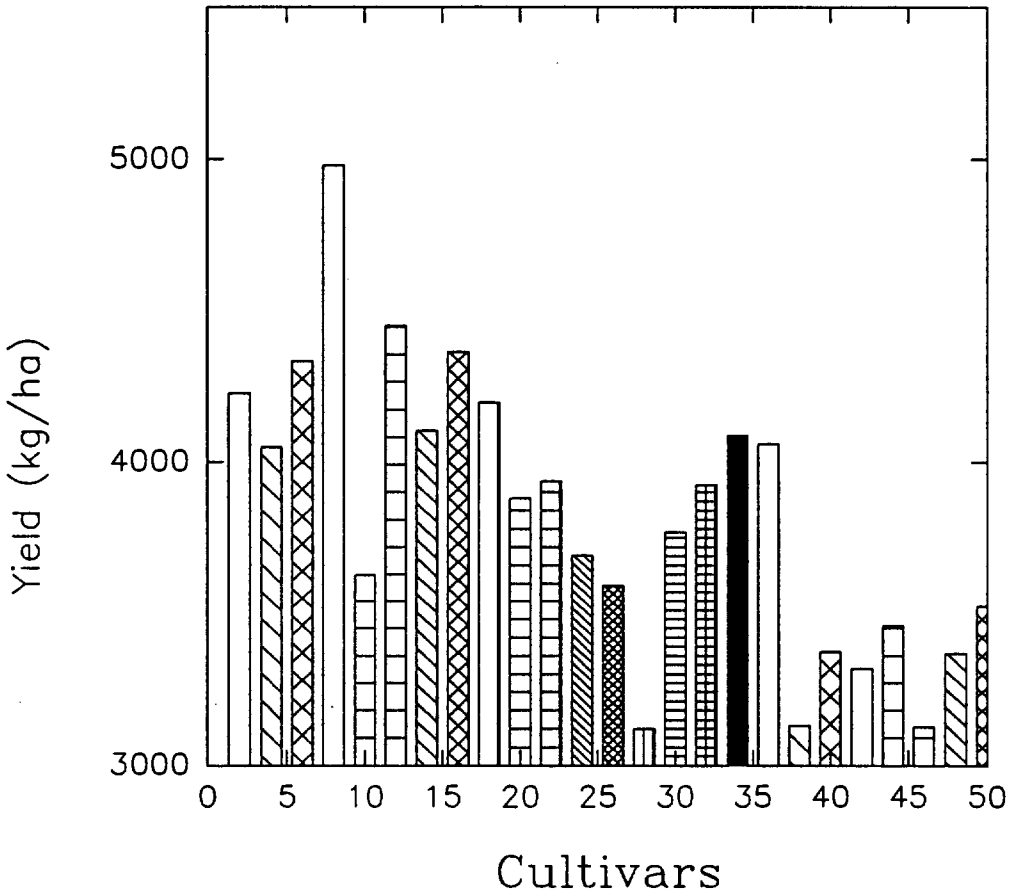

Fig. 4.2 Yields of selected rice cultivars from highly reduced soils at Korhogo, Côte d'Ivoire, West Africa

TASK V

Evaluation of methane emission from rice fields of Côte d'Ivoire, West Africa.

Abstract Methane emissions from the West Africa Rice Development Association (WARDA) rice fields in Côte d'Ivoire, West Africa, were measured during maximum tillering and booting/flowering stages in order to determine the magnitude of methane flux from rice cultivars at different locations and under various cultural practices. Gas collection chambers were installed in fields that were being used for breeding and nutritional studies of several rice cultivars. The trials were treated with 36 $kgha^{-1}$ 200 kg of 10-18-18 of NPK fertilizer. The balance of N was applied as urea nitrogen. The nitrogen response trials received N rates of 0, 30, 60, 90 $kgha^{-1}$ as urea nitrogen. All nitrogen was applied in three splits. Phosphorus (P) and potassium (K) were applied at 50 $kgha^{-1}$ as triple superphosphate (TSP) and 80 $kgha^{-1}$ as potassium chloride (KCl), respectively. Methane samples were collected in the morning and late afternoon. Some samples were also collected at night. Flooded rice fields emitted methane during tillering and booting/flowering stages. Flux measurements for some rice cultivars varied depending on growth stage and location. Methane fluxes determined at night were generally lower than daytime measurements. Urea nitrogen application resulted in a five fold increase in methane flux in three of the four rice cultivars

used. Lower methane fluxes were measured over plots lacking N and P applications. These surveys indicated that Côte d'Ivoire wetland rice soils contribute to global methane emission similar to other rice growing areas of the world. Additional research will be required to establish the magnitude and range of the fluxes.

