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CHEMICAL KINETICS OF AEROBIC SOILS AND RICE GROWTH

A Thesis

By

Dilip Kumar Kundu

Submitted to the Faculty of the Post Graduate School,
Indian Agricultural Research Institute, New Delhi
in partial fulfilment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in

SOIL SCIENCE AND AGRICULTURAL CHEMISTRY

New Delhi
1987

Approved by:

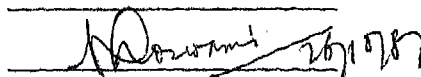
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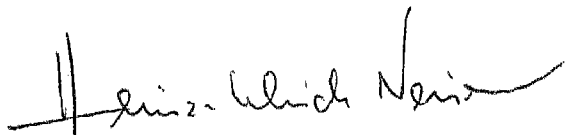
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This is to certify that the thesis entitled "Chemical Kinetics of Aerobic Soils and Rice Growth" submitted to the Faculty of the Post Graduate School, Indian Agricultural Research Institute, New Delhi, by Dilip Kumar Kundu, in partial fulfilment of the requirements for the award of the degree of DOCTOR OF PHILOSOPHY in SOIL SCIENCE AND AGRICULTURAL CHEMISTRY, embodies the results of a piece of bonafide research work carried out by him under my guidance and supervision and that no part of this thesis has been submitted for any other degree or diploma. The assistance and help received by him during the course of the investigation have been duly acknowledged.



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ACKNOWLEDGEMENTS

I gratefully acknowledge the award of a Research Fellowship by the International Rice Research Institute under the Joint Indian Agricultural Research Institute (IARI) - International Rice Research Institute (IRRI) Post Graduate Training Program that enabled me to conduct this research work at IRRI.

My sincere thanks are due to Dr. R. K. Chatterjee, Head, Division of Soil Science and Agricultural Chemistry, IARI, and the Chairman of my Advisory Committee, for his counsel and guidance throughout the degree program culminating in this thesis. I am extremely grateful to him for his meticulously going through the manuscript. I express my grateful appreciation to Dr. H. U. Neue, Soil Chemist and Head, Department of Soils, IRRI, and the Co-Chairman of my Advisory Committee, for his guidance, supervision, suggestions, encouragements and kind help in conducting this research work at IRRI, and preparation of the manuscript.

To the members of my Advisory Committee, Dr. N. N. Goswami, Dean and Joint Director (Education), Post Graduate School, IARI, Dr. K. N. Singh, Senior Scientist, Division of Agronomy, IARI, and Dr. Prem Narain, Director, Indian Agricultural Statistics Research Institute, I am grateful for their valuable advices and help during the course work and encouragement during the research work. To Dr. Goswami, I am specially grateful for his suggestions and advice given during his visit to IRRI.

I am deeply indebted to Dr. M. B. Sengupta, former Soil Physical Chemist, IARI, and Dr. F. N. Ponnampereuma, former Principal Soil Chemist, IRRI, for their invaluable guidance and advices as Chairman and Co-Chairman of my Advisory Committee during the formative stage of this research.

Valuable suggestions, advices and constant encouragement received from Dr. S. Nagarajah, Head, Division of Agricultural Chemistry, Central Agricultural Research Institute, Sri Lanka, and Dr. P. R. Bloom, Associate Professor, Department of Soil Science, University of Minnesota, USA, both Visiting Scientists at IRRI, in writing this manuscript are gratefully acknowledged.

I express my deep sense of gratitudes to Dr. M. S. Swaminathan, Director General, IRRI, Dr. S. K. De Datta, Principal Scientist and Head, Agronomy Department, IRRI, Dr. K. Kanungo, Advisor to the Planning Commission, Government of India and Consulting Economist at IRRI, and Dr. K. K. Jena, Collaborative Research Scientist, Plant Breeding Department, IRRI, for their encouragement and kind concern in my personal welfare.

I also wish to thank all the staff of the Soils Department, IRRI, especially Rhoda Lantin, Corinta Quijano, Alma Capati, Tess Cayton, Joey Solivas, Myrna Orticio, Bayani Palanginan, Vic Asio, Boy Azucena and Boning Mojado, for their help and cooperation during the conduct of the research; Bernie Mandac of Analytical Service Laboratory, IRRI, for her kind help in some

analyses; Joselito Real of Agronomy Department, IRRI, for his untiring help in statistical analyses of my data; Dr. M. G. Murty, Post Doctoral Fellow, and Messrs. P. S. John, B. Sivaprasad and M. K. Bashir, Research Fellows of IRRI, for sparing some of their valuable time in helping me whenever asked for; Evelyn Flordelis of the International Fertilizer Development Center (IFDC) Laboratory at IRRI, for her divine friendship and encouragement; Charo Galang and Ely Tabaquero of the Soils Department, IRRI, for their friendship and incomparable patience they showed in typing this manuscript.

The award of a Senior Research Fellowship by IARI, during the first two years of this degree program is gratefully acknowledged.

Finally, I would like to place on record my deep sense of gratitude to my parents, brothers and sisters for their sacrifices during my long stay outside home, and their continued encouragement and support in helping realize a dream.

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June 9, 1987

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INTRODUCTION

Upland rice is grown on about 20.4 million hectares or 14% of the world's cultivated rice area. Of the total global upland rice area, Asia occupies about 57% (11.6 million hectares) with 30% (6.15 million hectares) contribution from India alone (Dat 1986). In the upland rice-growing areas soils range from highly weathered Oxisols to Inceptisols and Entisols, land slopes range from steep to concave, and the amount of rainfall during the growing season ranges from high to low. However, one overriding difference that distinguishes upland from lowland soils is that upland rice soils are neither submerged nor saturated with water for any appreciable part of the growing season; they are mostly well-drained and aerobic.

In aerobic soils of upland or non-flooded fields, rice generally gives lower yields than in the same soils rendered anaerobic by submergence (Senewiratne and Mikkelsen 1961). Poor yield of upland rice is most commonly attributed to moisture stress (De Datta et al 1975), weed competition (Sankaran and De Datta 1985), and disease-pest problems (Ahn and Mukelar 1986). But even when these adverse factors are controlled, the yield of rice under non-flooded soil conditions remains lower than under flooded soil conditions (Westcott and Vine 1986). Decreased availability of several mineral nutrients and imbalanced

nutrition of rice under non-flooded conditions might also contribute to the poor performance of upland rice (Ponnamperuma 1975). Since moisture stress and aerobic soil conditions commonly operate together in the uplands, the role of aerobic conditions in growth retardation of rice has not been appreciated properly.

Moistening a dry soil sets in motion a series of chemical and physico-chemical changes that influence the rate and magnitude of nutrient release or removal and the generation of substances that can harm the crop plants. Ponnamperuma (1985) demonstrated how closely the growth of lowland rice is influenced by the chemical kinetics of flooded soils. He successfully associated some of the "physiological" disorders of rice with some specific unfavorable chemical factors operating in the soil. The growth of upland rice in some soils is known to suffer during the reproductive stage (IRRI 1971), whereas in some other soils it suffers right from the seedling stage. The chemical kinetics of aerobic soils in combination with plant analyses might be a valuable diagnostic tool to identify the adverse chemical factors responsible for such poor growth. Identification of the growth-limiting factors in aerobic soils may help in the development of suitable soil management practices. It will also assist plant breeders to breed rice cultivars that can perform well even under such adverse soil conditions.



Perusal of the literature shows that, while the chemistry of flooded soils has been studied extensively (Ponnamperuma 1972, 1984), no substantial effort has been made so far to study the chemical environment of aerobic soils in relation to the growth and mineral nutrition of upland rice.

The present investigation was therefore undertaken to compare the chemical environments of several soils of widely different characteristics under aerobic (non-flooded) and anaerobic (flooded) conditions. Its overall goals were to examine the role of aerobic soil conditions and their contribution to the poor performance of rice, and to identify the adverse chemical factors in aerobic soils responsible for poor growth and yield of upland rice. To achieve these goals, a series of experiments was conducted with the following objectives:

1. to examine the direct effects of aerobic and anaerobic conditions of two soils on rice growth (Experiment 1);
2. to study the chemical kinetics of four different soils under moist and flooded conditions in relation to the growth and mineral nutrition of rice (Experiment 2);
3. to study the chemical kinetics of soils under moist, wet, and flooded conditions in relation to the growth and mineral nutrition of rice (Experiments 3 and 4);

4. to study the growth and mineral nutrition of two rices in a near-neutral soil under non-flooded and flooded field conditions (Experiment 5); and
5. to study the growth and mineral nutrition of two rices in an acid upland, and the influence of some amendments on them (Experiment 6).

REVIEW OF LITERATURE

I. General Characteristics of Upland Rice Soils Compared with Flooded Soils

Upland rice is grown on soils which are well-drained. In a well-drained soil, most of the pore spaces surrounding individual soil particles and aggregates are gas-filled and interconnected with atmosphere. This permits relatively rapid gaseous diffusion of oxygen throughout the plant rooting depth. Though there may be a decrease in gaseous oxygen content with depth of some soils, there is sufficient molecular oxygen transport across the gas-liquid interface of the soil solution to maintain some dissolved oxygen in this solution. As a result, the soil is maintained in an oxidized condition. Excess water applied to a typical upland soil by precipitation, irrigation or temporary flooding will rapidly drain from the upper profile through the interconnected pore spaces. Much of this pore space is again filled with gas (which is continuous with the atmosphere) after draining for several hours. Thin, oxidized moisture films of one third bar tension or less will remain around individual soil particles and aggregates due to the hydrophilic nature of mineral and organic soil components. This relatively thin film of moisture on soil solids and root surfaces supports life by providing a medium for chemical

reactions affecting nutrient availability, serving as a nutrient and moisture reservoir and supporting transport of nutrients from soil solid phase to the plant root system.

Rate of oxygen diffusion in a non-flooded soil is dependent on the effective air-filled porosity (Kohnke 1968). The gaseous diffusion virtually ceases when the air-filled porosity in a soil drops to about 10% (Wesseling 1974). The soil moisture tension (SMT) is the most important factor controlling the aeration status of non-flooded soils. When SMT is lowered, changes in soil aeration will be small until a critical value is reached (usually about 20 cb of water tension). Below this point, changes will be large, the gaseous pore spaces become so restricted (<10%) that they are no longer continuous. At this value, there is little exchange of gas between the soil and atmosphere. The critical SMT below which there will be restricted soil aeration, will vary as a function of soil texture and aggregate size (Meek and Stolzy 1978). When the SMT is below the critical value, the change in oxygen level will depend on oxygen consumption. Oxygen consumption in soils again depends on source of oxygen demanding components (energy source), temperature and soil texture (Meek and Stolzy 1978). Incorporation of organic waste (crop residues, animal manures, city wastes) into soil increases microbial activity, exerts greater demand on soil oxygen, thus resulting in decreased oxygen concentration (Meek and Grass 1975). In most well

aerated soils (with SMT above critical value), oxygen consumption rates are usually lower than the potential oxygen diffusion rate from the atmosphere. As a result, the soil is maintained under aerobic or oxidized conditions. But in poorly aerated soils (SMT below critical value, gas-filled porosity <10%), oxygen diffusion cannot keep up with demand, resulting in slower renewal of oxygen as compared to consumption. This results in the formation of anoxic microsites in the soils (Reddy and Patrick 1983).

Flooding or waterlogging a soil virtually eliminates gas-filled pores and limits gas exchange between soil and air to molecular diffusion in soil water. This process is about 10^4 times slower than in air (Grable 1965). Consequently the oxygen supply of the soil is cut off and gases formed by soil metabolism accumulate. Within a few hours of flooding, microorganisms and roots use up the oxygen present in the water or trapped in the soil and render a submerged soil practically devoid of oxygen. Ponnampereuma (1972) summarized the evidence for the absence of molecular oxygen in flooded soils. The drastic restriction of gas exchange between a flooded soil and atmosphere leads to the accumulation in the soil of nitrogen, carbon dioxide, methane and hydrogen. The gases build up pressure and escape as bubbles. Carbon dioxide concentrations as high as 50% may persist for several weeks in cold, acid soils that are flooded (Ponnampereuma 1976). The mean temperature of

the surface layer was found 6°C lower for flooded soils than for well-drained soils (Bonneau 1982). Neue (1985) noted that flooding and puddling markedly decrease the bulk density of soils with high clay and organic matter content.

II. Physico-chemical and Chemical Changes in Soils Under Flooded and Non-flooded Conditions

Redox potential

Redox potential (Eh) is the most convenient electrochemical measurement that serves to distinguish a reduced soil from an oxidized or aerobic soil. Aerobic soils are characterized by highly positive potentials (+800 to +300 mV). Most of the flooded soils have large negative potentials (+200 to -400 mV) after a few weeks of submergence. Pearsall (1938) considered the redox potential range of +320 to +350 mV at pH 5 (corresponding to +200 to +230 mV at pH 7) as a borderline between reduced and oxidized soil conditions, because below this redox potential range soils contained NH_4^+ , Fe^{2+} and Mn^{2+} ions and above this range generally contained NO_3^- , Fe^{3+} and Mn^{4+} ions. Patrick and Mahapatra (1968) and Liu (1985) classified the oxidation-reduction status of soils into four categories, viz., (i) oxidizing (>400 mV), (ii) weakly reducing (+400 to +200 mV), (iii) moderately reducing (+200 to -100 mV) and (iv) strongly reducing (<-100 mV). Gambrell and Patrick (1978) gave the following potentials at pH 7 for the observations listed below:

| Observation | Eh (mV) |
|------------------------------|---------|
| Disappearance of O_2 | 330 |
| Disappearance of NO_3^- | 220 |
| Appearance of Mn^{2+} | 200 |
| Appearance of Fe^{2+} | 120 |
| Disappearance of SO_4^{2-} | -150 |
| Appearance of CH_4 | -250 |

The Eh is a useful guide to the sequence of soil reduction, but it does not indicate the capacity of the soil to resist Eh changes. Buffering agents in the oxidizing range are oxygen and nitrate, whereas in the reducing range ferric compounds dominate (Patrick 1982). Although redox potentials of flooded soils have been used in ecological studies (Aomine 1962, Ponnampereuma 1982), they are of limited theoretical or practical value. But potentials of interstitial water of flooded soils and sediments are thermodynamically meaningful and have been used successfully to explain the changes in concentration of ecologically important ions in soil solutions (Ponnampereuma 1972, Yamane 1978, Lindsay 1979, Rowell 1981).

Ponnampereuma (1972) reported that Eh fell rapidly after flooding, reached a minimum within a few days, rose rapidly to a maximum and then decreased asymptotically with time. Soil

properties markedly influenced the Eh kinetics. The course, rate and magnitude of the decrease in Eh on submergence were found to depend on the nature and amount of organic matter, the nature and content of electron acceptors, temperature and period of submergence (Ponnamperuma 1982, 1985).

Unlike in flooded soils, seasonal changes in Eh of non-flooded soils growing upland rice has not been studied thoroughly. Initial works at the Soils Department of the International Rice Research Institute (IRRI 1973) recorded solution Eh of several non-flooded soils. The Eh ranged between 350 and 600 mV throughout the growing season. Islam and Islam (1973) reported much lower values, ranging between 121 and 155 mV. From theoretical point of view, Eh changes in non-flooded soils should be small as long as sufficient gaseous oxygen is present in them. The Eh shows significant drop only when gas exchange between the atmosphere and the soil voids is restricted due to blocking of narrow pores by water films (following a rainfall or irrigation and impeded drainage of the soil) and the gaseous oxygen in soil is depleted by soil microorganisms. Soil management has a great effect on soil structure and porosity. Compaction can reduce the size of pores both between and within aggregates and so effects the distribution of anaerobic zones in soils (Cannell 1977). Parker et al (1985) have noted that oxygen content and redox potential of non-flooded fields decreased with increasing soil moisture and depth. Again, pH

and Eh of soils are linked together in various ways. Based on a theoretical relationship, Eh of the aerobic soils should change little with oxygen concentration but greatly with pH change in them (Rowell 1981).

pH

The change in pH due to submergence is a very important feature of lowland paddy soils. The direction, extent and rate of this change are closely related to the original pH and other properties of the soil. Ponnampereuma (1972) documented that the overall effect of flooding was to increase the pH of acid soils and depress that of the alkaline soils. Thus the pH values of most flooded mineral soils are between 6.7 and 7.2, and those of their interstitial solutions between 6.5 and 7.0. He further noted that in acid soils low in reducible iron, pH did not rise above 5.0 even after months of submergence; whereas in high pH soils low in organic matter, pH would not decrease below 8.0 (Ponnampereuma 1984). Recently Gang et al (1985) have reported similar effects of flooding on soil pH. In their study, organic manuring in acid soils was found to enhance the degree of pH rise on flooding.

Ponnampereuma attributed the pH increase in flooded acid soils to the reduction of Fe^{3+} to Fe^{2+} and described it in most acid mineral soils by the relationship:

$$Eh = 1.06 - 0.059 \log Fe^{2+} - 0.177 pH$$

The decrease in pH of sodic and calcareous soils and the check on the pH rise of acid soils are the results of accumulation of CO_2 . Following relationships between pH and the partial pressure of CO_2 ($^P\text{CO}_2$) were observed by Ponnampuruma et al (1969a):

| | |
|-----------------------|---|
| Sodic soil | $\text{pH} = 6.4 - 1.00 \log ^P\text{CO}_2$, |
| Calcareous soil | $\text{pH} = 6.1 - 0.66 \log ^P\text{CO}_2$, |
| Neutral soil | $\text{pH} = 6.1 - 0.64 \log ^P\text{CO}_2$, |
| Ferruginous acid soil | $\text{pH} = 6.1 - 0.57 \log ^P\text{CO}_2$ |

The pH of aerobic soils is governed by the nature of parent material, the degree of weathering and leaching, and the effects of any additions of amendments such as lime or fertilizer. In aerobic soils, pH is not affected very much by the oxidation and reduction processes involved in aerobic respiration. However, CO_2 is always produced by aerobic respiration and an increase in $^P\text{CO}_2$ reduces pH via the $\text{H}_2\text{CO}_3 - \text{HCO}_3^- - \text{CO}_3^{2-}$ system in the soil water. The effects are most marked in calcareous and sodic soils, where in equilibrium with the atmosphere pH are close to 8 and 9, respectively; but in the presence of 1% CO_2 in the soil atmosphere they are close to 7.5 and 8 (Rowell 1981). The production of weak organic acids during respiration may have a slight acidifying effect, and the oxidation of NH_4^+ to NO_3^- also causes a fall in pH. Reyes and Ponnampuruma (1972) observed that the pH of a normal

and a high pH aerobic soils remained almost unchanged throughout the season, whereas in an acid soil pH dropped markedly after 8 weeks.

Electrical conductivity

Previous studies on the kinetics of the electrical conductivity (EC) of soil solution showed that generally it increased on flooding, reached a peak and then declined to a fairly stable value (Ponnamperuma 1977). The initial increase in EC on submergence has been attributed to mobilization of Fe^{2+} and Mn^{2+} ; formation of NH_4^+ , HCO_3^- and RCOO^- ; and displacement of Ca^{2+} , Mg^{2+} , Na^+ and K^+ from the soil colloids by Mn^{2+} and Fe^{2+} . The subsequent decrease has been attributed to precipitation of Mn^{2+} as MnCO_3 , and Fe^{2+} as $\text{Fe}_3(\text{OH})_8$ and FeS , removal of HCO_3^- , conversion of RCOO^- and HCO_3^- to CH_4 . Wu et al (1985) have not found any decrease in EC following the initial increase upto first 3 weeks. Initial properties of soil, however, profoundly influence the EC kinetics. Redman and Patrick (1965) observed decrease in EC after submergence in some soils initially high in NO_3^- -N. Wu et al (1985) found high correlation between the EC increase on submergence and the organic matter status of soil. After the removal of most of the organic matter from the soil, the increase in EC was very small.

Generally, the EC of submerged paddy soils are higher than the corresponding upland soils. Wu et al (1985) found 20 to 70% increase in EC of five soils from China after having developed them to lowland paddies.

Nitrogen

Most of the nitrogen in soils is organically bound. This organically bound N is biologically transformed to inorganic N (NH_4^+ and NO_3^-) during organic matter decomposition. Mineralization (the biological transformation of organic N to inorganic N) occurs in both oxidized and reduced soils. Since the rate of organic matter degradation is considerably greater in aerobic soils, one would expect net N mineralization and subsequent availability to be higher under these conditions. However, the N requirements for anaerobic metabolism are lower than for aerobic metabolism, resulting in a greater release or availability of NH_4^+ -N than would otherwise be expected in reduced soils. This has been demonstrated experimentally by a number of investigators (Acharya 1935a, b, c; Abichandani and Patnaik 1958; Patrick and Wyatt 1964, Waring and Bremner 1964, Williams et al 1968, Yoshida 1971).

Patrick and Wyatt (1964) found a considerably higher rate of inorganic N release in flooded than in well-drained soils. In a number of soils, Waring and Bremner (1964) observed a more rapid rate of net mineralization under submerged than under

aerobic conditions. Quantitatively, they showed that in a two week period, for every 1 ppm of inorganic N produced aerobically, 1.23 ppm of inorganic N were produced under submerged conditions. Tusneem and Patrick (1971) noted that the mineralization rate of organic N of added residues was initially greater under submerged than under optimum moisture conditions. The difference was more pronounced at higher C:N ratios (>20) and persisted for about 2 months. Thereafter, the inorganic N still increased under optimum moisture regime and reached absolutely higher levels, while NH_4^+ accumulation gradually decreased under submerged conditions.

Works reviewed above indicate that organic N conversion to NH_4^+ occurs at all levels of soil aeration, but at varying rates. Under well-aerated conditions, very little or no NH_4^+ accumulates in a soil system, because of rapid oxidation of NH_4^+ to NO_3^- . Ammonium N accumulates in submerged soils, since they are devoid of O_2 . As early as 1928, Janssen and Metzger studied the changes in NO_3^- and NH_4^+ in a soil heavily manured with vetch under well-drained and flooded conditions. In the well-drained soil, NH_4^+ rose to 12 ppm in the soil solution at the end of 2 weeks and declined to almost zero at the end of 6 weeks, while NO_3^- steadily increased and attained a level of 40 ppm in the soil solution at the end of 10 weeks. Islam and Islam (1973) and Ponnampereuma (1975a) also noted progressive increase in

NO_3^- -N concentration in soil solutions of field capacity moist soils. Sahrawat (1982) studied the nitrification of soil N in several rice soils having a wide range of pH (3.4 to 8.6) and organic C (1.22 to 22.70%) by incubating them under aerobic conditions for 4 weeks at 30°C. It was found that two acid sulfate soils (pH 3.4 and 3.7) and a strongly acid soils (pH 4.4) did not nitrify during this period. Mineral and organic soils having pH >6.0 nitrified at rapid rates and accumulated NO_3^- -N ranging from 98 to 123 mg/kg of dry soil.