Introduction

The world is becoming increasingly concerned about the status of the atmosphere. This concern has led to the identification of methane and other greenhouse gases, which if present in abundance could lead to global warming. (Ramanathan, 1988). Increase in methane abundance in the atmosphere has been attributed to many global sources (Bolle et al. 1986).

Determining the emission levels of methane, the second most prevalent greenhouse gas, is important for several reasons. Firstly, methane concentration has doubled during the last 200 years and could increase further if measures are not taken to control the known emission sources. Secondly, one molecule of methane can trap about 30 times more heat than carbon dioxide (Neue, 1993). Cicerone and Oremland (1988) noted that atmospheric methane is increasing at the rate of 1% per year and this is likely to contribute more to future climatic change than any other gas except carbon dioxide. Methane also affects the chemistry and oxidation capacity of the atmosphere by influencing concentrations of tropospheric ozone, hydroxyl radicals, and carbon monoxide.

Flooding a rice field depletes soil oxygen thus causing anaerobic fermentation of soil organic matter. Methane is a major end product of anaerobic fermentation (Neue, 1993). It is produced by methanogenic bacteria that can metabolize only in the absence of free oxygen and is released from submerged soils to the atmosphere by diffusion and ebullition and through roots and stems of rice plants. Methanogens function in almost any anaerobic ecosystem and can withstand salinity, pH, and temperature extremes (Van Breemen and Feijtel, 1990). Production generally occurs at redox potentials of -150 mV or lower and pH of 6-8 (Wang et al., 1993). Wahlen et al.(1989) estimated that the total atmospheric content as 4700 Tg. (Note: Tg= 10^{12} grams). Cicerone and Oremland (1988) estimated the annual emission as 500 Tg with a net flux of 40 $Tgyr^{-1}$. It has been recently estimated that emission rates in wetland rice fields range from 20 to 100 Tg/yr with an average of 60 $Tgyr^{-1}$ (IPCC, 1992). Field measurements of methane have been recently carried out in many parts of the world (Cicerone and Shetter, 1991, Lindau et al., 1991, IRRI, 1992). Many of these studies found emission rates to be very variable with clear seasonal and diurnal patterns.

Although the total methane budget has been estimated, the various sources of emission have not been well documented. Some of the sources identified are anthropogenic, biogenic and fossil carbon (Wahlen et al. 1989). Flooded rice fields have also been identified as a major source of atmospheric methane (Neue, 1993). Some early work on rice field methane production included studies

by Cicerone and Shetter, 1981, Cicerone et al., 1983, Holzapfel-Pschorn et al., 1985 and Seiler et al., 1984).

It has been projected that by the year 2020, 200 million hectares of rice will have to be grown in order to produce the 680 million tons of rice that will be required by population increases (IRRI, 1988). To achieve the expected increase in yield, fertilization will be required. Fertilizer amendments to soils improves growth but also enhances methane production and emission as a result if increased organic matter production. Methane emission from this increased activity is therefore expected to increase by 20% (USEPA, 1990). The only bright side to these expected trends could be that sulfate containing fertilizers, if used, may enhance growth but could reduce methane production. However, these types of fertilizers exhibit other unwanted consequences. Furthermore, intermittent drying of flooded rice fields reduce total methane production and emission (Kimura, 1992, Sass et al., 1992).

Methane flux measurement for a given ecosystem vary wildly and tend to exhibit seasonal variations. There are no clear correlations which could be used to obtain reliable global scale extrapolations (Neue, 1993). Therefore, regional research efforts are required to provide the data base needed to complete this perplexing puzzle. Very little, if any, information is available on methane and other greenhouse gases emissions in West Africa. Collaborating scientists at WARDA expressed interest in methane production in rice fields at two research locations. In this

study, methane emissions from several WARDA rice fields were measured at Mbé and Korhogo, Côte d'Ivoire, to determine relative fluxes over bare soil and selected rice cultivars receiving various fertilizer treatments in order to obtain data on fluxes that are likely to occur in these rice fields.

Methods and materials

Methane fluxes were measured in rice fields representing several cultivars augmented with varying fertilizer rates. The fields were located at Mbé, WARDA's Headquarters and at Korhogo, another WARDA research site. The samples were collected during the maximum tillering and flowering stages. Daily temperature at Mbé ranged from about 21 degrees Celsius to 28 degrees Celsius and from 22 degrees Celsius to 35 degrees at Korhogo during the study period. The soils at both site varied from sandy clay loam to clay loam. The average pH of poorly drained Tropaquent at Mbé was 6.4 and it contained 2.2% organic matter and 4.4 $meq(100g)^{-1}$ bases. A similar poorly drained Tropaquent at Korhogo had an average field pH of 6.5 with 2.0% organic matter and 1.6 $(100g)^{-1}$ sum of bases. Prior to planting, rice straws and stubble were incorporated into the soil.

Gas samples were collected using 1 to 1.5 meter long PVC pipes with 16 cm inner diameter. One end of the pipe was inserted into the flooded soil to seal the bottom and the upper end was fitted with a plastic cap to which a septum was affixed for sampling with a syringe and hypodermic needle. After

installation, time was allowed for equilibrium to be established. The cap was then gently placed on the top and initial gas sample removed. The gas samples were placed in pre-evacuated vacutainers and sealed with epoxy for shipment to the Wetland Biogeochemistry Institute at LSU for analysis. Gas samples were removed from the chamber after 1, 2, 5, 10 30 minutes initially. Other samples were taken after longer periods. Due to the variation in the daily temperature most sampling were done during the morning and late in the afternoon hours. Few samples were also taken at night to determine the effects of long sampling time on methane fluxes.

Methane gas flux samples were collected from varietal breeding and nutritional study site located at Mbé and Korhogo. Varietal screening trials were treated at 36 $kgha^{-1}$ with 200 kg of 10-18-18. The balance Nitrogen (N) was applied as urea nitrogen. The nitrogen response trials received N rates of 0, 30, 60, 90 kg/ha as urea nitrogen. All nitrogen was applied in three splits. Phosphorus (P) and potassium (K) were applied at 50 $kgha^{-1}$ as triple superphosphate kg/ha as potassium chloride, respectively. The cultivars treated with uniform fertilizer rates were Suakoko 8, Bouaké 189, Tox 3118-6-E2-3-2, ITA 408, ITA 247 and CK 4. Cultivars used in nitrogen response studies (Bouaké 189, ITA 402, ITA 306 and ITA 212) were treated with N rates of 0, 30, 60 and 90 kg urea-Nha^{-1}. Fluxes were only determined in plots that received 0 and 30 kg Nha^{-1}. Methane fluxes were also determined in a study that involved complete fertilizer and complete fertilizer minus N, P, K, Ca, K, Mg and Zn treatments with Bouaké 189 as a

test cultivar.

One milliliter of the headspace gas was sampled by a syringe (Precision Sampling Corp., Baton rouge, LA) and measurements conducted with a Perkin-Elmer 900 gas chromatograph (Perkin-Elmer Corp. Norwark, CT) equipped with a flame ionization detector (Lindau et al., 1990).

RESULTS AND DISCUSSION

Soil redox potential and pH trends in rice fields

The soils at Mbé site had pH range of 6.0 to 7.0 while the Korhogo site had pH ranging from 5.8 to 6.8. Most methanogens are neutrophilic with optimal pH of 6.8 (Neue, 1992). The oxidation-reduction potential of fields were well below the preferred range of -200 to -250 mV for methanogenesis (Patrick and DeLaune, 1977, Bouwman, 1991). The average redox potential at both sites was 230 mV.

Methane fluxes in Uniformed fertilization trials

The methane flux measurements during tillering and booting at Mbé and Korhogo are shown in Tables 5.1a. The flux at tillering ranged from 9.2 $mg.m^{-2}.d^{-1}$ for Suakoko 8 to 83.7 $mg.m^{-2}.d^{-1}$ for Bouaké 189 at Mbé. The value determined for Suakoko 8 at booting/flowering was slightly higher than that obtained at tillering. The values for Bouaké 189 and Tox 3118-6-E2-3-2 were slightly lower. The fluxes determined from rice fields at Korhogo for Suakoko 8 was higher than that at Mbé. The methane flux for Bouaké 189 was lower at Korhogo. The values determined for ITA