Ponnamperuma (1985) reported that flooding rapidly decreased NO_3^- -N whereas generally increased NH_4^+ -N concentration in soils. The rate of disappearance of NO_3^- varied markedly with soil and temperature. The kinetics of ammonification also varied with the soil, temperature and pre-treatment of the soil. Air-drying four peat soils before anaerobic incubation caused a release in 8 week of 200-500 mg NH_4^+ /kg compared with almost zero for the non-dried wet peat soils (Sahrawat 1983).

Phosphorus

Although P itself is not normally biologically reduced in redox reactions in soils, it does undergo reactions that have a pronounced effect on its reactivity. Phosphorus is generally more available in submerged than in aerobic soils (Aoki 1941; Shapiro 1958 a,b; Mitsui 1960, Patrick 1964, Ponnamperuma 1965,

Murty and Singh 1975, Khalid et al 1976, Reddy and Patrick 1983). Ponnampetuma (1972, 1985) attributed the observed increase in soluble P upon flooding soils to (i) reduction of $\text{FePO}_4 \cdot 2\text{H}_2\text{O}$ to $\text{Fe}(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$, (ii) hydrolysis of FePO_4 and AlPO_4 in acid soils, (iii) desorption following reduction of Fe(III) hydrous oxides to Fe(II), (iv) release of occluded P, (v) increased mineralization of organic P in acid soils caused by increased pH, and (vi) increased solubility of apatite in calcareous soils due to drop in pH. Careful survey of literature, however, reveals that in a number of cases flooding did not increase P solubility in soils. Bartholomew (1931) noted a decrease in water soluble P due to flooding of soil. Paul and DeLong (1949) also recorded similar findings. These investigators attributed the reduced P availability partly to the transformation of inorganic phosphate to insoluble organic P complex and partly to the precipitation by Ca present at high concentration in the flooded soil. Gasser (1956) suggested that Al may stabilize insoluble organic P complexes in anaerobic soils, resulting in reduced P availability. Valencia (1962) noted that long-term flooding decreased P availability in 5 soils. Flooding either did not change or decrease extractable P in 8 of 26 soils studied by Redman and Patrick (1965). These 8 soils released relatively less amounts of Fe^{2+} in the solutions. Tusneem (1967) did not observe any increase in P availability due to flooding of an Ultisol low in total P content.

Ponnamperuma (1972) noted that flooding did not increase P solubility in a near-neutral clay, and an acid ferrallitic clay high in active Fe. Khalid et al (1977) reported an increase in soluble P in 13 of 20 rice soils when incubated under reduced vs oxidized conditions. Katyal and Venkatramayya (1983) did not find any appreciable change in water soluble P in a Vertisol from India.

Patrick and Khalid (1974) reported that reduced soils released more P to soil solutions low in soluble P and sorbed more P from solutions containing high levels of soluble P than did the same soils under oxidized conditions. It was suggested that the reduction of insoluble ferric oxyhydroxides to more highly dispersed ferrous forms increases the surface area of the reactive iron compounds responsible for P retention. This was supported by the recovery of more oxalate-extractable (poorly crystalline) iron from the reduced soils.

In alkaline soils, Turner and Gilliam (1976a,b) observed that increase in available P (expressed as anion resin-adsorbable P) under flooded conditions was not due to soil reduction of ferric phosphate but due to increased soil water content. Increased available P under water saturated conditions (oxidized or reduced) was attributed to the greater rate of diffusion to the resin particles. They observed increased rate of P diffusion with increase in soil water content.

Iron

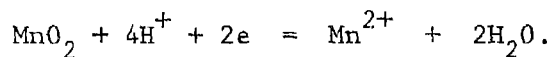
In aerobic soils the concentration of water-soluble Fe is governed largely by the solubility of ferric oxide hydrates. The solubility of these oxides is so low that in natural aerobic media the concentration of water-soluble Fe, theoretically, cannot exceed 0.001 ppm. The higher concentration (commonly 0.1 ppm) observed in aerobic soils are due to organic complexes and to colloidal ferrous oxide hydrates stabilized by organic matter (Krauskopf 1972). When a soil is submerged, the picture changes drastically. The ferric iron is directly and indirectly reduced to ferrous iron by microorganisms and large amounts of Fe are brought into solution. Ponnampuruma (1965, 1972) observed that on submergence the concentration of water-soluble Fe in soils increased to a peak value and then declined or reached a plateau. These changes varied with the pH and organic matter content of the soil, the content and reactivity of ferric oxides, presence of nitrate, temperature and the salt content of the soil. Acid soils high in organic matter and iron were found to build up concentrations as high as 600 ppm within 1-3 weeks after flooding and showed a roughly exponential decrease to levels of 50-100 ppm, which persisted for several months. Low temperature retarded the peak and broadened the area under it (Ponnampuruma 1976). In neutral and calcareous soils low in organic matter, the concentrations of water-soluble Fe were

lower, usually less than 20 ppm and sometimes even less than 1 ppm. Reyes and Ponnamparuma (1972) noted extremely low concentrations (less than 0.5 ppm) of water-soluble Fe in three non-flooded soils as compared to those in the corresponding flooded soils. Islam and Islam (1973) failed to detect any water-soluble Fe in five soils under field capacity moist conditions whereas it ranged between 80 and 230 ppm under the flooded conditions.

Gotoh and Patrick (1974) observed 50 to 100 ppm of water-soluble Fe in anaerobic soils as compared to less than 1 ppm in the aerobic soils. Using a wide range of closely controlled pH and Eh conditions in a soil suspension, they found that increases in water-soluble and exchangeable iron were favored by a decrease in both Eh and pH. They noted that the critical Eh for Fe^{3+} reduction and consequent dissolution was between +300 mV and +100 mV at pH 6 and 7, and -100 mV at pH 8; while at pH 5 appreciable reduction occurred at +300 mV. Their study further revealed that water-soluble Fe accounted for 76% of the water-soluble plus exchangeable fraction under the combination of pH 5 and Eh -250 mV, whereas it accounted for only 4% under the combination of pH 8 and Eh -250 mV. Sajawan (1985) has reported that solubility of Fe in soil suspension increased progressively with decrease in the redox (Eh/59.2 + pH) values.

Manganese

The behavior of Mn in paddy soils is similar to Fe in many respects. On flooding, insoluble oxidized manganic (Mn^{4+}) compounds are reduced to the more soluble manganous (Mn^{2+}) form



An increase in Mn^{2+} in the solution and on the exchange complex is one of the first measurable effects of reducing conditions. The release of Mn^{2+} into the soil solution precedes that of Fe^{2+} because Mn^{4+} is more readily reduced and rendered more soluble than Fe^{3+} .

Redman and Patrick (1965) observed approximately six times as much extractable Mn in flooded soils after 30 days of submergence as under air-dry conditions. Ponnampereuma (1965) noted that on submergence, the concentration of water-soluble Mn in soils increased, reached a peak and then declined. The decline after the peak was attributed to the precipitation of Mn^{2+} as MnCO_3 (Ponnampereuma et al 1969).

Soil pH has a remarkable effect on Mn solubility, and the concentration of Mn^{2+} in the soil solution is highly dependent on both pH and Eh. Turner and Patrick (1968) found no exchangeable Mn in an aerobic soil above a pH of 6, while in an anaerobic soil exchangeable Mn was present upto pH 11. They further noted that Mn^{4+} began to be reduced at an Eh of +400 mV and was essentially completely reduced at an Eh of +200 mV.

Gotoh and Patrick (1972) reported that both water-soluble and exchangeable Mn^{2+} increased with decrease in Eh and pH. Between pH 6 and 8, the conversion of insoluble Mn^{4+} to Mn^{2+} was dependent on both Eh and pH. At pH 5, the effect of Eh was minimal on Mn^{2+} solubility and in more acidic range (pH <5), pH alone could control the Mn^{2+} solubility in soils. They found that at pH 5, almost all of the soil Mn was converted from reducible to water-soluble plus exchangeable fraction even at Eh as high as +500 mV. At pH levels between 6 and 8, most of the conversion took place at relatively low potentials of +200 to +300 mV.

Due to this marked influence of pH on Mn solubility, Mn toxicity could be a problem in acid aerobic soils rich in active Mn (Ponnamperuma 1975a).

Reyes and Ponnamperuma (1972) found much higher concentration of water-soluble Mn in three soils under flooded than under non-flooded conditions. Under non-flooded conditions, the acid soil had 7 to 40 ppm as compared to almost no water-soluble Mn in the near-neutral and calcareous soils.

Sajawan (1985) has noted that solubility of Mn in soil suspension increased progressively with decrease in the redox (Eh/59.2 + pH) values.

Potassium, calcium, magnesium
and sodium

Potassium, Ca, Mg and Na are not involved in oxidation-reduction reactions and are therefore not directly affected by poor soil aeration and flooded conditions. However, flooding and reduction of soils may increase their concentrations in soil solution by accelerating the dissolution of solid compounds of these elements through the solvent action of CO_2 and by cation exchange reactions. In poorly drained and flooded alkaline soils, low O_2 and high CO_2 levels can result in dissolution of CaCO_3 and MgCO_3 and increase the Ca^{2+} and Mg^{2+} concentration of the soil solution (Ponnamperuma 1972). The large quantities of NH_4^+ , Fe^{2+} and Mn^{2+} ions released upon flooding may displace substantial quantities of Ca^{2+} , Mg^{2+} , K^+ and Na^+ from the exchange sites into the soil solution.

Substantial increase in the concentration of K^+ in soil solution due to flooding were recorded by several investigators (Clark and Resnicky 1956, Ponnamperuma 1965, Islam and Islam 1973, Pasricha and Ponnamepruma 1976). Close examination of the findings of these researchers reveals that the increases in solution K^+ concentration due to flooding were highest in the sandy soils rich in organic matter. Murty and Singh (1975) noted a sharp increase in water-soluble Ca in six soils during the first week of submergence and thereafter no consistent

change was observed. Sharma et al (1977) observed increased availability of Ca, Mg, K and Na in a silty clay loam (pH 8.3) after 60 days of flooding. The findings of Sims and Patrick (1978) that greater amounts of exchangeable iron, manganese, zinc and copper are present at low Eh and low pH than at high Eh and pH confirmed the role of Fe^{2+} and Mn^{2+} in cation exchange in flooded soils.

Zinc and copper

Zinc and copper are not as readily involved in soil oxidation-reduction reactions, but their solubility is affected by poor aeration caused by flooding. The solubility of Zn and Cu in soils is highly pH dependent and decreases by a factor of 100 for every unit increase in soil pH (Lindsay 1972, Sinha et al 1975, Maskina 1976).

Forno et al (1975) and Mikkelsen and Kuo (1976) reported that the concentration of Zn in soil solution decreased after flooding. Ponnampereuma (1977) noted that despite probable desorption from ferric- and manganic- oxide hydrates, flooding generally decreased the concentrations of soluble Zn and Cu in soils. He attributed this decrease in acid soils partly to the pH increase following soil reduction. But the concentrations of water-soluble Zn and Cu decreased also in calcareous and sodic soils under submergence, in spite of the decrease in pH brought about by the accumulation of CO_2 . It has been postulated that

the solubility of Zn and Cu in flooded soils is controlled by several metastable compounds like $Zn_3(PO_4)_2$, $ZnNH_4PO_4$, $Zn(OH)_2$, ZnS , $ZnCO_3$, $ZnSiO_3$ and $CuSiO_3 \cdot 2H_2O$ (IRRI 1971, Katyal 1972, Krauskopf 1972, Sinha et al 1975, Dhillon et al 1975). Most of these compounds are too soluble in soils to have a significant influence on Zn or Cu solubility.

However, Engler and Patrick (1975), Kittrick (1976) and Ayotade (1977) reasoned that ZnS is stable in flooded rice soils. Reddy and Patrick (1977) observed that chelated Zn and Cu in soil solution decreased with decreasing Eh from +500 mV to -200 mV. The instability of Zn and Cu chelates was attributed to chemical fixation (possibly with sulfide) of added Zn and Cu, and not due to chemical or microbial breakdown of the metal chelate complex. Pavanasivam and Axley (1980) noted that in presence of added SO_4^{2-} -S, flooding of a high pH silty loam reduced the availability of Zn. When SO_4^{2-} -S was not added to the soil, flooding the same high pH soil increased the Zn availability. At low pH on the other hand, regardless of SO_4^{2-} -S addition, flooding caused a reduction in the availability of Zn. Rajendran and Aiyer (1982) reported that drying of five acidic paddy soils enhanced the available Zn status. Sajawan (1985) found that Zn solubility in soil suspensions decreased with decreasing redox (Eh/59.2 + pH). He postulated that at low redox, the increased solubility of Fe could have a depressive effect on the solubility of Zn through the formation of $ZnFe_2O_4$ (franklinite).

Sulfur

Sulfur is subject to oxidation-reduction reactions and exists in soils at different valence states. The most common valences are +6 (sulfate), 0 (elemental S) and -2 (sulfide). The valence state of S in soil is governed to a large extent by the environmental conditions (O_2 and water content) that affect the composition and activity of the microflora.

In aerobic soils, the principal S transformations include (i) the oxidation of elemental S, thiosulfates and sulfides; (ii) mineralization of organic S; and (iii) incorporation of S and sulfates into microbial tissue, and uptake by plants. Under conditions of O_2 -free environment, sulfate-reducing obligate anaerobic bacteria use SO_4^{2-} -S as an electron acceptor, resulting in the formation of sulfides (Alexander 1977). These organisms are very sensitive to O_2 and cannot function in the presence of soil O_2 . Sulfate reduction was shown to occur in soils with Eh < -75 mV (Harter and McLean 1965), while Connell and Patrick (1968) reported sulfide formation in an anaerobic soil with Eh < -150 mV. Ponnampereuma (1978) suggested that sulfate reduction even in flooded soils only proceeds at localized, highly reduced spots. Rao et al (1984) found that SO_4^{2-} -S concentration decreased marginally during first 10 days and rapidly thereafter on submergence in eight different soils. Summarizing his own works, Ponnampereuma (1985) reported that in neutral and alkaline soils, the SO_4^{2-} -S concentration

decreased rapidly and was reduced to zero within 6 weeks of flooding. In acid soil, it first increased probably because of desorption and then decreased to zero. Kinetics of water-soluble sulfate in flooded soils have been found to be influenced by the properties of soils (pH, organic matter content, etc.) and temperature. Gupta (1974) and Pan (1985) reported that the rate of SO_4^{2-} -S reduction increased rapidly with temperature. The optimum pH range for maximum sulfide formation was found to be between 6.5 and 8.5 (Connell and Patrick 1968). Engler and Patrick (1973) demonstrated that a number of chemical oxidants like KNO_3 and MnO_2 were effective in promoting sulfide oxidation or retarding sulfide formation. It was suggested that effects on sulfide production were due to the oxidants' influence on soil Eh. Pan (1985) noted that addition of organic matter to flooded soils markedly increased the rate of SO_4^{2-} -S reduction.

Silicon

Although submergence of soil is believed to render Si more readily available to rice, there is no clear-cut demonstration of the increase in solubility of Si as a result of submergence. Reed and Sturgis (1939) reported that flooding caused an increase in the solubility of Si, although their figures clearly indicate that Si was consistently lower in the solution from flooded soil than from the well-drained. Ponnampetuma (1965,

1972) reported that submergence caused only slight increase in soluble Si in some soils whereas it did not produce any increase in the others. He attributed the observed increase under flooding to the release of Si following reduction of hydrous oxides of Fe^{3+} sorbing Si and action of CO_2 on aluminosilicates. Patrick and Reddy (1978) suggested that decomposing rice straw with its high silica content could also contribute to the increased Si content of the soil solution of flooded soils.

In fact, solubility of Si in soils is governed by complicated phenomena. Silicon is present in soils as amorphous and crystalline silica, aluminosilicates, and as silica adsorbed on or co-precipitated with hydrated oxides of Al^{3+} , Fe^{3+} and Mn^{4+} . Wilding et al (1977) noted that the concentration of soluble Si in soil lies approximately halfway between the equilibrium solubility of amorphous silica and quartz. Elgawhary and Lindsay (1972) concluded that a solid phase less soluble than amorphous silica and more soluble than quartz controls silica concentrations in soils. Other investigators suggested that the adsorption and desorption of soluble silica by soil components play a major role in determining the concentration of water-soluble Si in soils (Beckwith and Reeve 1963, 1964; McKeague and Cline 1963; Jones and Handreck 1963).

Concentration of Si in solution at any given time is related closer to the relative rates of the above processes than to equilibrium concentrations. In various ways, pH may affect the concentration of water soluble Si in soils. Alexander et al (1954) found that the solubility of amorphous silica is lowest at pH 7-8. The solubility increased slightly at lower and sharply at higher pH values. Beckwith and Reeve (1964) and Baumann as cited by Iler (1979) noted that sorption of silica by soil was highest at pH 9 and decreased markedly both at higher and lower pH. Iler (1979) reported that monosilicic acid combines with metal ions to an increasing degree with increasing pH, resulting in the decrease in concentration of monosilicic acid (soluble silica).

III. Growth and Mineral Nutrition of Rice Under Flooded and Non-flooded Conditions of Soils

Growth

As early as 1943, Cralley and Adair found that rice plants grown on continuously submerged plots were taller, tillered more profusely, had higher grain: straw ratio and gave significantly higher yields than the plants grown on the plots kept continuously moist. Chakladar (1946) noted that even the best known upland varieties of rice gave lower yields when grown under upland (non-flooded) than under lowland (flooded) soil conditions. Similar findings were subsequently recorded by many

other investigators (Senewiratne and Mikkelsen 1961, Chaudhry and McLean 1963, Yoshida 1975, Singh et al 1977, De Datta 1981, Ismunadji 1985).

Poor growth and yield of upland rice have more commonly been attributed to weed infestation (Sankaran and De Datta 1985), moisture stress (Moolani and Sood 1967; Jana and Ghildyal 1969; Jana and De Datta 1971; De Datta et al 1973, 1975; Yoshida 1975; De Datta 1981) and disease-pest problems (Ou et al 1975, Ahn and Mukelar 1986). Others have suggested that decreased availability of several mineral nutrients and imbalanced nutrition of rice under non-flooded conditions of soils greatly contribute to the poor performance of upland rice (Ponnamperuma 1955, 1965, 1975; Shapiro 1958a, Jeffery 1963; Halm 1967; Yoshida 1975, Singh et al 1977; Chahal et al 1980; Ismunadji 1985).

Recently, Westcott and Vines (1986) have reported that even after complete elimination of moisture stress and disease-pest problems, yield of rice under non-flooded conditions did not exceed 62-75% of that under the flooded conditions. They have suggested that the yield difference could be due to difference in nutrient availability under the two different moisture regimes.

Mineral nutrition

Nitrogen. Zsoldos (1958) studied the effects of aerobic and anaerobic conditions on short-term uptake of N by rice seedlings from nutrient solution. He did not find any difference in N uptake between the two treatments. Senewiratne and Mikkelsen (1961), Chaudhry and McLean (1963) and Halm (1967) reported no significant effect of soil-submergence on N concentration in the shoots. In fact, these researchers and Ismunadji (1985) noted higher concentrations of N in the plant tissues under non-flooded compared to the flooded treatments probably because of its dilution in tissue; because dry matter yield was much higher under the flooded conditions. Several investigators, on the contrary, reported higher concentration of N in rice plants grown under flooded than under the non-flooded conditions of soil (Shapiro 1958a, Enyi 1966) and sand culture (Baruah and Singh 1980). In these cases, dry matter yields were comparable under flooded and non-flooded treatments.

Phosphorus. The short-term uptake study of Zsoldos (1958) showed no effect of the anaerobic conditions of nutrient solution on P uptake by rice seedlings. Senewiratne and Mikkelsen (1961) and Enyi (1966) found no significant difference in P concentration in shoots between the flooded and non-flooded soil conditions. Cherian et al (1968) did not find any consistent effect of soil submergence on P content of rice plants.

Sanchez and Briones (1973) reported that in soils of high P availability, there was no difference in growth and P uptake by rice between the constant flooding and partially oxidized treatments. They further noted that in soils of low P availability, partially oxidized conditions produced lower yields and lower P uptake in comparison to constant flooding.

Several other investigators (Chaudhry and McLean 1963, Halm 1967, Patrick and Fontenot 1976, Chahal et al 1980, Bora and Goswami 1983, Ismunadji 1985) found that plants grown under anaerobic or flooded conditions contained remarkably higher concentrations of P than those grown under aerobic or non-flooded conditions.

Potassium. Senewiratne and Mikkelsen (1961) found no significant effect of soil submergence on K concentration in rice plants. Enyi (1966), Halm (1967), Cherian et al (1968), Sharma et al (1975) and Jha et al (1978) noted that plants growing under non-flooded conditions had remarkably higher concentration of K than that under the flooded conditions. On the contrary, some researchers reported higher concentrations of K in plants under flooded than under the non-flooded conditions (Singh 1966, Baruah and Singh 1980, Ismunadji 1985). The conflicting results may be due to the differences in the properties of soils used, but this aspect has not been considered by these workers.

Calcium, magnesium and sodium. Enyi (1966) and Yoshida (1975) found no appreciable difference in Ca and Mg concentrations in plants between the flooded and non-flooded conditions. On the other hand, Cherian et al (1968) and Sharma et al (1975) noted that flooding of soils consistently decreased Ca and Mg concentrations in rice plants. Enyi (1966) recorded consistent increase in tissue Na content due to flooding of soils.

Iron. Rendering the atmosphere overlying the flood-water anaerobic, Mandal (1962) obtained higher Fe content in rice shoots. Many other researchers have reported significantly higher concentration of Fe in plants under flooded than under non-flooded conditions of soils (Yoshida 1975, Jugsujinda and Patrick 1977, Singh et al 1977, Chahal et al 1980, Tiller 1982, Gupta et al 1982, Sajawan and Lindsay 1986).

On the otherhand, Senewiratne and Mikkelsen (1961) and Chaudhry and McLean (1963) did not find any significant difference in plant Fe concentrations between the flooded and non-flooded conditions of soil. Cherian et al (1968) and Patrick and Fontenot (1976) also found no consistent effect of soil reduction or flooding on Fe contents of rice plants. Probably effect of flooding on total Fe content in rice plants varies with soil properties which have not been considered by these workers.

Manganese. Mandal (1962) noted that under anaerobic environment, rice plants had higher Mn content. Many other investigators reported higher concentration of Mn in plants under flooded than under the non-flooded regimes of soils (Cherian et al 1968, Singh et al 1977, Chahal et al 1980, Tiller 1982, Sajawan and Lindsay 1986).

In sharp contrasts to the above findings, Senewiratne and Mikkelsen (1961) noted significantly higher concentration of Mn in rice plant grown under non-flooded than under flooded conditions. They suggested that the higher Mn content of rice plants under non-flooded conditions (789 ppm under non-flooded against 102 ppm under flooded) affects the indole acetic acid oxidase mechanism resulting in retarded growth and depressed grain yields. Enyi (1966, 1968) and Kamada (1980) found higher Mn content in plants grown under moist than under flooded regime. They attributed it to a probable antagonism between Fe and Mn. Weeraratna (1969) noted that flooding caused increased uptake of Mn by plants in a soil collected from a field which had been under lowland conditions for a long time, but decreased it in a soil collected from an upland field. He noted much higher concentration of available Fe under flooded condition of the 'upland' soil compared to that in the other soil and attributed the decreased Mn uptake in the former case to the antagonistic influence of excessive Fe. Of the four soils studied, Tiller and Wasserman (1973) obtained increased Mn

content in tissue in three soils with pH ≥ 6.8 and decreased tissue Mn content in one acidic soil (pH 5.6) due to flooding. Yoshida (1975) reported that flooding increased Mn content in plants in a near-neutral soil but decreased it in an acid soil.

Zinc. Many researchers reported higher uptake of Zn by rice plants under non-flooded than under the flooded conditions of soils (Enyi 1966, Cherian et al 1968, Beckwith et al 1975, Kamada 1980, Tiller 1982, Singh et al 1984, Sajawan and Lindsay 1986). On the otherhand, Singh et al (1977) reported increased concentration of plant Zn due to flooding of the field.

Of the four soils studied, Tiller and Wasserman (1973) found that flooding increased plant Zn concentrations in two alkaline soils and decreased it in an acidic and near-neutral soil. Data presented by Tiller (1982) indicate that flooding caused marked decrease in tissue Zn concentration in acidic soils. In the alkaline soils, flooding either increased or did not change the Zn concentration in plants.

Copper. Cherian et al (1968) and Singh et al (1984) found no influence of soil-flooding treatment on Cu content in rice. Data presented by Enyi (1966), Kamada (1980) and Tiller (1982) indicate that Cu concentrations in rice plant were higher under non-flooded than under the flooded conditions of soils.

Silica. Pande and Mitra (1970), Rao (1971), Yoshida (1975) and Ismunadji (1985) reported higher concentration of silica in rice grown under flooded than under the non-flooded conditions of soils. Jha et al (1978), on the other hand, did not find any appreciable difference in silica content in rice between the flooded and moist regimes.

IV. Use of Equilibrium Soil Solution for Characterizing Soil Chemical Environment

Soil solution consists largely of thick films of water containing dissolved substances in quasi or dynamic equilibrium with the solid and gas phases of the soil. It may be regarded as the intermicellar or bulk solution in equilibrium with the double layer of ions on the solids in the soil (Soil Science Society of America 1978, Bolt 1976, Lindsay 1979). Much evidence has been presented that shows that the composition of the equilibrium soil solution is a useful reflection of the soil chemical environment, relates to plant growth (Pearson 1971), and yields similar critical nutrient values as in solution culture studies (Bennett and Adams 1970).

Under field conditions, the composition of soil solutions varies with the water content of the soils. For submerged paddy soils in pots, the clear solution drawn by gravity through a sintered glass tube at the bottom of the pot is considered the equilibrium soil solution and thermodynamically meaningful phase (Ponnamperuma et al 1967, Ponnamperuma 1972 and 1984).

The water content of soils growing upland crops fluctuates between a lower limit, at which plants wilt permanently, and an upper limit, which for most soils is approximately two times the water content at the permanent wilting point (Bower and Wilcox 1965). A satisfactory method for characterizing the chemical environment of soils in relation to plant growth should utilize an extract having a composition as representative of the soil solution as possible. An ideal method would consist of measuring the composition of an extract obtained at field water content, but the difficulty of obtaining such extracts in unaltered state prohibits their routine use. The next higher feasible water content is the saturation percentage. A method making use of the extract filtered from a saturated soil paste was adopted by the United States Salinity Laboratory (Richards 1954). Although this technique does not extract the solution at field moisture content, it is the next best method for relating the composition of the soil extract to plant growth (Bower and Wilcox 1965). Based on the saturation extract procedure, Geraldson (1957) developed a soil test for field crops in Florida and this procedure is currently being used by several soil testing laboratories in the United States (Holcomb et al 1982). Nemeth et al (1970) successfully used the saturation extracts of soils as representative soil solutions in their study. Mohiddin (1982) has noted that the saturation extracts of soils are the much-used approximation of soil solutions.

For comparative study of chemical kinetics of soils under aerobic and submerged (reduced) conditions, where the chief objective is to ascertain the effect of soil reduction brought about by submergence on soil chemical changes, it is desirable to collect equilibrium soil solutions from both the treatments at comparable water content. Kundu et al (1987) have described a method for collecting representative solutions (equilibrium saturation extract) from aerobic soils in pots. The special feature of the method is that it can be used to collect representative solutions of aerobic soils in situ and in presence of growing plants.

Experiment I

Direct Effects of Aerobic and Anaerobic Conditions of Two Soils on the Growth of Rice

Aerobic conditions prevalent in well-drained soils have been suggested to decrease availability of several mineral nutrients and cause imbalanced nutrition in rice (Ponnamperuma 1975). Since this adverse effect is often compounded with that of moisture stress, role of aerobic conditions of soils on growth retardation in rice has not been appreciated properly. The present preliminary experiment was conducted to examine the direct effects of aerobic and anaerobic conditions of two different soils on early vegetative growth of rice.

MATERIALS AND METHODS

For this greenhouse experiment one acid soil from Luisiana and a calcareous soil from Pila were used. General properties of the soils are presented in Table 3 and 4 (Luisiana II and Pila II). Nitrogen, P and K were added to the air-dry, sieved soils at the rates of 100, 50 and 50 mg/kg soil, respectively. Reagent grade ammonium sulfate, monocalcium phosphate and potassium chloride were used as the fertilizer materials. After thorough mixing of the fertilizer materials with the soils (900 g in each lot) on a polythene sheet, the air-dry soils were brought to the field capacity (FC) moisture by adding required

required amount of demineralized water. The moistened soils were then placed into wide mouth nalgene bottles (17.5 cm high x 8.5 cm diameter) by gentle tapping to ensure a uniform bulk density in all the bottles. The experimental set-up is illustrated in Figure 1. One bright platinum electrode was installed in each bottle at about 10 cm depth for in situ measurement of soil redox potential. Two pre-germinated seeds of IR43 were dibbled at about 1 cm below the soil surface in each bottle. One week after emergence, one seedling was pulled out from each bottle saving one seedling of uniform vigour for further growth. Soil surface in each bottle was then covered with a thin (3 mm) layer of quartz sand and the following three treatments (unreplicated) were imposed on each soil:

1. Field Capacity Moist Aerobic: surfaces of field capacity moist soils in the bottles were kept open to atmosphere without putting any further cover on them;
2. Field Capacity Moist Anaerobic: surfaces of FC moist soils in the bottles were sealed air-tightly with 3 mm layer of 2:1 mixture of paraffin-petroleum jelly; and
3. Flooded: soils in the bottles were submerged with demineralized water to maintain a 3 cm level of standing water.

Moisture levels of the FC moist soils in the bottles were maintained every other day by adding required amount (known by

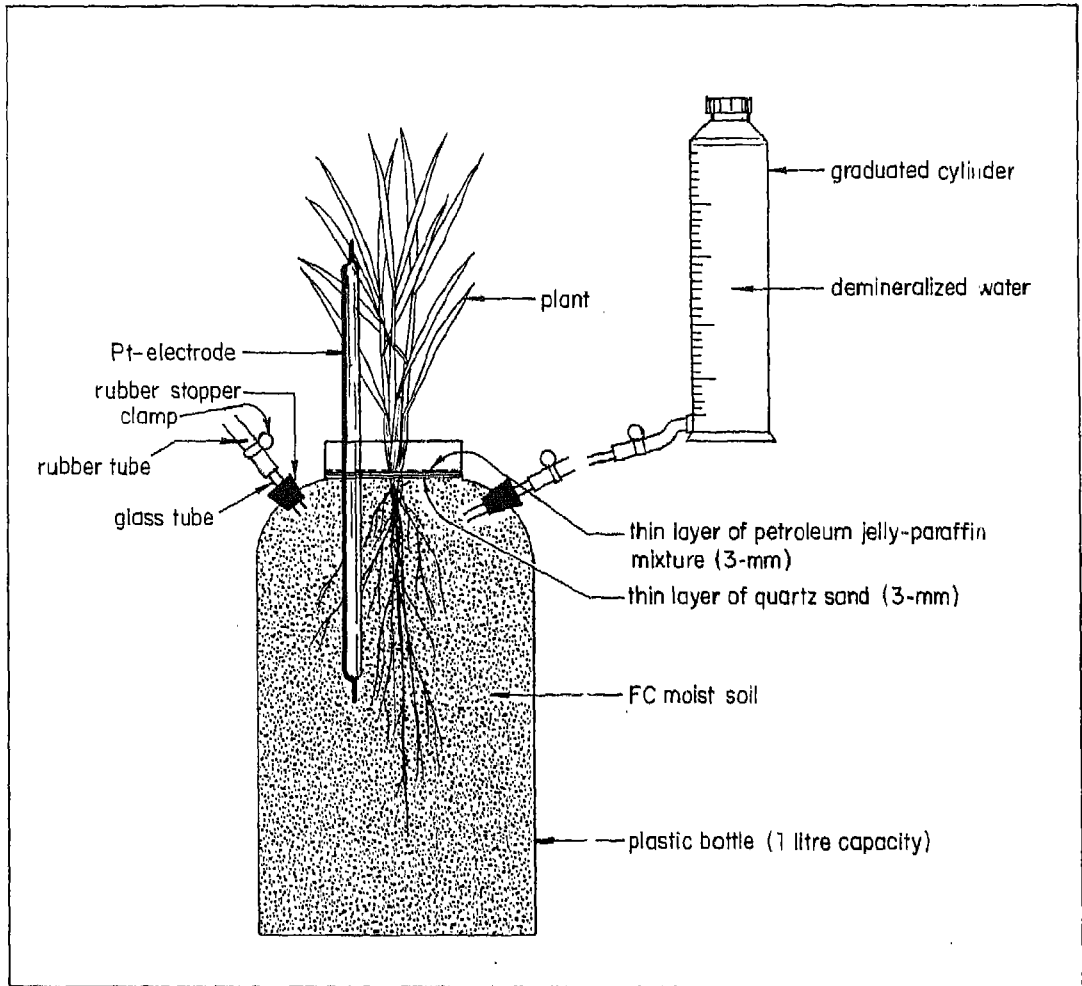


Fig. 1 . Set-up used for the bottle experiment.

weight difference) of demineralized water. Soils under the FC moist anaerobic treatment were watered through the shoulder assembly of the bottles from a graduated cylinder as illustrated in the figure. Redox potential measurements were made at fortnightly intervals using the platinum electrodes installed and a calomel half cell. The calomel electrode was pushed into the soil mass through the opening made by removing one shoulder assembly of the bottle. This opening was sealed air tightly between measurements. Measured redox potentials were corrected for the difference in half cell potentials between the saturated calomel electrode and the standard hydrogen electrode by adding 242 mV to the potentiometer readings.

The plants were grown for seven weeks after imposition of the treatments and plant heights were recorded. The shoots were then harvested, dried in an oven at 60°C temperature and weighed for dry matter yield.

RESULTS AND DISCUSSION

The soil redox potentials measured in situ under the three different treatments are presented in Table 1. The data clearly show that cutting of air entry into the FC moist soils by sealing the mouth of containers caused reduction in both Louisiana and Pila soils. The degree of reduction brought on by this way was almost same as that caused by waterlogging. Data presented in Table 2 show that soil reduction markedly increased

the height and dry matter yield of rice in both the soils under FC moisture regime. Perhaps increased availability of some important nutrient elements under the reduced conditions of the soils was responsible for this better growth. Patrick and Fontenot (1976) also noted enhanced vegetative growth of rice in a non-flooded soil under reduced condition. However, they attained the reduced conditions under non-flooded regime by passing N_2 gas through the soil column. Result of the present experiment further shows that presence of excess water in the anaerobic or reduced Pila soil augmented the rice growth whereas the same (flooding treatment) proved detrimental in the reduced Luisiana soil (Table 2). Available nutrients in soils are delivered to plant roots primarily by mass flow and diffusion. The delivery rate of nutrients by both these mechanisms decreases as the moisture content of soil decreases (Parish 1971). Greater growth of rice in flooded- anaerobic than in the FC moist- anaerobic Pila soil could partly be explained by the higher mobility of nutrients in presence of higher water supply. Poor growth of rice in the flooded- anaerobic Luisiana soil might have been due to probable excessive uptake of Fe by plant to the toxic level. Symptoms similar to that of Fe toxicity were observed on leaves of the plant grown under this treatment. Probable restricted uptake of Fe by plant from the FC moist- anaerobic conditions might have been optimum for rice growth in the strongly acidic Luisiana soil.

Table 1. Redox potentials of two soils under three different treatments.

| Soil | Treatment | Redox potential (mV) | | | |
|----------|--------------------|---|------|------|------|
| | | Weeks after imposition of the treatments | | | |
| | | 1 | 3 | 5 | 7 |
| Luisiana | FC moist aerobic | 663 | 745 | 815 | 848 |
| | FC moist anaerobic | 305 | -115 | -110 | -154 |
| | Flooded | 110 | -145 | -132 | -154 |
| Pila | FC moist aerobic | 370 | 540 | 774 | 738 |
| | FC moist anaerobic | 220 | -123 | -115 | -119 |
| | Flooded | 200 | 50 | -50 | -100 |

Table 2. Height and dry matter yield of 8 week old IR43 plants grown in two soils under three different treatments.

| Soil | Treatment | Height (cm) | Dry matter yield (mg) |
|----------|--------------------|----------------|--------------------------|
| Luisiana | FC moist aerobic | 36 | 400 |
| | FC moist anaerobic | 56 | 720 |
| | Flooded | 36 | 530 |
| Pila | FC moist aerobic | 42 | 520 |
| | FC moist anaerobic | 54 | 700 |
| | Flooded | 71 | 920 |

Experiment 2

Chemical Kinetics of Four Soils Under Moist and Flooded Conditions in Relation to Growth and Mineral Nutrition of Rice

Results of the previous preliminary experiment indicated that aerobic or oxidized conditions of soils limit growth of rice plants. In an attempt to identify the specific chemical factors that adversely affect rice growth in aerobic soils, chemical kinetics of four soils were studied under field capacity moist and flooded conditions.

MATERIALS AND METHODS

The experiment was conducted in the greenhouse of Department of Soils of the International Rice Research Institute (IRRI) in the 1985 Dry Season. Surface soil (0-20 cm) samples collected from the following four sites of Philippines were used for the study:

1. Luisiana, Laguna (acid soil)
2. Block UK1, IRRI Farm, Maahas, Laguna (near neutral soil)
3. Pila, Laguna (calcareous soil).
4. Burabod, Malinao, Albay (acid-sulfate soil)

Throughout this thesis these soils will be referred to as Luisiana, Maahas A, Pila and Burabod soils, respectively. While the Luisiana soil was obtained from the greenhouse stock, the other three soils were collected freshly for this experiment.

General properties of the soils are furnished in Tables 3 and 4.

Table 3. Some physical properties of the soils used.

| Soil | Classification | Particle Size Distribution | | | Textural Class | Moisture Content at | |
|----------|----------------|----------------------------|--------|------|----------------|---------------------|--------------|
| | | Sand | Silt % | Clay | | Field capacity | Saturation % |
| Luisiana | Tropudult | 8 | 33 | 59 | clay | 35 | 51 |
| Maahas A | Tropudalf | 25 | 46 | 29 | clay loam | 25 | 59 |
| Pila | Tropaquept | 46 | 38 | 16 | loam | 30 | 44 |
| Burabod | Sulfaquept | 61 | 26 | 13 | sandy loam | 25 | 57 |
| Rotonda | Eutropept | 25 | 48 | 27 | loam | 30 | 51 |
| Maahas B | Tropaquept | 17 | 42 | 41 | silty clay | 32 | 53 |

Table 4. Some physico-chemical and chemical properties of the soils used.

| Soil ^a | pH (1:1 water) | Organic carbon ----- % | Active | | CEC | Exchangeable | | | | Al Satn. (%) | Available | | Total | | Available | | |
|----------------------|----------------------|---------------------------------|--------|-------|-------|--------------|-------|------|------|--------------------|-----------|------|-------|-------|-----------|------|---|
| | | | Fe | Mn | | Ca | Mg | K | Na | | Al | Zn | Cu | N | P | N | P |
| Luisiana I | 4.5 | 2.38 | 5.87 | 0.038 | 19.62 | 12.50 | 5.26 | 0.33 | 0.47 | 0.59 | 3.0 | 3.30 | 6.30 | 0.243 | 173 | 3.1 | |
| Luisiana II | 4.5 | 2.62 | 5.19 | 0.172 | 14.87 | 7.50 | 3.62 | 0.41 | 0.26 | 2.57 | 17.3 | 2.10 | 1.82 | 0.249 | 214 | 5.3 | |
| Maahas A I | 6.6 | 1.69 | 3.27 | 0.194 | 35.70 | 18.00 | 11.84 | 2.25 | 0.96 | nd | nd | 0.34 | 0.06 | 0.138 | 45 | 30.1 | |
| Maahas A II | 6.6 | 1.58 | 3.27 | 0.202 | 36.10 | 17.50 | 11.51 | 1.90 | 1.60 | nd | nd | 0.32 | 0.04 | 0.142 | 67 | 29.7 | |
| Pila ^b I | 7.6 | 1.84 | 0.85 | 0.112 | 44.90 | 44.90 | 8.88 | 1.15 | 0.65 | nd | nd | 0.00 | 0.06 | 0.228 | 70 | 45.9 | |
| Pila ^b II | 7.6 | 1.62 | 0.91 | 0.106 | 40.30 | 40.40 | 7.24 | 0.72 | 0.65 | nd | nd | 0.00 | 0.02 | 0.185 | 53 | 37.3 | |
| Burabod I | 3.9 | 1.84 | 0.39 | 0.001 | 12.80 | 5.00 | 1.15 | 0.20 | 0.43 | 5.43 | 42.4 | 1.36 | 5.90 | 0.167 | 65 | 10.9 | |
| Burabod II | 3.8 | 1.62 | 0.47 | 0.002 | 12.03 | 5.00 | 0.99 | 0.26 | 0.56 | 4.78 | 39.7 | 1.66 | 3.90 | 0.165 | 102 | 9.9 | |
| Rotonda | 6.1 | 1.58 | 1.23 | 0.096 | 24.30 | 15.50 | 6.58 | 1.20 | 0.69 | nd | nd | 0.94 | 0.56 | 0.147 | 91 | 54.5 | |
| Maahas B | 6.6 | 1.81 | 3.27 | 0.174 | 45.00 | 23.50 | 16.45 | 2.15 | 1.82 | nd | nd | 0.66 | 0.06 | 0.178 | 138 | 23.9 | |

^a I - 1985 Experiment. II - 1986 experiments.

^b Calcareous soil with 10.3% free CaCO₃.

nd - not determined.

Preparation of the bulk soils

The bulk soil samples collected from the fields were air-dried under shade by spreading on plastic sheets in the greenhouse. The dried samples were then crushed gently by using wooden hammer and passed through a 1 cm sieve to obtain small granular clods. The samples were not crushed into finer particles to avoid any undesirable drainage problem during the course of the experiment. Since aerobic condition of soils was one treatment under this study, free drainage of the potted soils was to be ensured.

Greenhouse procedure

Ten kilogram portions of each soil were thoroughly mixed on a polythene sheet with reagent grade ammonium sulfate, monocalcium phosphate and potassium chloride to supply N, P and K at the rates of 100, 50 and 50 mg/kg soil, respectively. The fertilized soils were then placed in 16 liter glazed porcelain pots fitted with drainage tubes (coarse sintered glass tube wrapped by glass wool and nylon net) at the bottom (Fig. 2). The pots were placed in the greenhouse tanks filled with water (upto the level 7-8 cm below the rim of pots) to minimize temperature fluctuations in potted soils. Soils in all the pots were first brought to the field capacity moisture level by adding required amount of demineralized water. Two bright

platinum electrodes and one tensiometer were installed in each pot at 10 and 15 cm depth, respectively. The whole greenhouse set-up is shown in Plate 1.

For collecting soil solution at 0 week, all the pots were made saturated by demineralized water. The saturation extracts were then recycled three times through the soils before collecting the final extracts as representative soil solutions.