Table 5.1a Methane fluxes at different growth stages at research sites in Côte d'Ivoire, West Africa

Site/Cultivar	Growth stage	Flux ($mg.m^{-2}.d^{-1}$)
Mbé		
Suakoko 8	Tillering	9.2
Bouaké 189	Tillering	83.7
Tox 3118-6-E2-3-2	Tillering	30.0
Suakoko 8	Booting/flowering	15.6
Bouaké 189	Booting/flowering	59.4
Tox 3118-6-E2-3-2	Booting/flowering	11.5
Korhogo		
Suakoko 8	Tillering	35.2
Bouaké 189	Tillering	69.0
ITA 408	Tillering	12.2
ITA 247	Tillering	41.6
Mbé		
Bare soil/azolla		960.0
Bare soil		28.9
Korhogo		
Bare soil		54.4

408 and ITA 247 were quite different. Differences in cultivars may have contributed to one cultivar (ITA 247) emitting three times more methane per hour than ITA 408.

Differences were observed between the growth stages. Methane emission is known to increase during the vegetative phase, to decrease after panicle initiation and to increase after flowering before declining at the end of the season (Neue, 1992). Differences in emission levels are usually associated with increased efficiency of gas transport through the plants, an expanding root system developed by rapidly growing rice plants during tillering or increasing availability of root exudates and root liter. Increased litter or organic matter increase bacterial fermentation and the subsequent increase in methanogenesis and methane emission (Sass et al. 1991). Since no measurements were made at end of the season, it is not feasible to explain all of the trends, but the data clearly show larger flux values at maximum tillering than at booting for rice cultivars at Mbé.

Methane fluxes determined over flooded fields with azolla *pinnata* and bare soil revealed large differences. It appears as though azolla contributed to methane emission in these fields. The results of the bare soil studies at Mbé and Korhogo were also different. This suggests that the two sites affected emission differently. The large flux measured from the bare soil and bare soil/azolla sites could be due to the presence of cracks in the soil surface as these sites were not permanently flooded.

Night time methane fluxes

Lower methane flux were observed from night measurements (Table 5.1b). The results obtained are supported by previous research which has shown that emission mediated by rice plants are highest in the early afternoon and lowest late at night following the daily air and topsoil temperature changes (Neue, 1992).

Methane fluxes in nitrogen trials

Methane gas flux in rice fields treated with varying N rates are presented in Table 5.2. The addition of 30 kg urea-N per hectare substantially increased methane flux over the zero treatment in three of the four cultivars used in this investigation. Urea application increased methane fluxes by 523, 502, 527 percent for cultivars Bouaké 189, ITA 402 and ITA 212, respectively. Lindau et al. (1991) reported significant effect on methane emissions with increasing amounts of urea-fertilizer applications to flooded Louisiana rice plots. Methane fluxes are known to be strongly influenced by type, method of application, and rate of fertilizer application (Cicerone & Shetter, 1981, Schütz et al., 1989).

Fertilizer nutrients effects on methane gas emission

The effects of the removal of certain fertilizer nutrients on methane gas emission are given in Table 5.3. The flux measured in plots receiving complete fertilizer rate and in plots

Table 5.1b Overnight methane fluxes

Cultivar	Growth stage	Flux ($mg.m^{-2}.d^{-1}$)
Suakoko 8	Tillering	4.5
Bouaké 189	Tillering	5.9
Tox 3118-6-E2-1-3-2	Tillering	4.2
ITA 408	Tillering	2.6
ITA 247	Tillering	8.2
CK 4	Booting	8.7
Tox 3118-6-E2-1-3-2	Booting	14.5

Table 5.2 Effects of nitrogen fertilization on methane emission from rice fields at Mbé, Côte d'Ivoire, West Africa

Cultivar	Nitrogen rate	Flux ($mg.m^{-2}.d^{-1}$)
Bouaké 189	0	6.7
	30	35.0
ITA 402	0	11.5
	30	58.0
ITA 306	0	10.3
	30	14.9
ITA 212	0	17.5
	30	92.2

Table 5.3 Methane emission from Bouaké 189 as affected by different fertilizer nutrients at Mbé, Côte d'Ivoire, West Africa, 1993