Eight pre-germinated seeds of IR43 or IR46, according to the treatments, were dibbled in each pot at about 1 cm depth after the sampling of 0 week solutions. While moisture level in the soils under the moist regime was maintained around field capacity with the help of tensiometers and by adding demineralized water whenever necessary throughout the experimental period, the soils under the flooded treatment were maintained saturated for about first 10 days until the seedlings were established. At the time of watering, sufficient care was taken to maintain the soil surfaces as undisturbed as possible. Free drainage of the moist soils in pots was maintained throughout the growing season by keeping the outer end of drain tubes open into the receiving containers (glass bottles)

At about 10 days after dibbling, seedlings in each pot were thinned out to keep four healthy and uniform ones. The flooding treatment of the soils was imposed at this stage by supplying a 3 cm level of standing water which was maintained thereafter till the maturity and harvest of the crop. Because of severe chlorosis, seedlings grown on the calcareous Pila soil under the

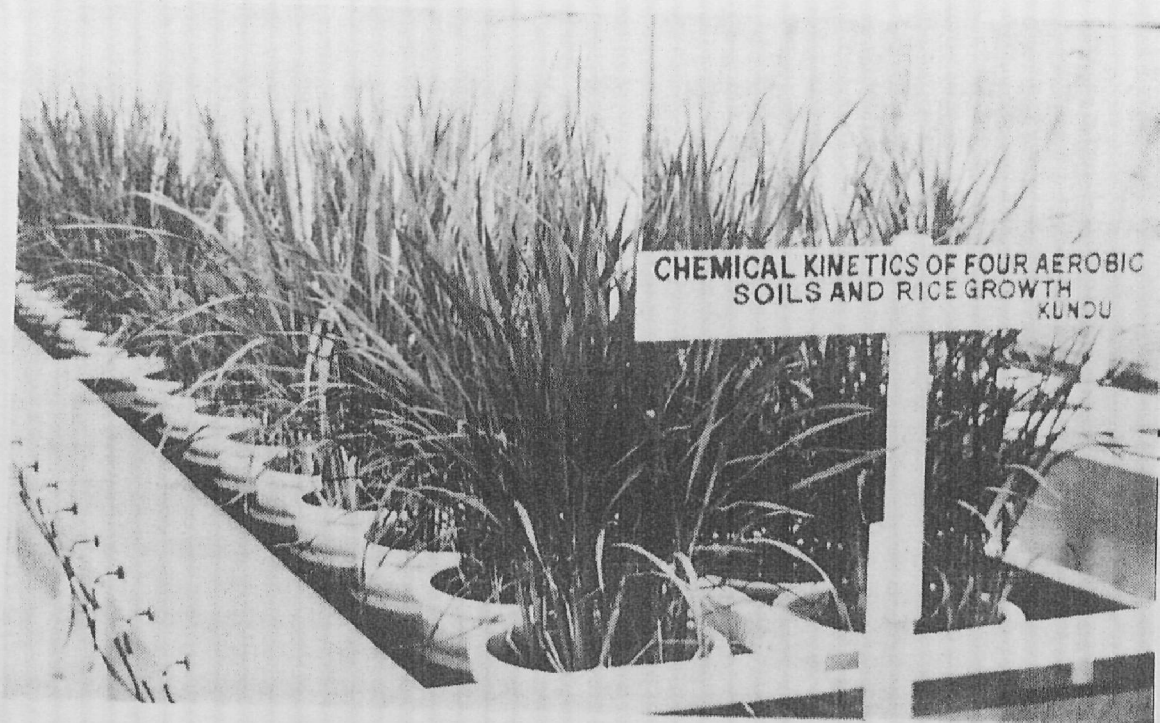


Plate 1. Experimental set-up in the greenhouse.

moist regime were very poor. Some of the seedlings were almost dying. Those dying plants were replaced by the healthy seedlings of the same variety from the other pots within first two weeks.

For recording dry matter yield and for analysis of plants for mineral nutrients at vegetative growth stage, two diagonal hills per pot were harvested at 8 weeks after dibbling. The remaining two hills in each pot were grown to the maturity and harvested.

Soil redox potentials in situ were measured weekly by using saturated calomel electrode and a portable potentiometer (Model: CORNING pH/Temp Meter 4).

Preparation of soil samples for analyses

Before mixing with fertilizers sub-samples were collected from the homogenized bulk soil samples, crushed in pestle and mortar, and passed through a 2 mm sieve. Samples were then quartered to a final weight of about 1 kilogram. A portion was ground further to pass through an 80 mesh sieve. The coarse and fine samples of each soil were then stored separately in polythene bags for laboratory analyses.

Sampling of soil solutions

Soil solution from flooded pots were drawn by gravity. Equilibrium saturation extracts were collected as the representative solutions of the field capacity moist aerobic



soils by the method described by Kundu, Ponnampereuma and Neue (1987). At fortnightly intervals, soil solutions from all the pots (regardless of the moisture regimes) were collected under anoxic conditions in a 125 ml and a 50 ml Erlenmeyer flasks deaerated previously with nitrogen gas. The set-up used for soil solution sampling is shown in Fig. 2.

Soil analyses

Physical analyses

- a. Particle size analyses of the soils were done by the Hydrometer method (Day 1965).
- b. Moisture content at saturation and field capacity:
The saturation moisture percentage of the soils was determined by Keen-Raczkowski Box method (Sankaram 1966) and the field capacity by the method described by Dastane (1967).

Chemical and Physico-chemical analyses

- a. pH (1:1 soil:water) using a Beckman pH meter (Peech 1965).
- b. Cation exchange capacity (CEC) was determined by summation for the strongly acidic Luisiana and Burabod soils, by neutral $1(N)NH_4OAc$ method for the near-neutral Maahas A soil and by $1(N)NaOAc$, pH 8.2 method for the calcareous Pila soil (Chapman 1965).

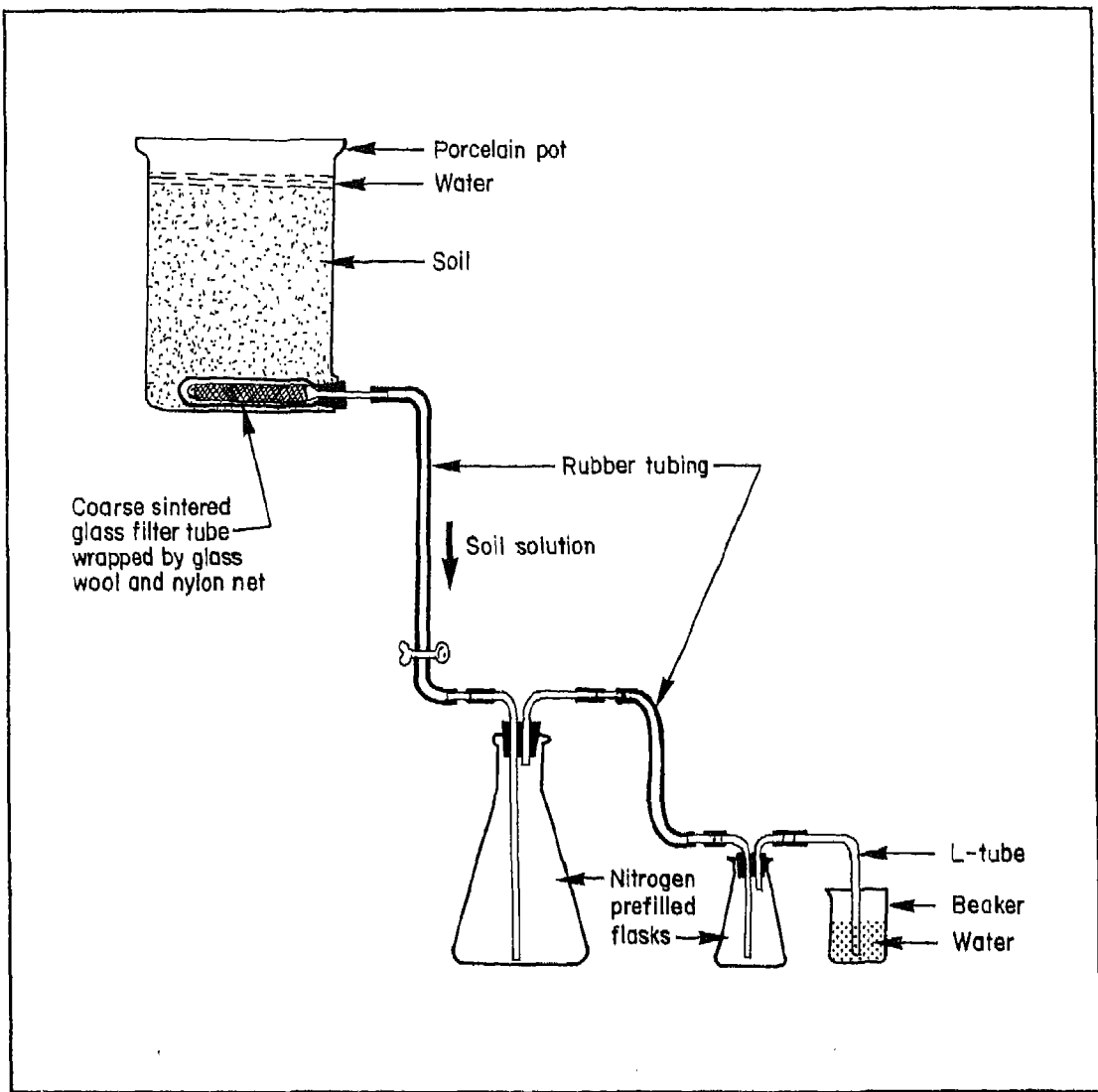


Fig. 2 Set-up for the sampling of soil solution.

- c. Exchangeable bases (Ca, Mg, K, Na) with neutral 1(N) NH_4OAc (Chapman 1965).
- d. Exchangeable Al and H in the acid soils by Yuan (1959) method.
- e. Organic carbon by Walkley and Black wet digestion method using 0-phenanthroline-ferrous complex indicator (Allison 1965).
- f. Total N by macrokjeldahl method (Bremner 1965).
- g. Available N by anaerobic incubation method (Waring and Bremner 1964).
- h. Active Fe and Mn by EDTA-dithionite extraction (Asami and Kumada 1959).
- i. Available P by Olsen's method (Olsen et al 1954).
- j. Available Zn and Cu by 0.05 (N)HCl extraction (Ponnamperuma et al 1981).
- k. Free CaCO_3 in the calcareous soil by the acid neutralization method described by the USDA Salinity Laboratory Staff (Richards 1954).

Analyses of soil solutions

Electro-chemical analyses. The pH, Eh and EC were determined simultaneously in an electrometric cell (IRRI 1965) fitted with a glass electrode, a saturated calomel electrode, two bright platinum electrodes and a conductivity cell (Fig. 3). Temperature of the soil solutions was adjusted to 25°C by

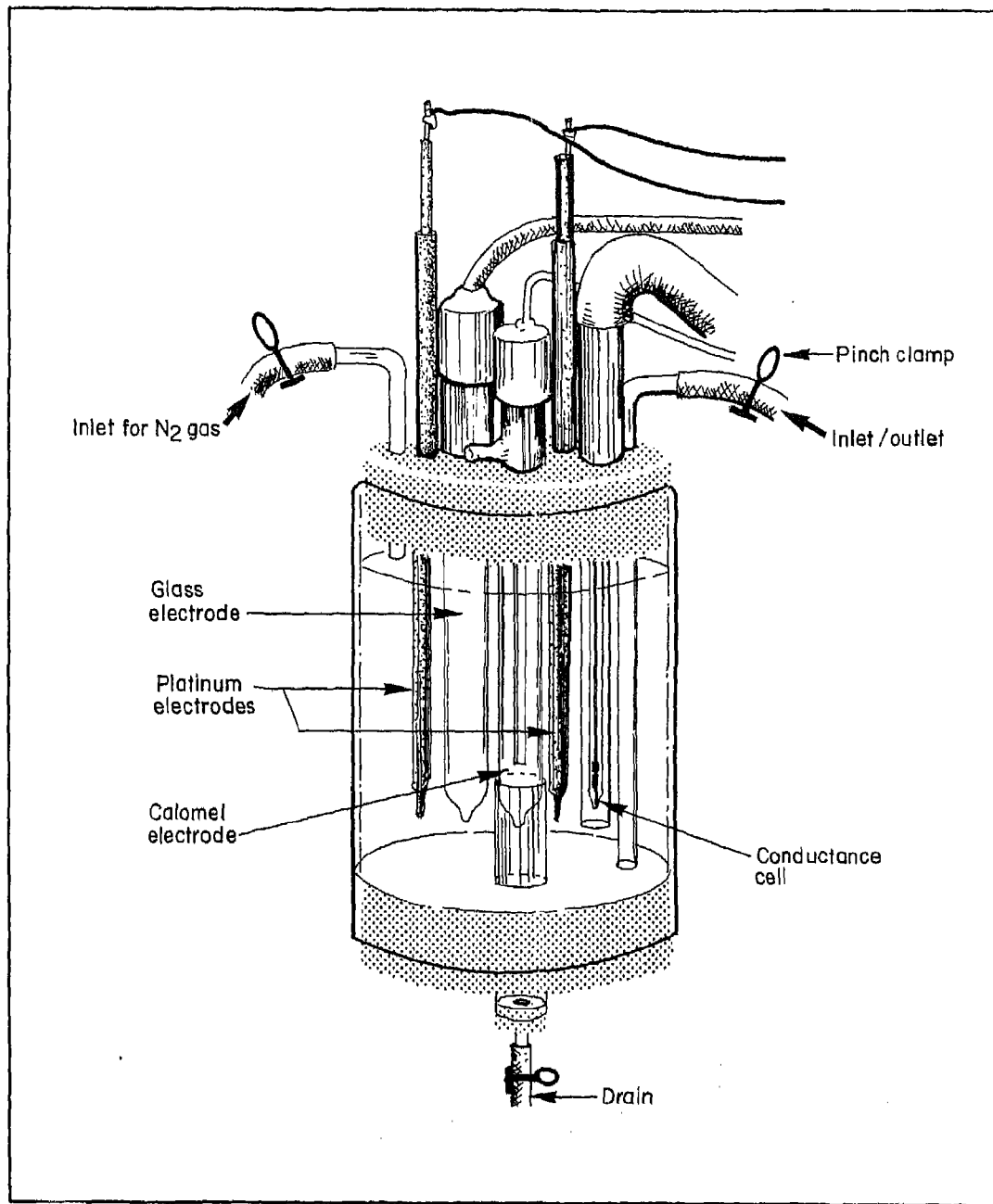


Fig. 3 The electrometric cell.

keeping the samples in a thermostat for about one hour before the measurement. The electrometric cell was flushed with N_2 gas before transferring the soil solutions into it under a mild pressure of nitrogen. This ensured an anoxic environment during the electrochemical determinations.

Chemical analyses. Immediately after the electrochemical analyses, the soil solution samples were removed for oxidizable matter, P and Zn estimations. A part of the remaining soil solutions was acidified with a few drops of 6(N)HCl to prevent oxidation and another part was flocculated by shaking with a few drops of 10% $AlCl_3$ and 25% NaOH solution. After flocculation, the clear aliquots of the samples were decanted carefully and saved for nitrate and sulfate analyses. The acidified part of the soil solutions was used for ammonium, K, Ca, Mg, Fe, Mn, Cu, Si and Al determinations.

Bicarbonate in the soil solutions were determined in the fresh and unaltered samples collected in the small (50 ml) sampling flasks. The samples were titrated immediately after opening the flasks.

- a. Oxidizable matter in soil solution was determined by the method prescribed by the American Public Health Association (1953) and modified by Ponnampetuma (1955).

- b. P in the solutions were analyzed by the benzene-isobutanol extraction method described by Martin and Doty (1953) and modified by Ponnampuruma (1955).
- c. Soil solutions were analysed for HCO_3^- by the differential titration method of DiLallo and Albertson (1961). The partial pressure of CO_2 ($^P\text{CO}_2$) was computed from HCO_3^- , pH and EC using the relation,
- $$^P\text{CO}_2 = (\text{H}^+) (\text{HCO}_3^-) \times 10^{7.85}$$
- where $^P\text{CO}_2$ is the partial pressure of CO_2 in atmosphere, (H^+) is the activity of H^+ ions derived directly from pH, (HCO_3^-) is the activity of bicarbonate, which is calculated from the concentration of HCO_3^- and the activity co-efficient derived from the ionic strength (Ponnampuruma et al 1966).
- d. $\text{NH}_4\text{-N}$ was determined by micro-kjeldahl distillation (Bremner 1965) using Kjeltec Auto 1030 Analyzer.
- e. $\text{NO}_3\text{-N}$ was estimated colorimetrically by the brucine procedure prescribed by Knoll (1945).
- f. Sulfate in the solutions were determined by turbidimetric method standardized by PCARR (1980).
- g. Si was analyzed colorimetrically by molybdenum blue method (Hesse 1971).

- h. Fe, Mn, Zn, Cu, Mg and Al in the soil solutions were determined by atomic absorption spectrophotometry using a Perkin Elmer Model 5000.
- i. Ca, K and Na were measured by atomic emission spectrophotometry using Perkin Elmer Model 5000.

Plant growth observation and yield data gathered:

1. Visual symptoms of any nutritional disorder.
2. Plant height and tiller number every week upto 12 weeks.
3. Dry matter yield of 8 week old shoots.
4. Straw yield at maturity.
5. Grain yield.

Plant tissue analysis

Sample preparation. Shoots sampled at 8 weeks after dibbling and straw harvested at maturity were washed with a mild detergent solution and subsequently with demineralized water. The washed samples were dried at 60°C temperature in an oven for 2 to 3 days, chopped with a stainless steel scissors and then ground by using a stainless steel mill (Cristy and Norris Beater Cross Grinder). The panicle (grain plus hull) samples were dried and ground in the same way. The ground samples were stored in envelopes and redried before analysis.

Analytical procedure:

- a. Total N was analyzed by wet digestion with concentrated sulfuric acid according to the microkjeldahl method (Yoshida et al 1976).
- b. Total P in the extracts obtained by digesting the samples in tri-acid ($\text{HNO}_3\text{-H}_2\text{SO}_4\text{-HCl(0}_4)$) mixture, after appropriate dilution, was analyzed by the vanado- molybdophosphoric acid method (Yoshida et al 1976).
- c. Crude SiO_2 in the samples were determined gravimetrically by the procedure outlined by Yoshida et al (1976).
- d. Ca, Mg, K, Na, Fe, Mn, Zn and Cu were analyzed in the tri-acid digested extracts (Yoshida et al 1976), after required dilution, by atomic absorption- and emission- spectrophotometry using a Perkin Elmer Model 5000.

Experimental Factors and Levels

Soils

Four soils used for the experiment were:

- | | | |
|----------------|---|---------------|
| S ₁ | - | Luisiana soil |
| S ₂ | - | Maahas A soil |
| S ₃ | - | Pila soil |
| S ₄ | - | Burabod soil |

Moisture regimes

The following two moisture regimes were studied:

- M_1 - Moist (Constant field capacity moisture, aerobic)
 M_2 - Flooded (Constant submergence with 3 cm level of standing water)

Cultivars

Two varieties were used in this trial

- V_1 - IR43, an upland variety
 V_2 - IR46, a lowland variety

Experimental Design

For this 4 x 2 x 2 factorial experiment, the pots were laid out in a Randomized Complete Block Design with 3 replications.

RESULTS AND DISCUSSION

Electro-chemical and Chemical Kinetics of the Soil Solutions

On all the sampling dates soil solutions were collected and analyzed from each of the 48 pots (4 soils x 2 moisture regimes x 2 varieties x 3 replications). As the varietal treatment did not show any consistent effect, the solution analysis data for the two varieties and three replicates were pooled together. The Tables 1-19 of the Appendix give the mean values of the physico-chemical and chemical analyses of the solutions of four soils under two moisture regimes. The results are presented graphically in the following pages.

Electro-chemical kinetics

Redox potential (Eh). The changes in Eh of the soils under two different moisture regimes and of the solutions collected therefrom during the growing period of rice are presented in Figures 4 and 5, respectively. While Eh decreased sharply to reach negative values within 3 weeks of flooding, under the field capacity moisture regime it remained much higher and positive throughout the season indicating oxidized status of the soils. Although the measured values of Eh clearly indicated oxidized and reduced status of the moist and flooded soils, respectively, one point that calls for comment is the difference between soil Eh and solution Eh. The solution Eh was lower than

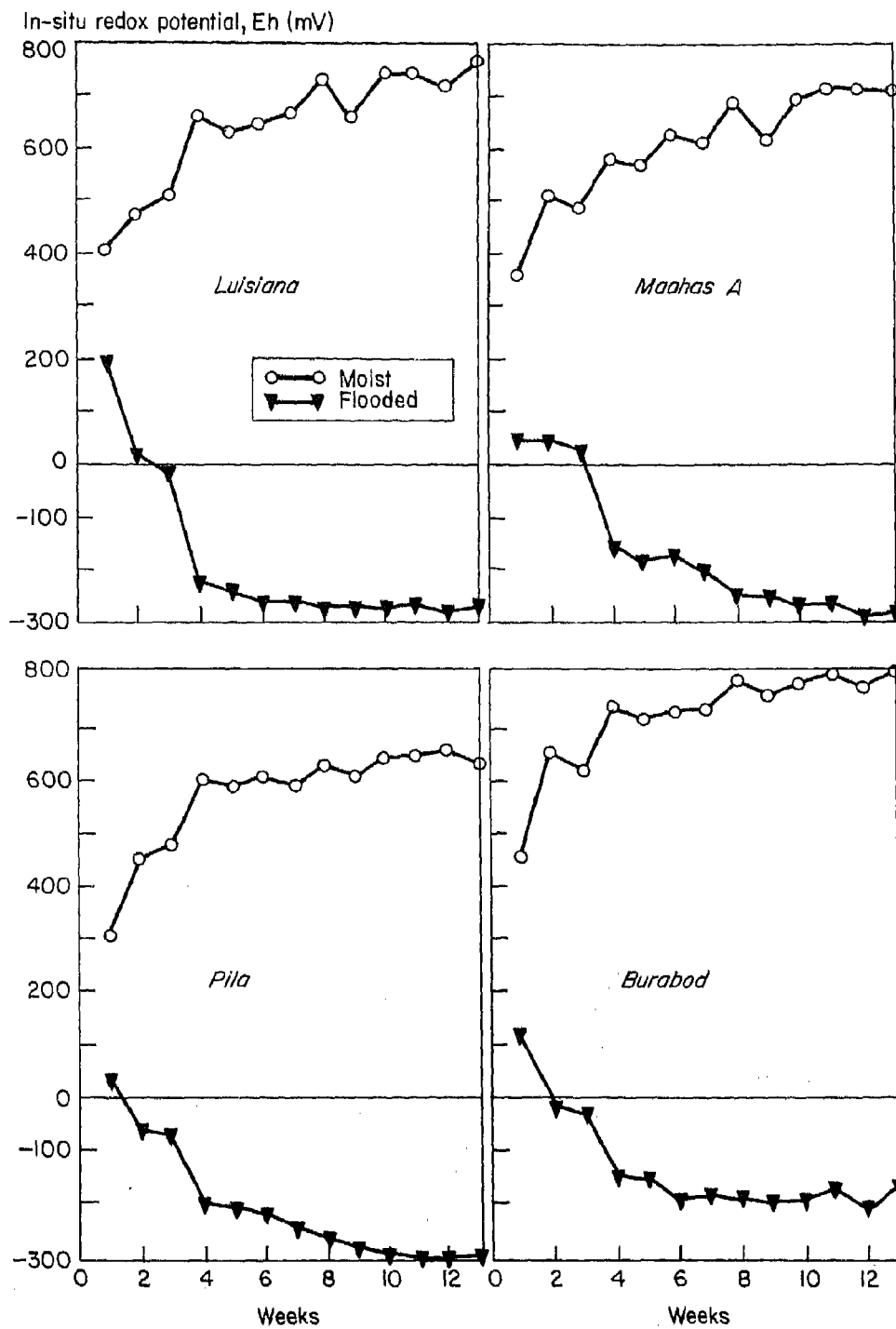


Fig. 4 Kinetics of Eh in four soils under moist and flooded conditions.

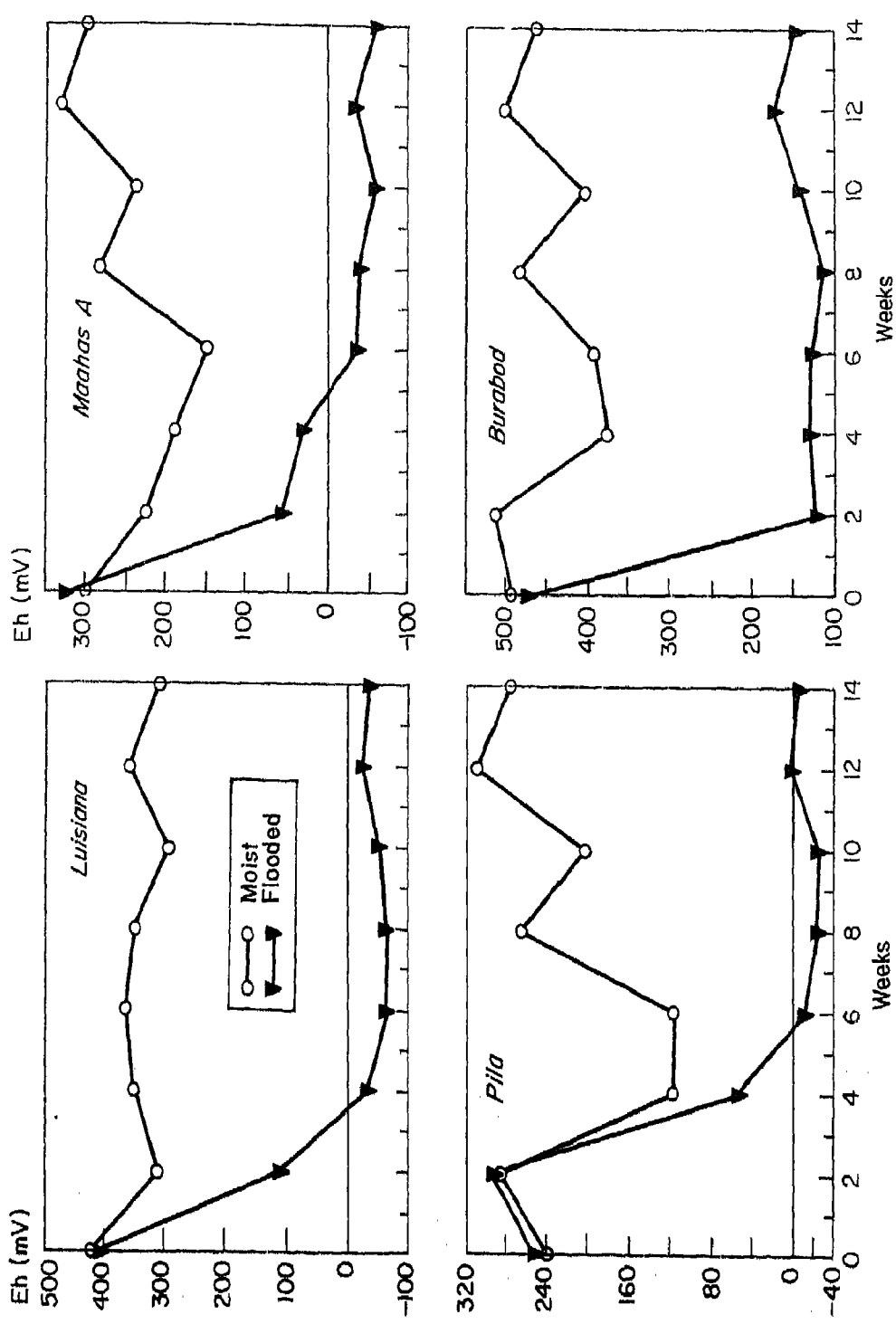


Fig. 5 Kinetics of solution Eh in four soils under moist and flooded conditions.

soil Eh under aerobic condition, whereas under submerged condition solution Eh was higher than soil Eh. This observation is in close agreement with those of Ponnampereuma (1972), Sato and Yamane (1973). Ponnampereuma (1972) suggested that the differences between soil and solution Eh might be due to the presence of an oxidant or reductant in the solid phase. From various points of view, he noted that the potential of the liquid phase of a soil is much more meaningful and reliable than the potential of the soil itself. It will not be irrelevant to mention here that the reported critical redox potential values, for identification of dominant redox systems operating in soils, are of soils and not of the solutions (Yamane 1978).

Soil properties markedly influenced the Eh kinetics of both flooded and moist soils. Clear influence of pH on the Eh values of aerobic soils was observed. The strongly acidic Burabod soil showed highest Eh and the calcareous Pila soil presented lowest values of Eh.

The rate and degree of reduction under flooded condition also varied markedly with soils. While the solution Eh dropped to as low as -25, -59 and -63 mV in flooded Pila, Maahas A and Luisiana soil respectively, it did never reach below +115 mV in the Burabod soil. Amount of easily decomposable organic matter, active Fe and Mn content, nitrate content in soil and temperature have been noted by Ponnampereuma (1985) as important factors that influence the degree of reduction in flooded soil.

Probably the strong acidity of the Burabod soil, pH of which did never reach beyond 5.7, was responsible for relatively lower degree of reduction under submergence. Retardation of the fall of Eh due to a strong acidity was noted earlier by Yamane (1953).

Since low Eh has been known to favor N fixation and increase the availability of P, Fe, Mn and Mo (Ponnamperuma 1972, 1978, 1982), the aerobic soils provide unfavorable redox potentials for rice growth.

pH. Figure 6 presents the kinetics of solution pH of four soils under flooded and field capacity moisture regimes. Flooding increased the pH of acidic soils and decreased that of the calcareous soil. Although pH of the Luisiana, Maahas A and Pila soils under submergence converged to neutrality, it did not reach above 5.7 in case of the Burabod soil. This observation is in close agreement with that of Ponnamperuma (1972) who did not get pH higher than 5.5, even after months of submergence, in an acid sulfate soil low in active Fe.

Unlike under submergence, solution pH of the aerobic soils did not change favorably with time. The high pH of the calcareous Pila soil and the low pH of the acidic soils persisted throughout the growing season. However, a sharp initial drop in pH was noted in the Maahas A, Pila and Luisiana soil within first 2 to 4 weeks. This pH change was important in

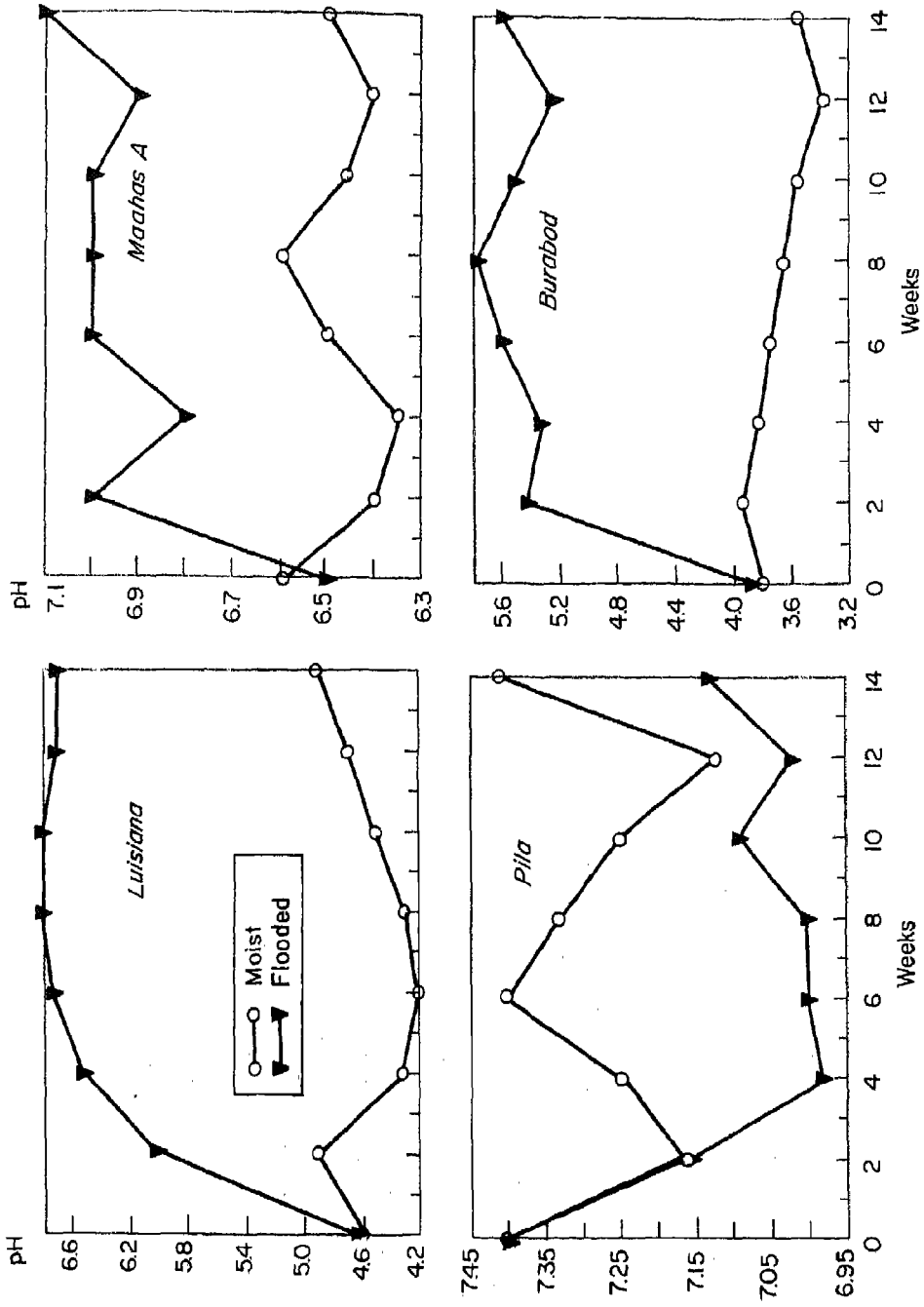


Fig. 6 Kinetics of solution pH in four soils under moist and flooded conditions.

case of the Luisiana soil, as it aggravated the acidity problem. Careful examination of the data reveals that this initial drop in pH was associated with the increase in NO_3 concentration in these soils. Production of H^+ as a result of nitrification of NH_4^+ in these aerobic soils could interpret this observed change in pH.

As the concentration of water-soluble aluminum in a soil is known to be related to pH (Raupach 1963) by

$$\text{pAl}_M = 2 \text{ pH} - 4.41,$$

a pH below 4.5 existing in the aerobic acid soils could produce toxic concentration of Al. And it could be a serious factor limiting rice growth in the aerobic Burabod soil.

Electrical conductivity (EC). The kinetics of solution EC of the soils are illustrated in Fig. 7. The EC increased on flooding, attained a maximum and declined thereafter. The acidic soils showed steep increase in EC during the first 4 weeks of flooding and then declined sharply, whereas EC of the flooded Maahas A and Pila soils showed a slow decline after attaining the peak values. The EC kinetics in the Burabod and Luisiana soils were strikingly similar to the kinetics of water-soluble Fe and Mn (Figs. 13 and 14).

The EC of the moist Luisiana, Maahas A and Pila soils increased first to reach a peak (much lower than those under flooded condition) and declined thereafter, in striking similarity to the kinetics of NO_3 (Fig. 11).

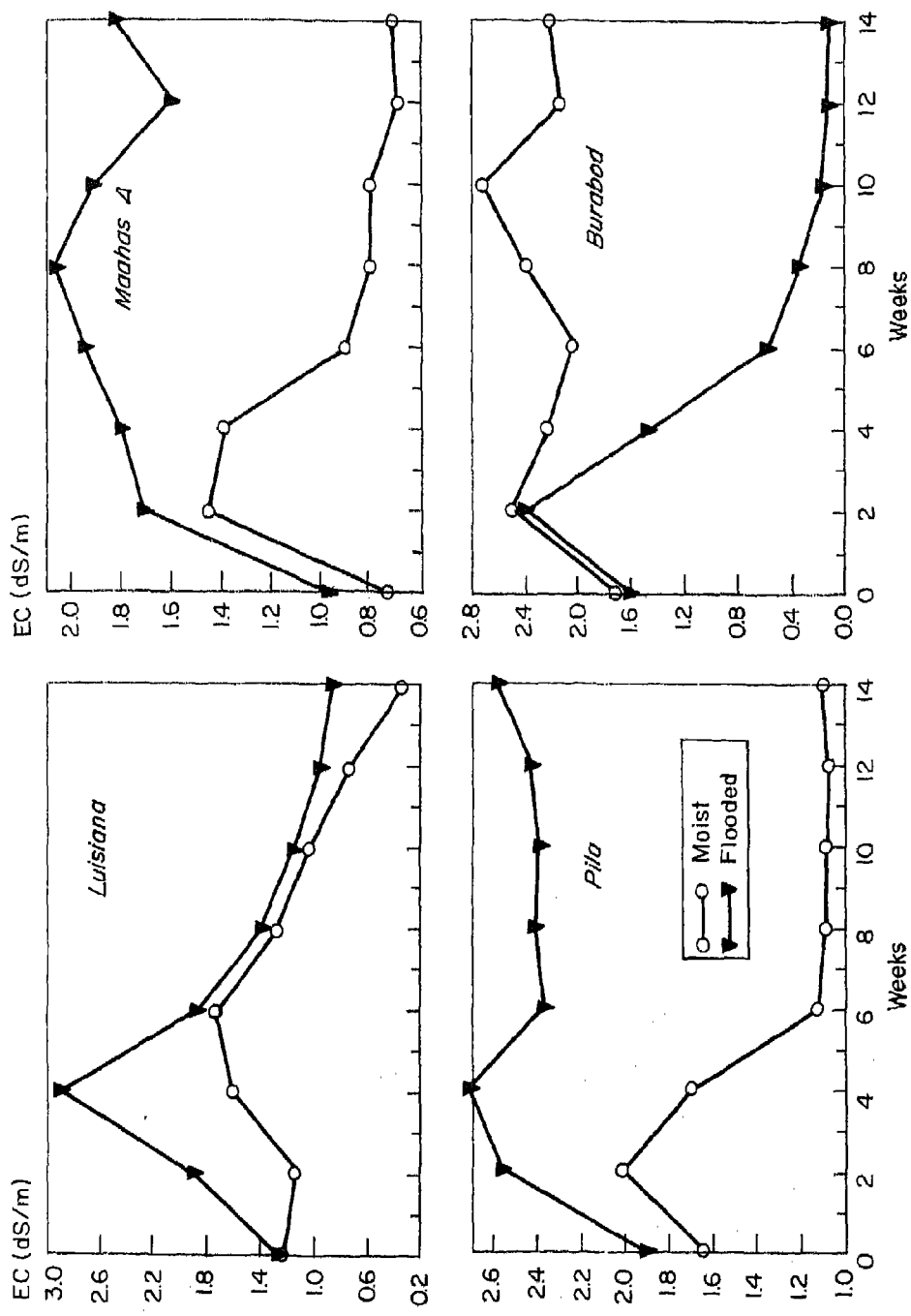


Fig. 7 Kinetics of electrical conductivity in four soils under moist and flooded conditions.

A curious feature of the Burabod soil is that the EC was markedly lower under flooded than under the moist condition. The chemical analyses revealed that water-soluble Fe, Mn, Ca, Mg and Al decreased sharply after 2 weeks of flooding, and the concentrations of water-soluble Mn, Ca, Mg and Al were markedly higher under moist than under flooded condition. Possibly, under flooded condition Fe and Mn were removed as insoluble compounds like FeS and MnCO_3 , Al solubility decreased due to pH increase, and Ca, Mg and some other cations were adsorbed on the solid phases following sharp decrease in anion (dominantly SO_4^{2-}) concentration in the solution (Fig. 18).

Chemical kinetics

Oxidizable matter. Oxidizable matter as determined by oxidation of the samples with KMnO_4 under mild conditions includes Fe^{2+} , NO_2^- , S^{2-} alcohols, aldehydes, ketones, reducing sugars, aliphatic hydroxy and unsaturated acids, mercaptans, organic sulfides, ferulic acid, sinapic acid and other unknown reducing substances. As it is not an absolute measure of the concentration of reduced products, it can not be used to characterize the degree of reduction of widely different soils. But for a given soil, this determination provides a simple and satisfactory index of the extent of reduction (Ponnamperuma 1972).

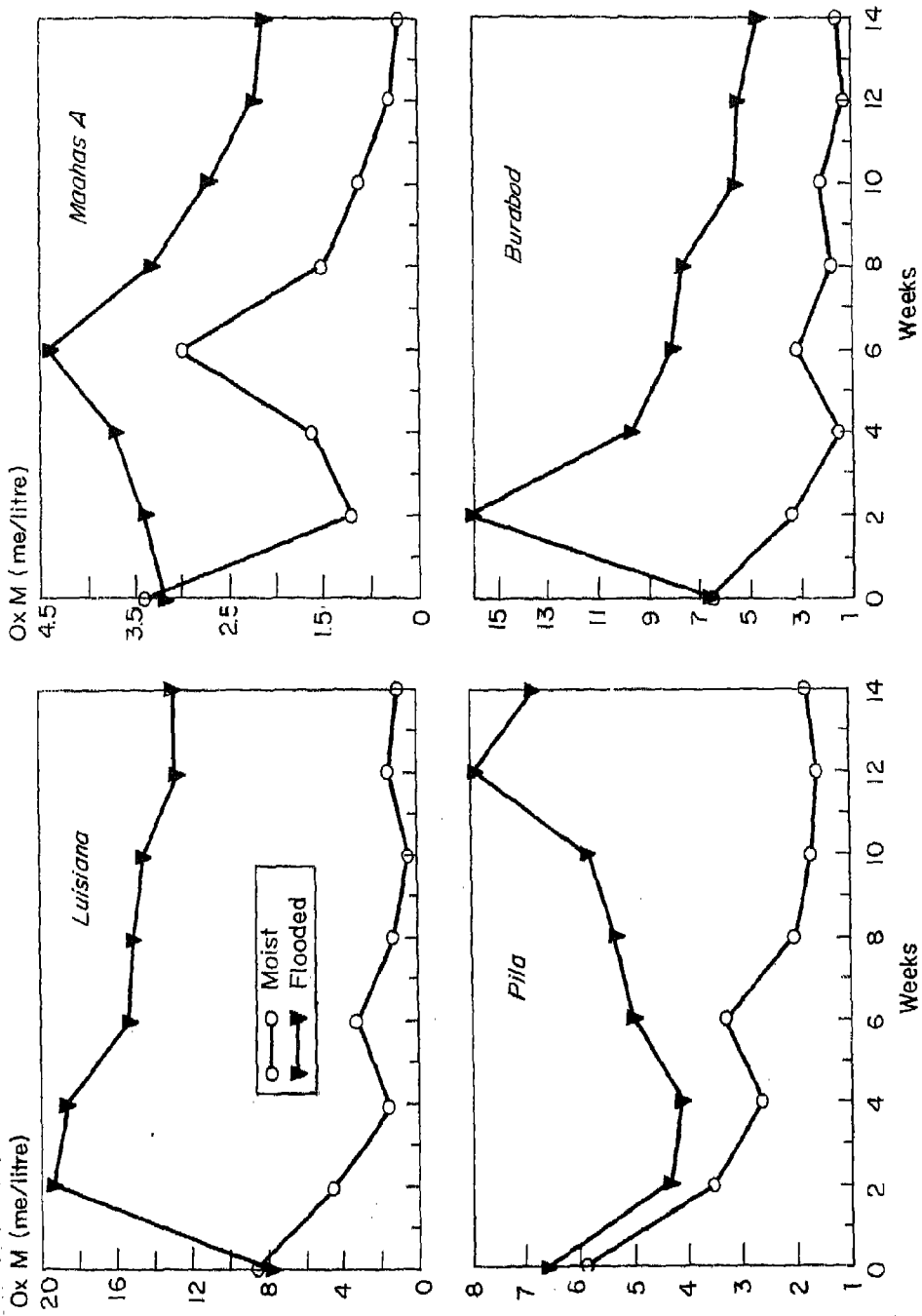


Fig. 8 Kinetics of water-soluble oxidizable matter in four soils under moist and flooded conditions.

Figure 8 shows that the oxidizable matter content in all the soils under flooding increased to reach a peak and declined thereafter. The peaks occurred early (in 2 weeks after flooding) in the acidic soils and late in the near-neutral and calcareous soils. Under the field capacity moisture regime, the oxidizable matter content decreased with time and were markedly lower than that under flooded regime in all the four soils throughout the growing season.

Partial pressure of CO_2 ($^{\text{P}}\text{CO}_2$). Figure 9 illustrates changes in $^{\text{P}}\text{CO}_2$ with time in soils under two moisture regimes. The $^{\text{P}}\text{CO}_2$ increased to reach a peak in 4-6 weeks after flooding and declined thereafter to a fairly stable value. In the flooded acidic soils, $^{\text{P}}\text{CO}_2$ reached upto 45-55 kPa and sharply declined then to stabilize at 10-20 kPa. In the near-neutral Maahas A and the calcareous Pila soils, it reached upto 15-17 kPa and then slowly declined to stabilize at 12-14 kPa. The decline in $^{\text{P}}\text{CO}_2$ after reaching peaks has been attributed by Ponnampuruma (1972) to the escape, leaching, removal as insoluble carbonates, dilution by CH_4 produced during the decomposition of organic acids and bacterial reduction of CO_2 to CH_4 . The sharp decline after 4-6 weeks of flooding in the Rurabod and Luisiana soil were probably due to the formation of insoluble carbonates.