Fertilizer type	Flux ($mg.m^{-2}.d^{-1}$)
Complete	51.0
Complete minus N	40.2
Complete minus P	37.0
Complete minus K	46.2
Complete minus Ca	50.0
Complete minus Mg	47.5
Complete minus Zn	58.8

receiving the complete fertilizer minus zinc were not significantly different. No differences were observed between N and P and between K, Ca and Mg. The removal of N and P slightly lowered methane gas flux. Fertilization improves plant growth and therefore methane emission (Kimura, 1992, Sass et al., 1992). The lower fluxes observed for treatments lacking N and P, two essential plant nutrients, certainly attests to the role of fertilization in methane emission. Reduction in methane fluxes could have also been caused by the oxidation of methane by methanotrophs in the rhizosphere. De Bont et al. (1978) counted ten times more methane-oxidizing bacteria in the rhizosphere than in the bulk of the anaerobic soil and one-third more than in the oxidized soil-water interface. However, these authors concluded that the use of oxygen by reduced substances and microbes other than methanotrophs at the region of root-soil interface exceeds the supply of oxygen by roots. As these authors suggested, the large variability in root-oxidizing power of rice cultivars, warrants more detailed study.

The results from this study have shown that flooded rice fields of Côte d'Ivoire are a source methane emission in West Africa. Fertilizer application enhanced methane emission during tillering and booting/flowering stages.

Comparison with other world methane data

Despite the limited scope of this investigation, it is worth noting the similarities and differences among these studies and

those conducted in other parts of the world. This study was carried out in fields that had different varieties and different fertilizer levels. The field sites studied also had rice straws and stubble incorporated with the soil prior to fertilization and planting. In comparison to the data presented by Sass (1994) (Table 5.4), there are many similarities. There is close agreement between the values at the lower end of the ranges with those obtained from studies reported in the Table 5.4 except for China and the Philippines. In the case of the nitrogen response data, the average flux of 11.4 $mg.m^{-2}.d^{-1}$ for the zero treatment and the 50 $mg.m^{-2}.d^{-1}$ for the 30 $kgha^{-1}$ treatment compare very well with the 0.01 $g.m^{-2}.d^{-1}$ and the 0.05 $g.m^{-2}.d^{-1}$ reported for Japan, Thailand and the USA. The average flux for the complete fertilizer study was about 47.2 $mg.m^{-2}.d^{-1}$. This value is very close to the 0.04 and 0.05 $g.m^{-2}.d^{-1}$, reported as minimum values for Thailand and the USA, respectively.

The measured flux of 960 $mg.m^{-2}.d^{-1}$ from the bare/azolla samples indicated that natural systems produce and emit more methane than rice soil containing rice plants at this location. These flux were similar to that reported by Wang et al. for China (Table 5.4).

Conclusions

In comparison to world wide methane emission data, our results have revealed, the rice fields of Côte d'Ivoire evolve methane to the atmosphere at rates similar to that reported for other rice growing areas. Methane flux measurements ranged from

about 3 $mg.m^{-2}.d^{-1}$ at tillering for some cultivars to about 90 $mg.m^{-2}.d^{-1}$ for others depending on location and fertilizer treatment. Base on these investigations, it is essential that detailed research activities be designed to monitor fertilizer, seasonal temperature effects on methane flux in rice fields of Côte d'Ivoire and other rice producing countries of the region in order to enhance global understanding of this very important greenhouse gas.

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IMPACT, RELEVANCE AND TECHNOLOGY TRANSFER

The potential usefulness of the results and publications resulting from the research conducted attest to the success of this investigation. Contacts and links were established that will maintain lasting scientific cooperation in the West African region. This project provided a forum for researchers with mutual interests in factors limiting rice production to meet and discuss mutual scientific pursuits. Contacts made with farmers we believe did positively impact their views on the relationships between scientists and themselves. Farmers we interacted with expressed views which indicated that they are willing to collaborate and implement production practices for increasing rice production. Farmers were made aware of the significance of flooding or draining practices for weed control in bottomland rice paddies and the potential for Fe toxicity at critical stages during the rice growing season. Also some select farmers were informed of the significance of timing fertilizer application for enhanced rice production. Local research staff at WARDA were trained to monitor soil pH and oxidation-potential developed keen interests in application of the methods and assisting interested farmers in selecting suitable sites for rice cultivation. Discussions were initiated among interested parties for proposing new ideas for improving rice yields.

One of the principal investigators at WBI visited WARDA