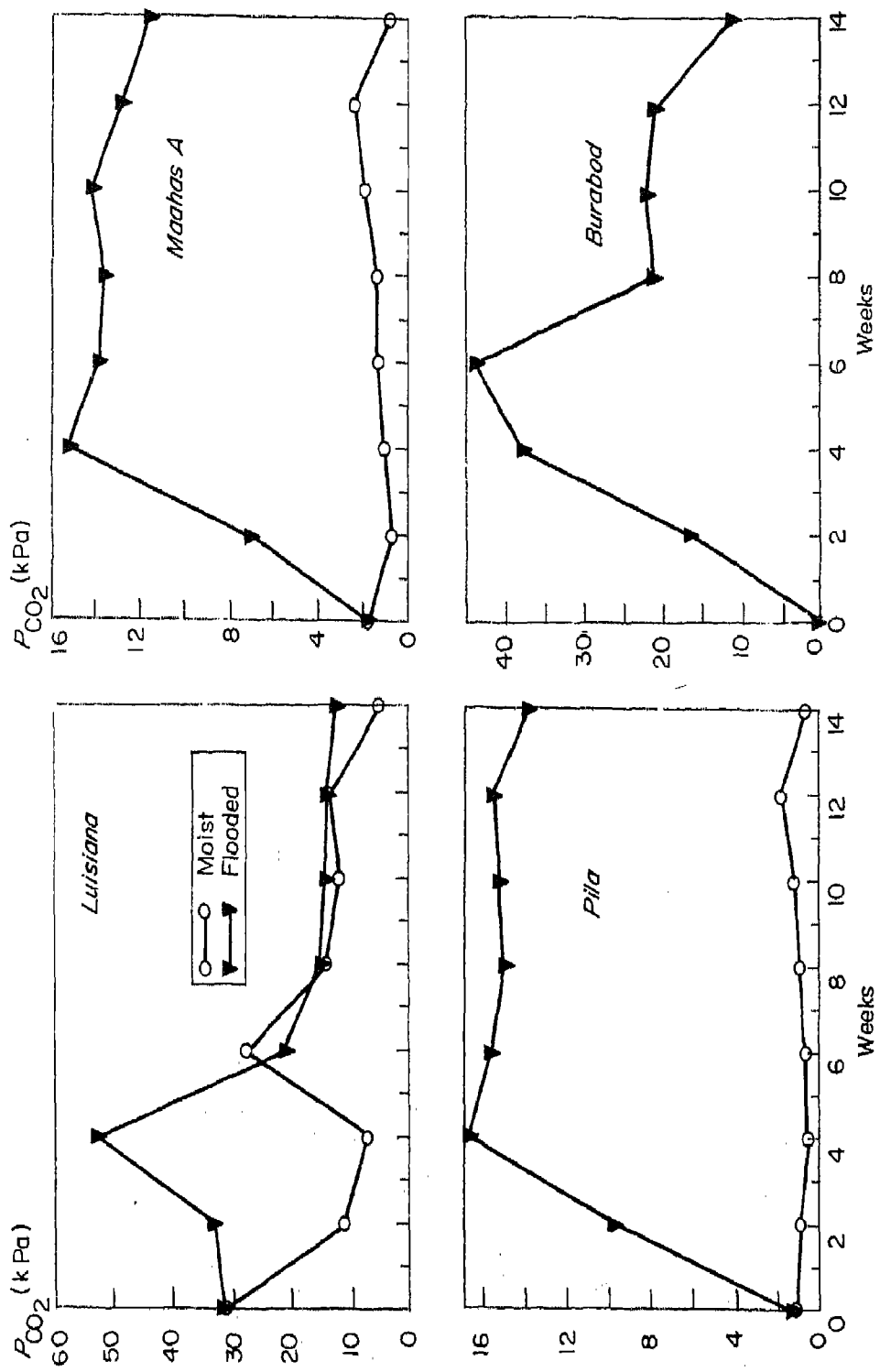


Fig. 9 Kinetics of partial pressure of CO₂ in four soils under moist and flooded conditions.

Under the field capacity moisture regime, $P\text{CO}_2$ in the Maahas A and the Pila soils were remarkably lower (1-2 kPa) than that under flooded conditions and did not change appreciably with time. In the moist Luisiana soil it varied mostly between 7 and 15 kPa, and after 6 weeks of flooding virtually there was no difference in $P\text{CO}_2$ between the moist and flooded regimes. The $P\text{CO}_2$ of the moist Burabod soil (pH 3.9) could not be determined by the method (using pH, HCO_3^- and EC) adopted in this experiment.

The effect of pH on carbonate equilibria involving Ca and Mn can be described by

$$\text{pH} + \frac{1}{2} \log \text{Ca} + \frac{1}{2} \log P\text{CO}_2 = 4.92 \text{ and}$$

$$\text{pH} + \frac{1}{2} \log \text{Mn} + \frac{1}{2} \log P\text{CO}_2 = 4.06 \text{ (Ponnamperuma 1982).}$$

According to these relationships, at high pH and low $P\text{CO}_2$ (5kPa or 0.05 atm) the concentrations of Ca and Mn may be too low for growth of rice as shown below:

| | | | | |
|------------------------|-------|------|-----|-----|
| pH | 8.5 | 8.0 | 7.5 | 7.0 |
| Ca^{2+} (ppm) | 0.08 | 0.8 | 8.0 | 80 |
| Mn^{2+} (ppm) | 0.003 | 0.03 | 0.3 | 3 |

On the otherhand, $P\text{CO}_2$ value greater than 15 kPa has been speculated to retard root development leading to wilting and reduced nutrient uptake (Dent 1986).

Nitrogen.

- a. Ammonium: The concentrations of NH_4^+-N in the soil solutions collected from the flooded and moist soils on different sampling dates are presented in Fig. 10. Under flooded condition NH_4^+-N concentration increased with time, reached a peak of 30-45 ppm in the acidic soils and 10-18 ppm in the near-neutral and the calcareous soils within first four weeks and sharply declined thereafter. The NH_4^+-N kinetics under moist or aerobic condition markedly varied with soils. In the moist Maahas A and Pila soils NH_4^+-N decreased sharply to trace amount within first two weeks, whereas in the acidic soils it increased first to reach a peak in first two weeks and slowly declined thereafter. Throughout the growing period of rice, concentration of NH_4^+-N in the moist soils were markedly lower than that under the corresponding flooded ones, with the only exception of the strongly acidic Burabod soil. In the Burabod soil, the average concentration of NH_4^+-N during the growing season did not differ appreciably with the moisture regimes. Under such strongly acidic environment in the moist regime, the nitrification was virtually absent. Hence under both moist and flooded conditions N was present only in NH_4^+ form.

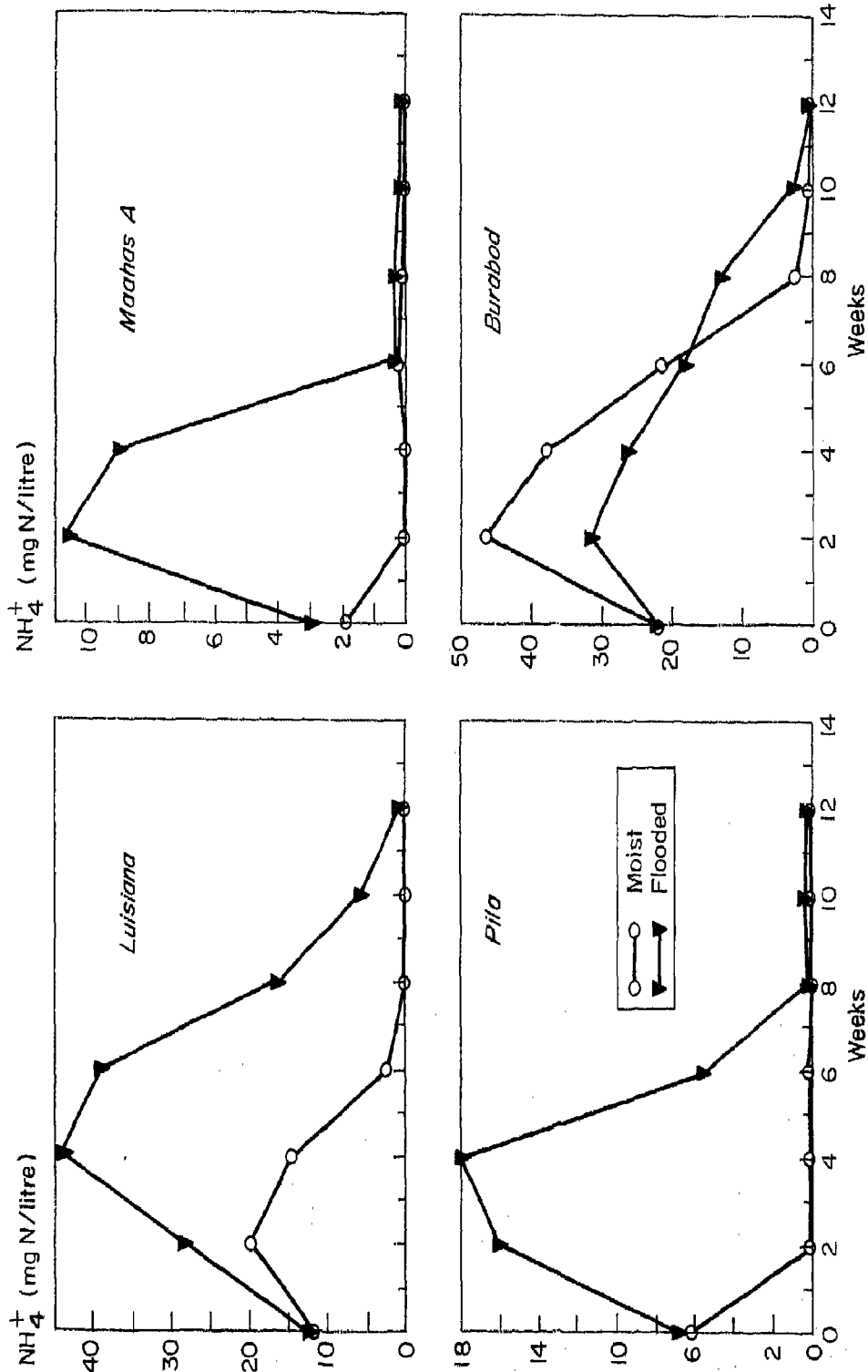


Fig. 10 Kinetics of water-soluble NH_4^+ -N in four soils under moist and flooded conditions.

The concentration of ammonium in the soil solution of a flooded soil is governed by two main factors: 1) the total ammonium content of the soil and (2) the cation exchange equilibria in the soil. The total ammonium concentration at any time represents the balance between the initial ammonium content and ammonia released from organic matter on the one hand, and losses by immobilization, volatilization and assimilation by the plants on the other. An increase in concentration of other cations may cause an increase in the concentration of ammonium in solution by displacing NH_4^+ from the exchange complex. The observed kinetics of $\text{NH}_4^+\text{-N}$ in the solutions of all the flooded soils could be interpreted by the facts mentioned above. The higher peaks of the acidic soils could be attributed to the higher available N status, lower CEC and higher release of Fe^{2+} and Mn^{2+} in solution of these soils than in the other two soils. The decline in the $\text{NH}_4^+\text{-N}$ concentration following the peaks might have been due mainly to the assimilation by growing plants.

Concentration of ammonium in the solutions of moist or aerobic soils was found to be strongly related to pH. In the near-neutral Maahas A and the calcareous Pila soils, all the $\text{NH}_4^+\text{-N}$ virtually disappeared in first two weeks. On the other hand, considerable amount of solution $\text{NH}_4^+\text{-N}$ was determined in the acidic soils even upto eight weeks after plant growth. It is worthy of note that the high concentration of solution $\text{NH}_4^+\text{-N}$ was present in the acidic Luisiana soil in spite of a high rate (higher than that in the Maahas A and Pila soils) of nitrification.

- b. Nitrate: The kinetics of the $\text{NO}_3^-\text{-N}$ concentration in three soils are illustrated in Fig. 11. As the concentration of $\text{NO}_3^-\text{-N}$ in the solution of the strongly acidic Burabod soil was very low (Appendix Table 8) regardless of the moisture regime, they are not shown here graphically. $\text{NO}_3^-\text{-N}$ disappeared from all the soils soon after flooding, whereas under aerobic conditions it increased with time to reach a peak of 90 ppm in Maahas A and Pila, and 225 ppm in the Luisiana soils in the first 2-6 weeks and declined thereafter.

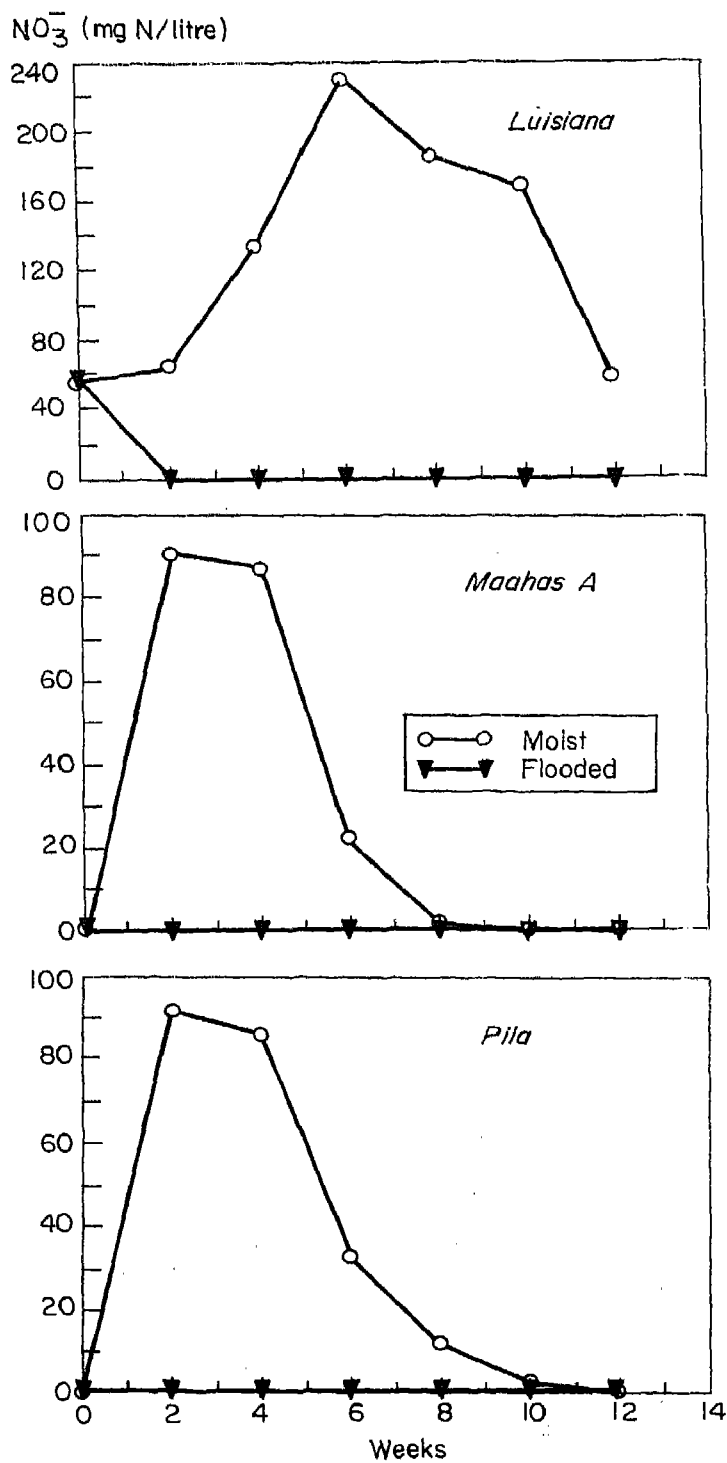


Fig. 11 Kinetics of NO_3^- -N in the solutions of three soils under moist and flooded conditions.

The rapid loss of nitrate from the flooded soils is undoubtedly due to active denitrification under the anaerobic conditions. On the otherhand, the steep rise in the NO_3^- -N concentration in the aerobic soils is due to the nitrification process. However, the almost undetectable concentration of NO_3^- -N in the moist Burabod soil might have been due to probable absence of the nitrifying bacteria in such a strongly acidic environment. Decline in the NO_3^- -N concentration following the peaks in the moist soils could be due largely to the assimilation by growing plants.

Comparison of the Figs. 10 and 11 reveals that NH_4^+ -N was the only source of mineral nitrogen present in all the flooded soils as well as in the moist Burabod soil. In the moist Louisiana soil, both NH_4^+ and NO_3^- forms were present. On the otherhand, NO_3^- was the only important source of mineral nitrogen supply in the moist Maahas A and Pila soils.

The kinetics of nitrogen shows that the solutions of the flooded Maahas A and Pila soils were almost devoid of mineral N at 6-8 weeks after flooding. Clear nitrogen deficiency symptoms appeared on the plants growing under these treatments approximately at the same time.

Phosphorus. Fig. 12 shows that flooding increased the concentration of water-soluble P in the Burabod and the Pila soils. This increase was transitory in the Luisiana soil. After attaining a peak, the P concentration decreased sharply in these 3 soils. In the Maahas A soil, however, there was no increase in P solubility and the P concentration declined steadily with time after flooding. In all the four soils under study, concentration of water-soluble P under moist conditions were lower than under flooded conditions. However, this difference was convincing only in case of the Burabod and the Pila soils.

The observed increase in the concentration of water-soluble P in the acid-sulfate Burabod soil could be attributed to the (a) hydrolysis of Fe (III) and Al phosphates, (b) release of P held by anion exchange on clay and hydrous oxides of Fe (III) and Al, and (c) reduction of Fe (III) to Fe (II) with liberation of sorbed and chemically bound P. The first two reactions are due to the pH increase brought about by soil reduction (Ponnamperuma 1972). In the calcareous Pila soil the observed increase in P solubility was probably a consequence of the decrease in pH on flooding, for the solubility of hydroxy-apatite, fluor-apatite, β -tricalciumphosphate and octacalcium phosphate increases as pH decreases (Lindsay 1979).

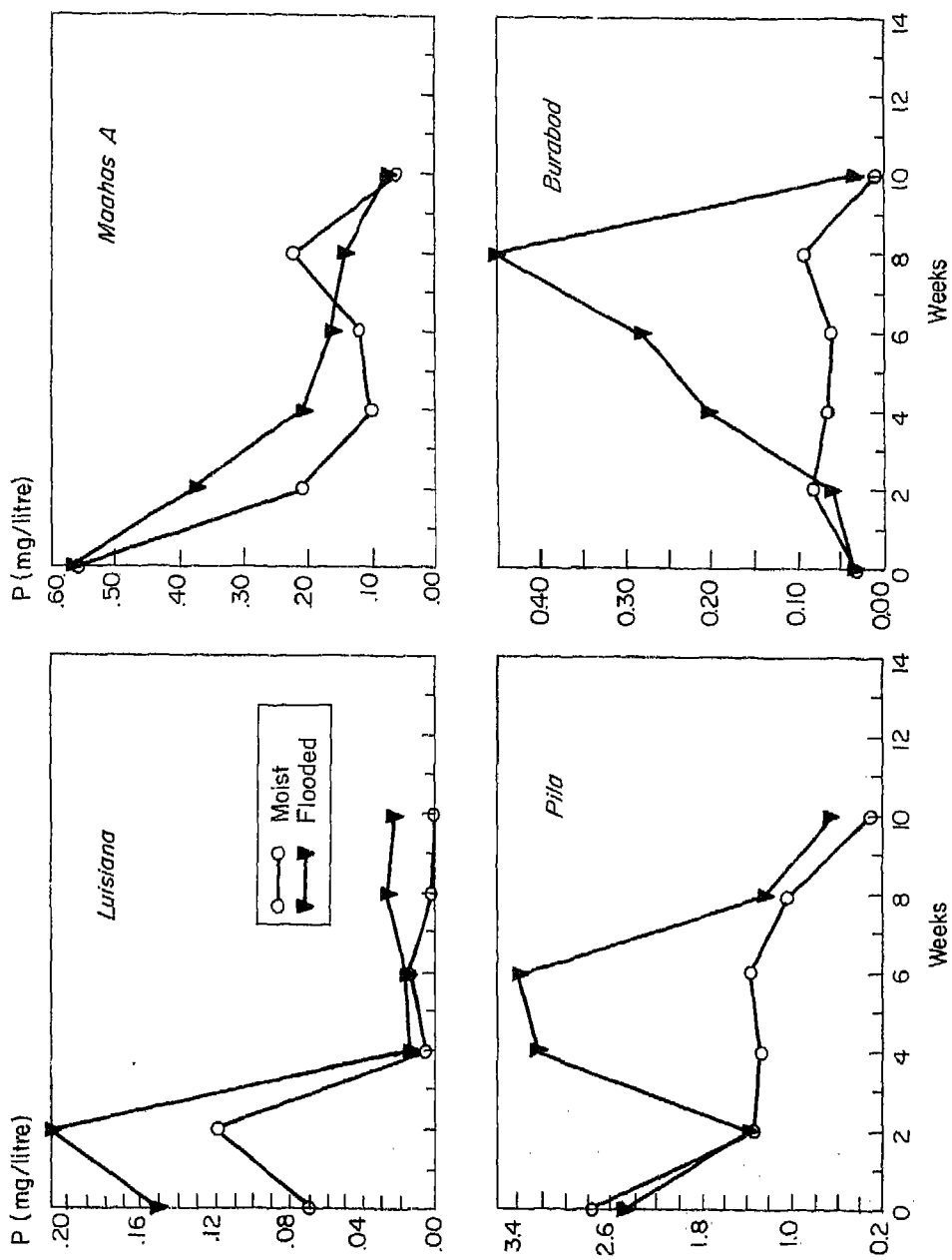


Fig. 12 Kinetics of water-soluble P in four soils under moist and flooded conditions.

The observed kinetics of water-soluble P in the flooded Maahas A and the Luisiana soils are in conformity with the findings of Ponnampereuma (1972) who did not get any increase in P solubility, due to submergence, in a near-neutral and a ferralitic acid soils.

The decline in the P solubility after the initial increase in the flooded soils may be due to the resorption by clay and hydrous oxides of Al in the anaerobic zone (Gasser and Bloomfield 1955, Bromfield 1960) or reprecipitation of the soluble P diffused to the oxidized zone (Hynes and Greib cited by Ponnampereuma 1972). Noncalcareous sediments are known to adsorb and retain more P than calcareous lake sediments (Williams et al 1970, Shukla et al 1971). This explains why the increase in concentration of water-soluble P were transitory or none in the flooded Luisiana and Maahas A soils compared to the calcareous Pila soil.

Iron. The kinetics of the concentration of water-soluble iron in the four soils under two moisture regimes are presented in Fig. 13. On flooding, the Fe concentration increased to reach a peak of 500 ppm within two weeks in the Burabod and 375 ppm within four weeks in the Luisiana soils and then declined. In the Maahas A the Pila soils peak concentrations of 43 and 5 ppm, respectively were attained at 12 weeks after flooding. Compared to those under flooded conditions, water-soluble Fe concentrations in the aerobic soils were extremely low

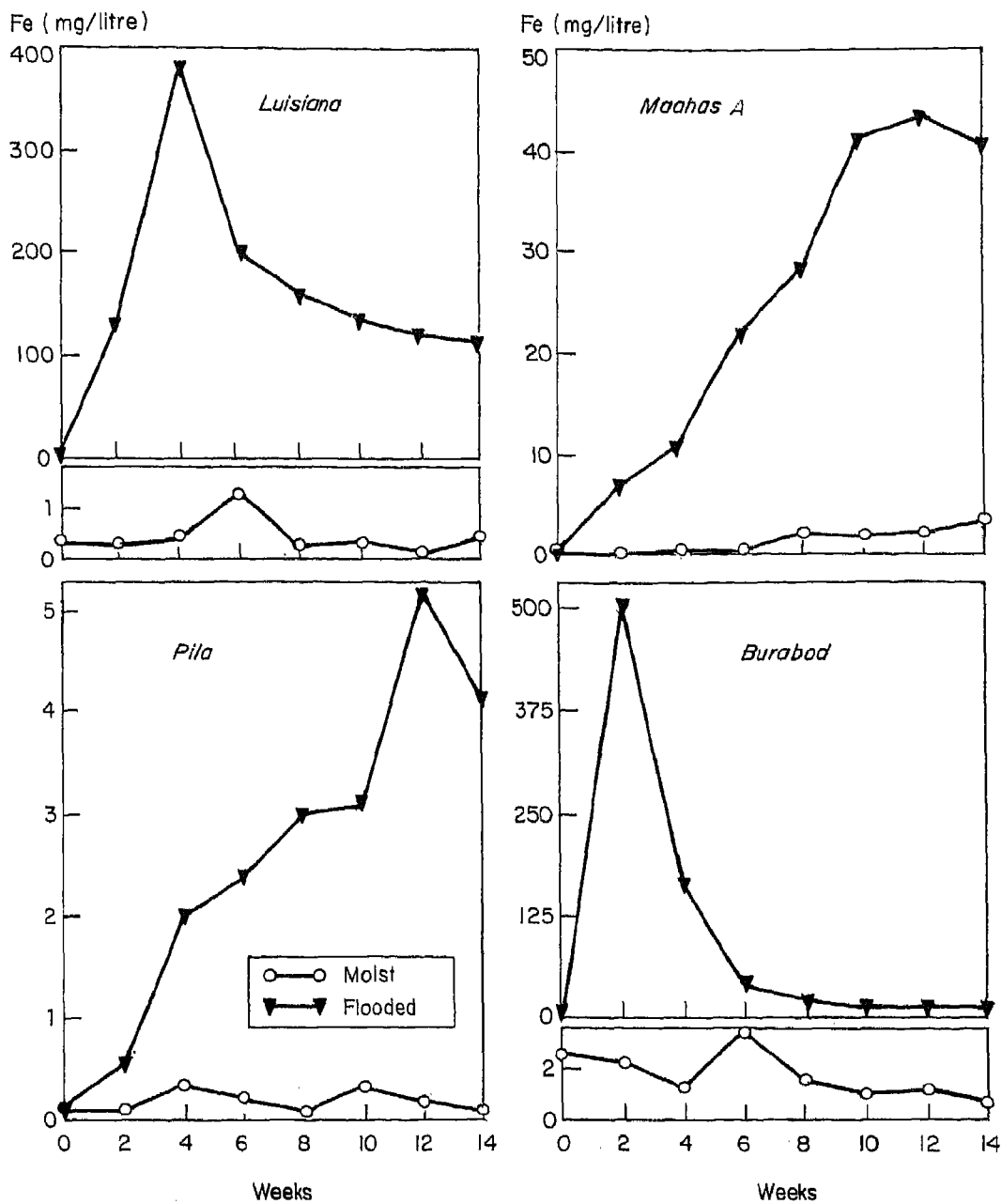
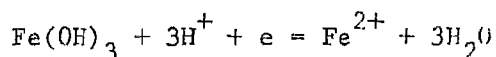


Fig. 13 Kinetics of water-soluble Fe in four soils under moist and flooded conditions.

throughout the growing season. In aerobic soils the concentration of water soluble Fe is governed largely by the solubility of Fe (III) oxide hydrates. The solubility of these oxides is so low that in natural aerobic media the concentration of water soluble Fe, theoretically, cannot exceed 0.001 ppm. The higher concentrations observed in the aerobic soils are due to organic complexes and to colloidal Fe(III) oxide hydrates stabilized by organic matter (Krauskopf 1972).

Ponnamperuma et al (1967) noted that the increase in concentration of water-soluble Fe following flooding could be described for most soils (except organic soils, acid-sulfate soils, acid soils low in active iron and soils with apparently highly crystalline Fe(III) oxides) by the equilibrium,



Very high concentration (375 ppm) of water-soluble Fe in the flooded Louisiana soil was undoubtedly caused by its higher active iron- and organic matter content. However, surprisingly the highest concentration (500 ppm) of Fe was found in the flooded Burabod soil which had the least content of active iron. Probably the reactivity of the Fe(III) oxides in this soil was much higher than in the other soils. Asami as cited by Ponnamperuma (1972) observed that 5 to 50% of the free iron oxides present in a soil may be reduced within a few weeks of submergence depending on the crystallinity of the oxides, the organic matter content and the temperature. He reported higher

degree of reduction in the oxides of lower crystallinity. Also, Ponnampereuma (1972) asserted that soil properties influence the kinetics of water-soluble Fe more drastically than that of total iron.

After the peak, the subsequent decrease in water-soluble Fe concentration in many flooded soils (with the exceptions given earlier) is due probably to precipitation of $\text{Fe}_3(\text{OH})_8$ or $\text{Fe}_3\text{O}_4 \cdot n\text{H}_2\text{O}$ (Ponnampereuma et al 1967) and in some soils due to formation of FeS (IRRI 1972). The observed steep decline (from the peak of 500 ppm to as low as 15 ppm within eight weeks) in the Burabod soil was suspected to be due to formation of FeS.

As the peak concentration of water-soluble Fe in the Burabod soil crossed the toxic limit of 500 ppm (Ponnampereuma et al 1955, Nhung and Ponnampereuma 1966) Fe toxicity could be a problem in this soil under flooded condition.

Manganese. Changes in the concentration of water-soluble Mn with time in the flooded and moist soils are shown in Fig. 14. On flooding, Mn concentrations increased in the Luisiana, Maahas A and Pila soils to reach a peak of 25-40 ppm in first 4-6 weeks and then declined. In the flooded Burabod soil, without any peak formation, it declined sharply.

Under FC moisture regime, water-soluble Mn was almost undetectable in the near-neutral Maahas A and calcareous Pila soils but quite appreciable in the acidic soils. The

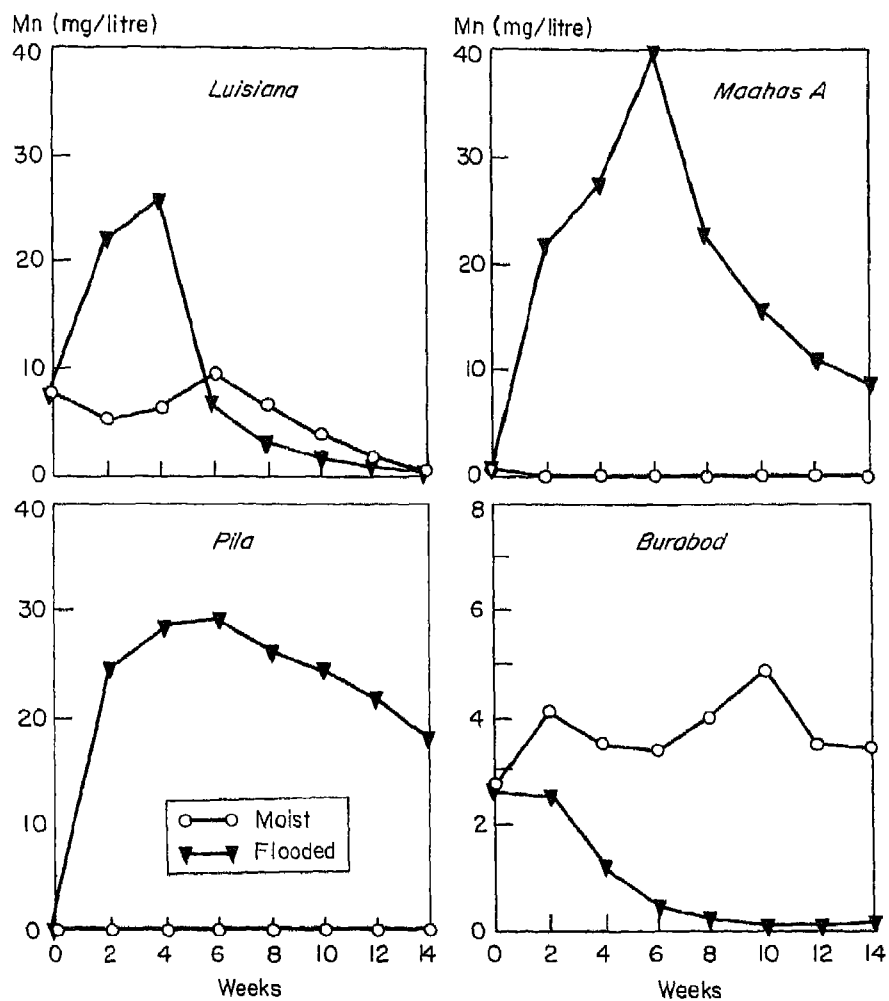
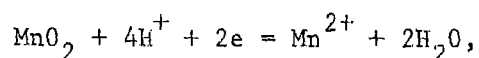


Fig. 14 Kinetics of water-soluble Mn in four soils under moist and flooded conditions.

concentration in the moist acid soils increased further with drop in pH to give as high as 5-10 ppm of water-soluble Mn. In the Burabod soil, Mn solubility was consistently higher under moist than under flooded condition.

The increase in the concentration of water-soluble Mn on flooding is attributed mainly to the reduction of Mn (IV) oxides to Mn (II)



and the subsequent decrease to the precipitation of MnCO_3 (Ponnamperuma et al 1969). Although the concentration of Mn^{2+} in the soil solution is determined by both pH and Eh, pH alone can strongly control Mn solubility at pH values below 5 (Adams and Wear 1957). The observed appreciable concentrations of Mn in the aerobic acid soils are therefore in conformity with the above principle.

Potassium. The kinetics of water-soluble K in four soils under two moisture regimes are presented in Fig. 15. Although changes in the K concentration with time followed a similar trend (increased initially followed by decrease) under both the regimes, the concentration under field capacity moisture regimes were lower than that under flooding in the Maahas A, Pila and Luisiana soils. This finding compares favourably with those of Ponnamperuma (1965) and Islam and Islam (1973). The observed increase in the K concentration maybe attributed largely to its

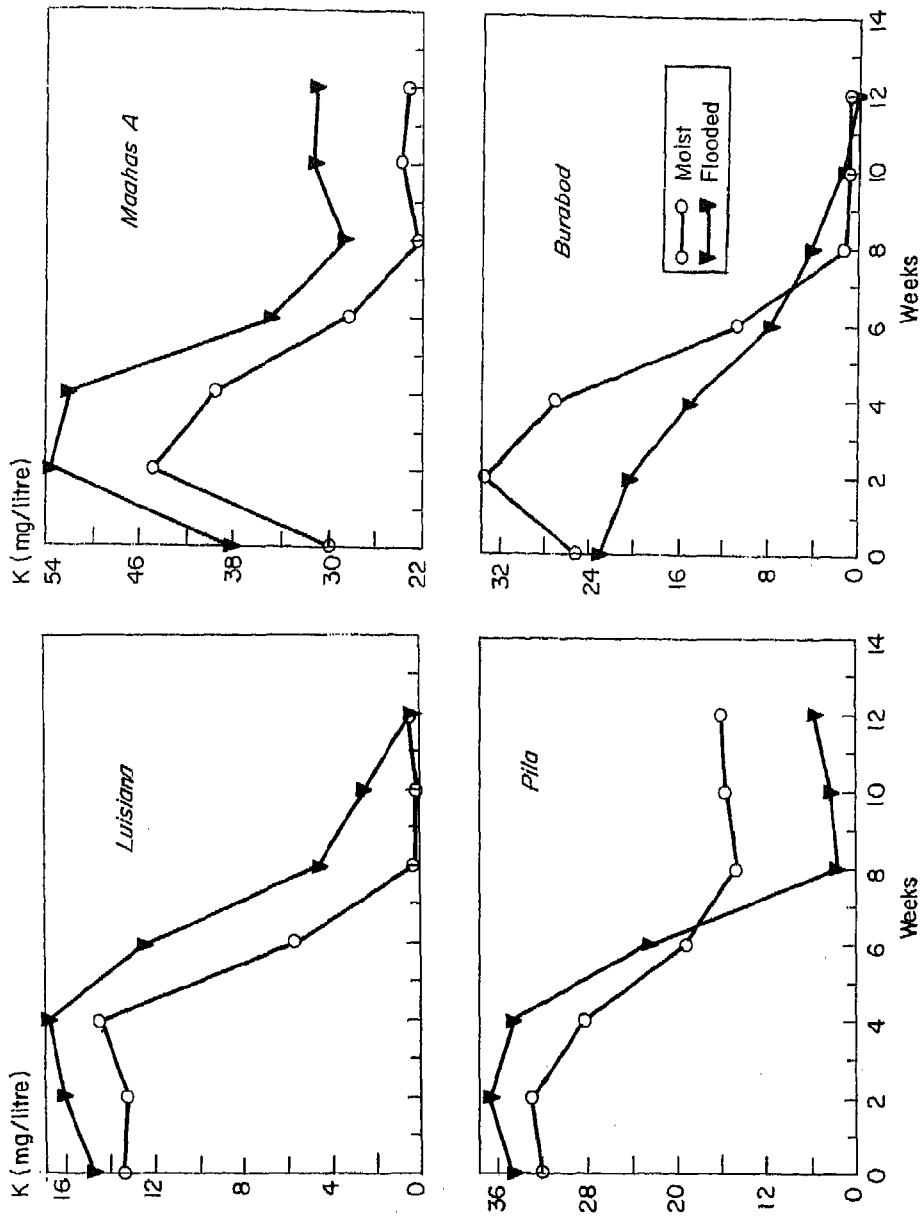


Fig. 15 Kinetics of water-soluble K in four soils under moist and flooded conditions.

displacement from the exchange sites into the solution by the large quantities of Fe^{2+} and Mn^{2+} ions released upon flooding.

In the strongly acidic Burabod soil, however, the concentration of solution K was higher under the moist than under flooded condition. This might have resulted from the re-adsorption of K from solution on the exchange sites, under the submergence, following sharp decline in the concentration of anions (dominantly SO_4^{2-}) in the solution.

Calcium and magnesium. Figures 16 and 17 show that the concentrations of Ca and Mg in the soil solutions increased with time to reach a peak and declined thereafter. Under flooded regimes, this decline following the peak formation were very sharp in the acidic soils and very slow or negligible in the Maahas A and Pila soils.

In the Maahas A, Pila and Luisiana soils the concentrations of water-soluble Ca and Mg under moist or aerobic conditions were much lower than under flooded conditions, the difference being narrower in the Luisiana soil especially after the peak formation. In the Burabod soil, however, both Ca and Mg concentrations were consistently much higher under moist than under flooded condition.

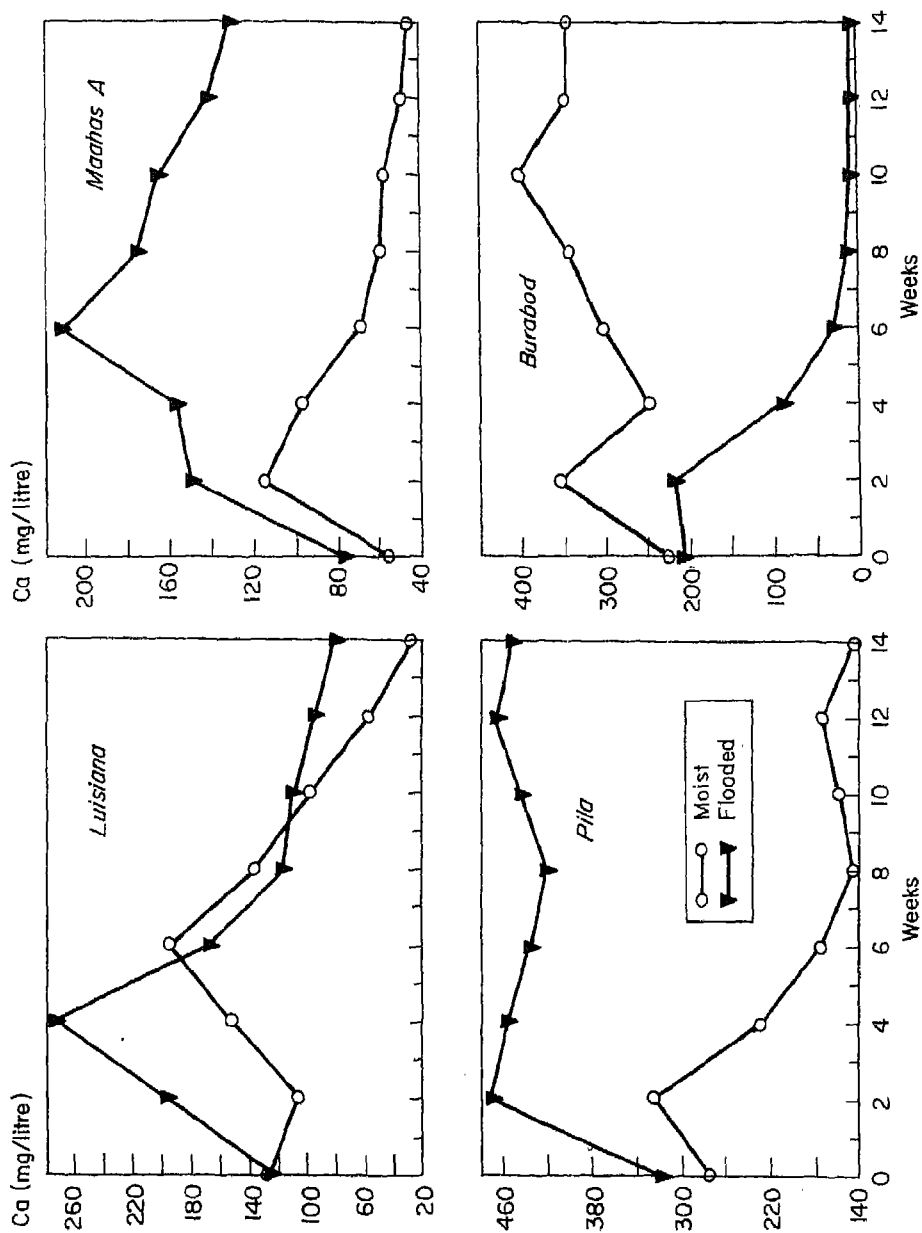


Fig. 16 Kinetics of water-soluble Ca in four soils under moist and flooded conditions.

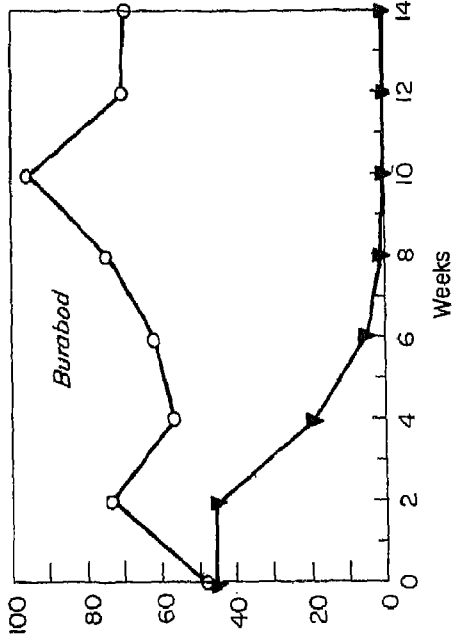
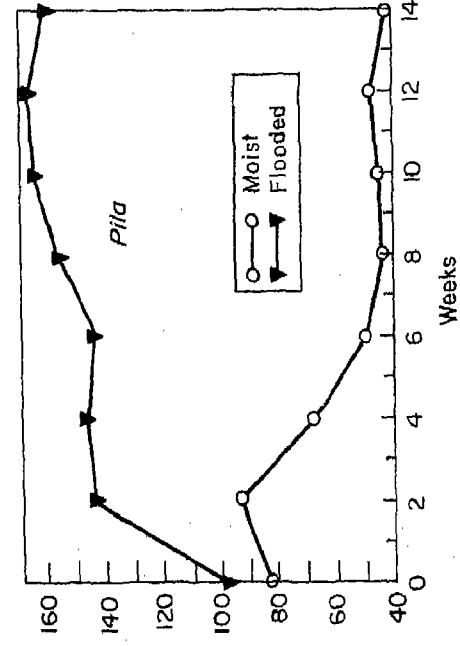
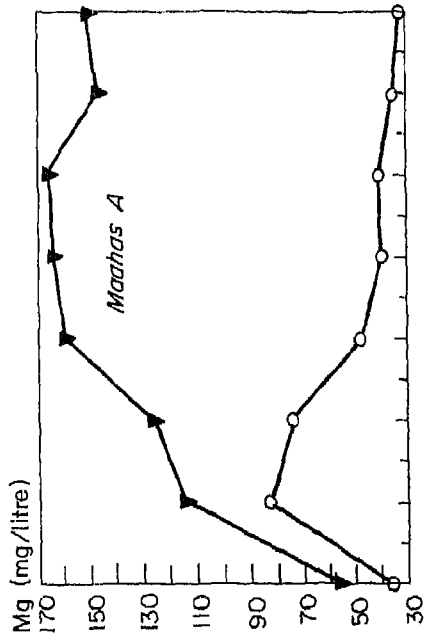
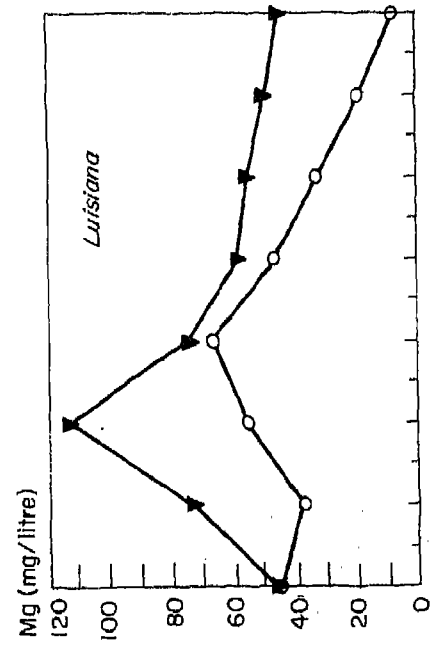
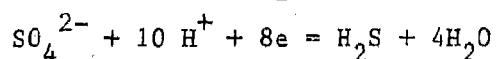


Fig. 17 Kinetics of water-soluble Mg in four soils under moist and flooded conditions.

The higher solubility of Ca and Mg commonly observed under flooding may be attributed to the accelerated dissolution of their solid compounds through the solvent action of CO_2 as well as by the displacement of Ca and Mg from the exchange sites into the soil solution mainly by the large quantities of Fe^{2+} and Mn^{2+} ions released upon soil reduction (Ponnamperuma 1965). The reverse effect of flooding on the solubility of Ca and Mg observed in the Burabod soil might have been caused by the re-adsorption of these cations from solution on the exchange sites, following the large imbalance between the cationic and anionic concentrations in the solution resulted chiefly from decreased SO_4^{2-} concentration.

Sulfate. The kinetics of water-soluble SO_4^{2-} in four soils under moist and flooded conditions are presented in Fig. 18. Under flooded condition, the SO_4^{2-} concentrations in the near-neutral Maahas A and calcareous Pila soils decreased steadily to a very low level within first 8 weeks. In the flooded acidic soils, it first increased probably because of desorption following increase in pH and then decreased sharply to very low levels within 8 weeks. The decline in the sulfate concentration under flooding is due largely to its reduction to sulfide, mostly in the form of H_2S ,



In normal soils, H_2S readily reacts with Fe^{2+} ions and with iron compounds to give $\text{FeS}\cdot\text{H}_2\text{O}$ which gradually changes to

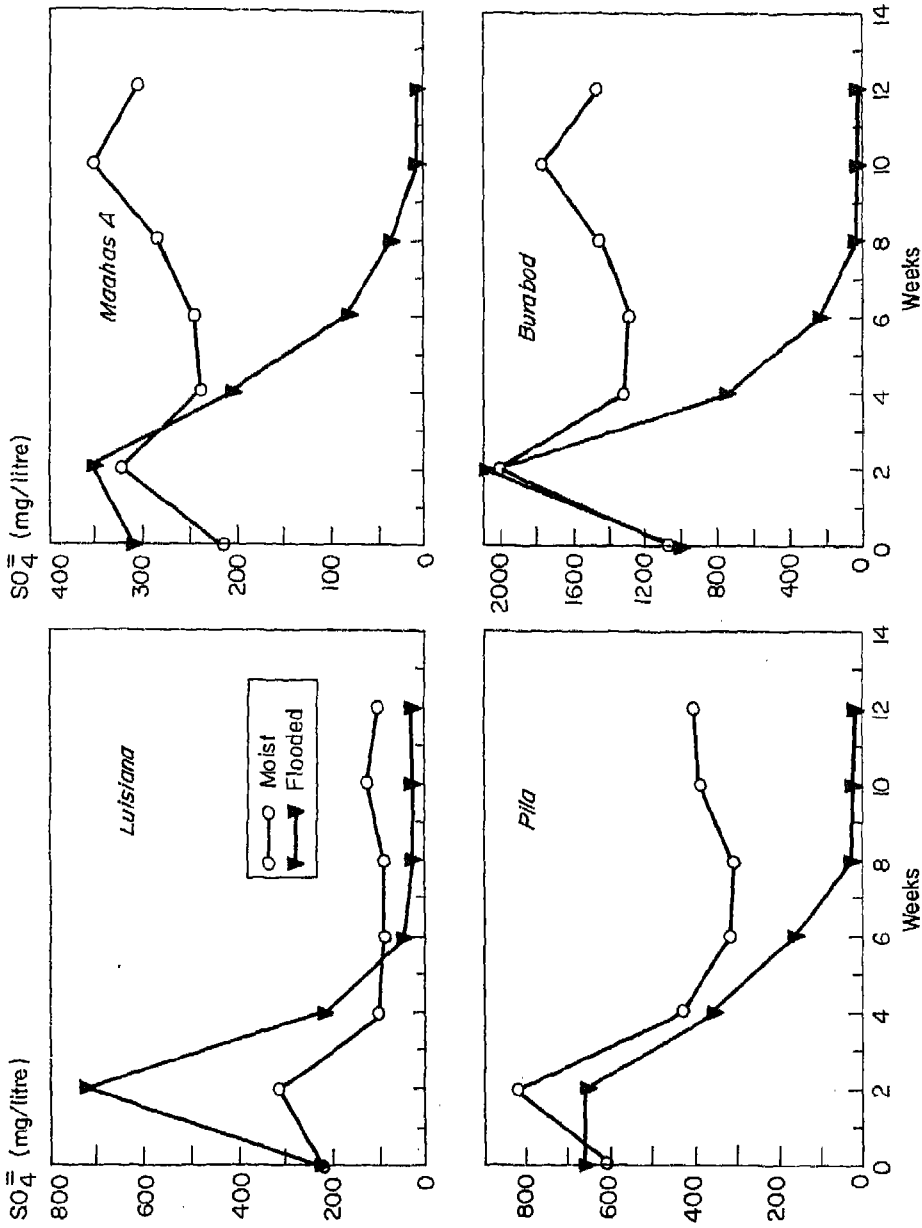


Fig. 18 Kinetics of water-soluble SO_4^{2-} in four soils under moist and flooded conditions.

makinaite and later to pyrites (FeS_2) (Berner cited by Ponnamperna 1972). Thus in normal soils, H_2S is hardly detectable. But in soils low in iron, sufficient free H_2S may be present to interfere with water and nutrient uptake and injure rice plants (Mitsui 1960). The conversion of sulfate to insoluble sulfides in flooded soils does not lower appreciably the availability of sulfur to rice plants apparently because bacteria present in the oxidized rhizosphere can oxidize sulfide to sulfate.

All the soils maintained much higher concentrations of water-soluble SO_4^{2-} under moist conditions than under the flooding. This increase, however, was relatively less pronounced in the Louisiana soil. The concentration of SO_4^{2-} in the solution of aerobic soils is controlled mainly by (i) the oxidation of elemental sulfur, sulfides and organic sulfur compounds to sulfate, (ii) the reduction of SO_4^{2-} and incorporation of sulfur into microbial tissues, and (iii) the sorption-desorption equilibria in the soils. The total water-soluble SO_4^{2-} concentration at any time represents the balance between the initial SO_4^{2-} content and net gain in SO_4^{2-} through the above phenomena on the one hand, and losses by leaching and assimilation by the plants on the other. Relatively lower concentration of SO_4^{2-} in the solution of moist Louisiana soil maybe attributed partly to the greater sorption of SO_4^{2-} on the hydrous oxides presumably present in high amount in this soil.

Silicon. Figure 19 shows that the concentration of water-soluble Si in the Pila soil increased with time after flooding and then declined slowly to reach almost the original level. In the other three soils, flooding did not increase the solubility of Si and the concentration decreased gradually from the onset of the flooding.

Throughout the growing season, concentration of the water-soluble Si was higher under the moist or aerobic conditions than under flooding in all the soils except the calcareous Pila loam in which the higher Si concentration was recorded under the flooded condition.

Although it is believed so, there is no clear-cut demonstration of the increase in solubility of silicon in soils as a result of flooding. The slight increase, whenever reported, has been attributed to the release of Si following (a) reduction of hydrous oxides of Fe (III) sorbing Si and (b) action of CO_2 on aluminosilicates (Bricker et al 1968). The subsequent decrease has been attributed to the recombination with aluminosilicates, following the decrease in P^{CO_2} (Ponnamperuma 1972).

In the present investigation, pH was found to have a strong influence on the Si solubility in soil. In the pH range under study (3.8 - 7.6), any increase in pH generally decreased the solubility and vice versa. Thus the decrease in pH, from its original value of 7.6 to about 7.0, increased the solubility of

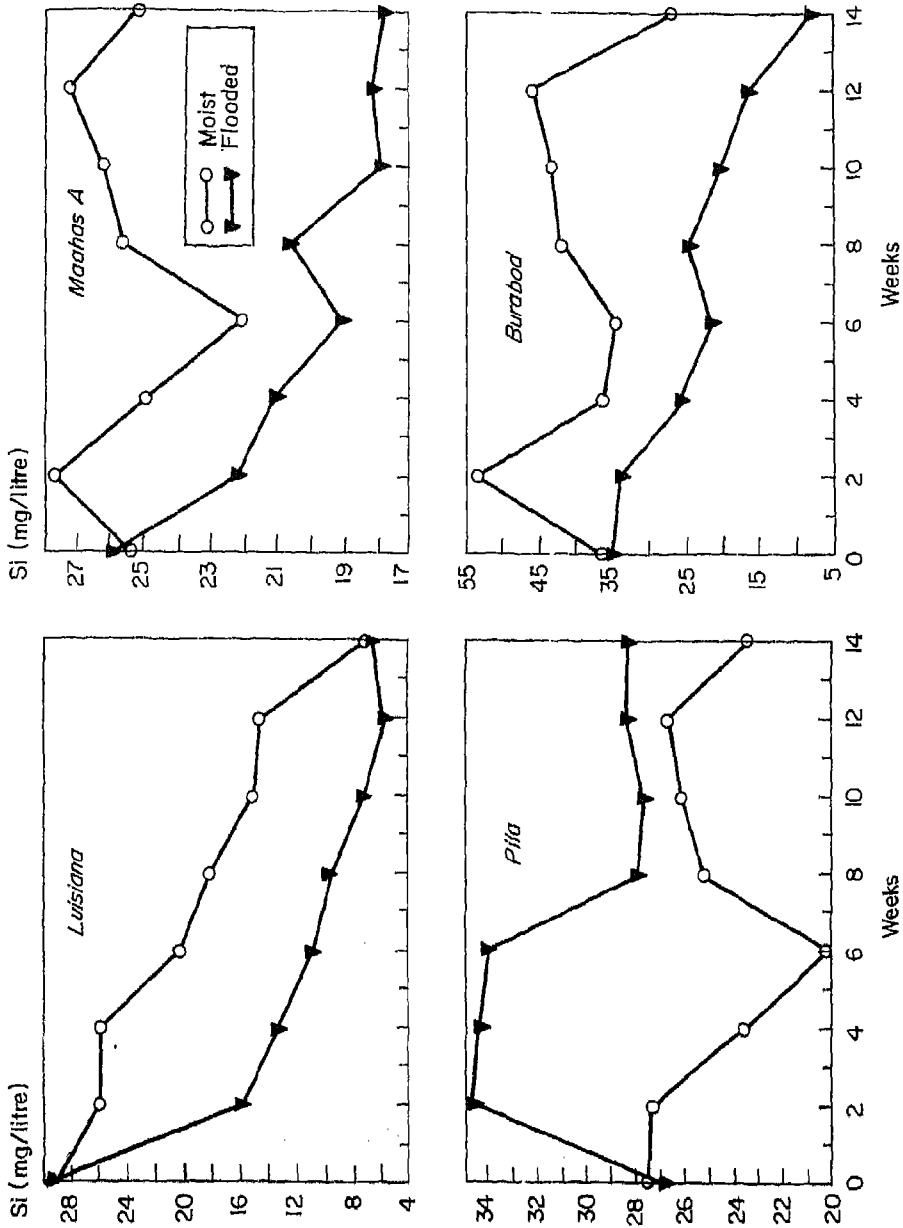


Fig. 19 Kinetics of water-soluble Si in four soils under moist and flooded conditions.

Si in the Pila soil under flooding; whereas in the other soils flooding increased pH and decreased Si solubility. The present observation is in conformity with those of Beckwith and Reeve (1964) and Jones and Handreck (1967) who reported that the concentration of soluble Si in soils increased as pH decreased in the range of 3-9.

Zinc and copper. Kinetics of the concentrations of water-soluble Zn and Cu in soils under two different moisture regimes are presented in Fig. 20 and 22, respectively. As the concentration of Zn in the solution of the calcareous Pila soil was very low regardless of the moisture regime (Appendix Table), its kinetics is not shown graphically. Likewise, as the concentrations of water soluble Cu in the Luisiana, Maahas A and Pila soils were very low irrespective of the moisture regimes, Cu kinetics of only the Burabod soil is presented.

The figures show that the concentrations of water-soluble Zn and Cu in the soils under moist conditions were appreciably higher than those under the flooded conditions. The present result is in conformity with that of Ponnampuruma (1976).

In the acidic soils, the decrease in Zn and Cu concentrations may be attributed partly to the increase in pH following soil reduction, because the solubility of Zn and Cu decreases 100 fold for each unit pH increase (Trierweiler and Lindsay 1969, Norwell and Lindsay 1969). In the near-neutral as well as high pH soils, the decreased solubility of Zn on flooding may be attributed partly to the probable formation of ZnS.

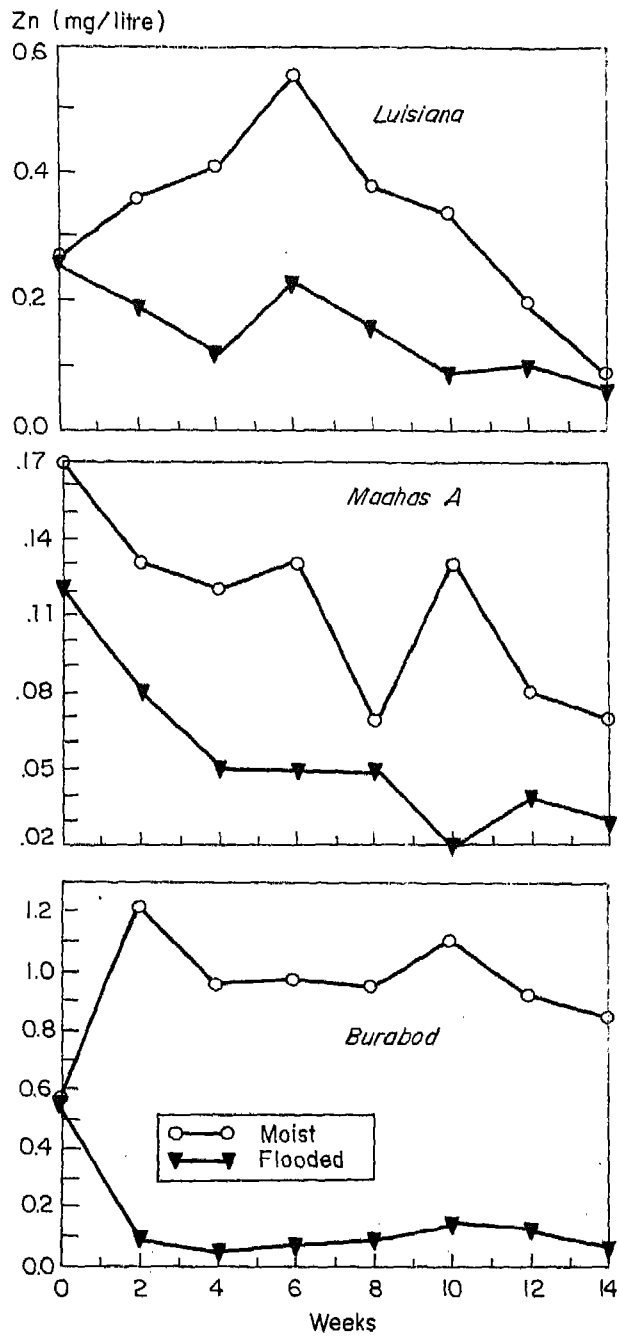


Fig. 20 Kinetics of water-soluble Zn in three soils under moist and flooded conditions.

Aluminum. Changes in the concentrations of water-soluble Al in the Luisiana and Burabod soils under the two different water regimes are presented in Fig. 21. The figure shows that in both the acidic soils, Al concentrations were much higher under moist than under the flooded conditions. The concentration of water-soluble Al was negligible under flooding as compared to that under the moist or aerobic condition of the Burabod soil. Aluminum concentration was very high (ranging between 30 and 70 ppm) in the aerobic Burabod relative to that (0.2 - 0.5 ppm) in the aerobic Luisiana soil, which may be attributed to the lower pH as well as higher percent Al saturation of the Burabod soil.

The marked effect of pH on the concentration of water-soluble Al was described by Raupach (1963) with the equation, $\text{pH} - \frac{1}{2} \text{pAl}_M = 2.2$. According to this relationship, the activities of water-soluble Al at pH 3.0, 3.5, 4.0, 4.5 and 5.0 will be 700, 70, 7, 0.7 and 0.07 ppm, respectively. The present observations appeared to conform reasonably well to the above relationship. Such high concentration of soluble Al as observed in the aerobic Burabod soil could be toxic to the growing rice plants.

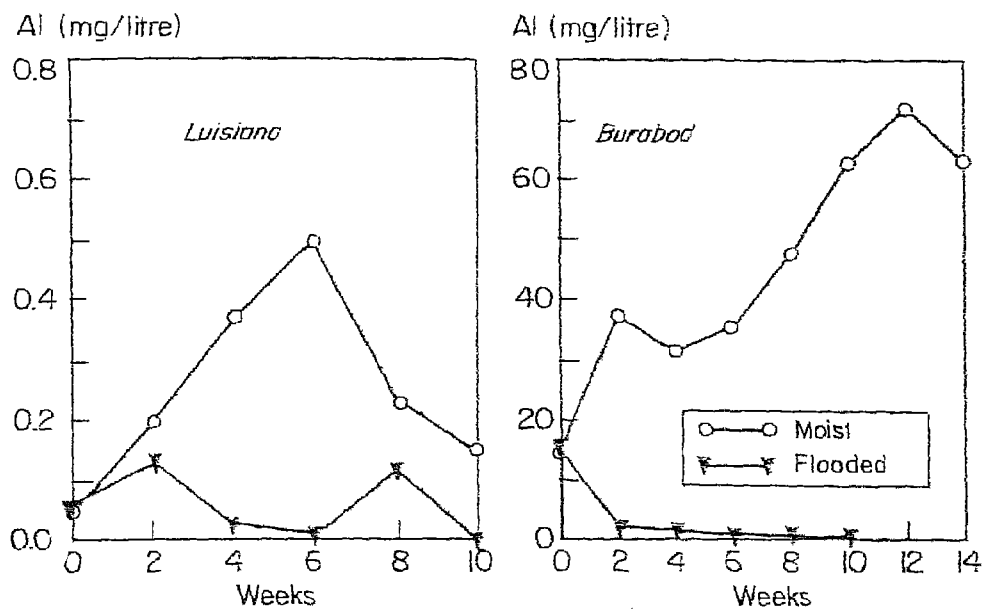


Fig. 21 Kinetics of water-soluble Al in two acid soils under moist and flooded conditions.

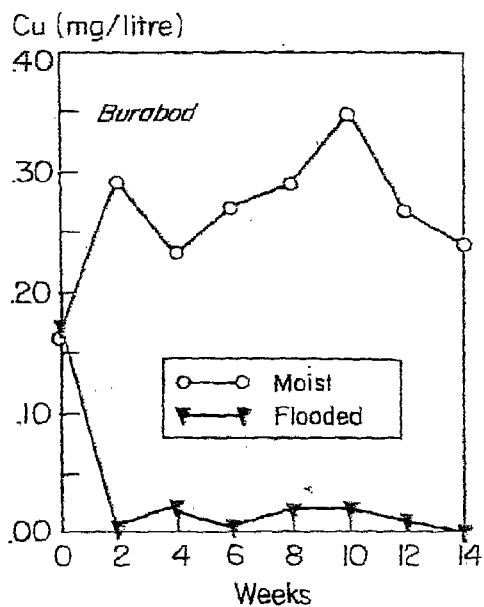


Fig. 22 Kinetics of water-soluble Cu in an acid soil under moist and flooded conditions.

To summarize, the nutrient kinetics study showed that compared to that under flooded (anaerobic) conditions, in the field capacity moisture (aerobic) regimes:

- i. P solubility was lower in all soils,
- ii. Fe solubility was extremely low in all soils,
- iii. Al solubility was very high in the strongly acidic soils,
- iv. Concentrations of water-soluble K, Ca and Mg were lower in most soils (except the acid sulfate soil from Burabod),
- v. Mn concentrations were almost undetectable in near-neutral and calcareous soils, but higher in the acidic soils, and
- vi. Si concentration was lower in the calcareous soil but higher in the acidic soils.

Mineral Nutrition of Two Rices in Four Soils Under Moist and Flooded Conditions

Concentrations of mineral nutrients in the 8 week old shoots and in the straw at harvest are presented in Table 5 and 7, respectively. As the yields under flooded conditions were much higher than under moist conditions, the concentration of nutrients might be affected by the dilution factor. Therefore, total uptake of the nutrients by the shoots and by the plants (straw plus grain) at harvest were also computed and are presented in Table 6 and 8 respectively. The results are discussed in the following pages:

Nitrogen

The concentration and total uptake of N in shoots were slightly lower under moist than under flooded conditions of the acidic soils (Luisiana and Burabod). In the Maahas A and Pila soils, however, shoots had significantly lower N concentrations (lower than the critical limit 2.5%) under flooded than under moist conditions, and the plants exhibited typical N deficiency symptoms starting from 6 weeks after flooding. The significantly higher total N uptake observed under flooded than under moist conditions of these soils (Table 6) indicates that the lower N concentration in shoots was caused by mere dilution in plants and does not implicate poor N availability under this treatment.

N concentration in straw and particularly the total N uptake at harvest were found to be lower under moist than under flooded conditions of the acidic soils. In the Maahas A and Pila soils, N concentrations and total N uptake in the plants at maturity were influenced by the moisture regimes in same way as observed in case of the 8 week old shoots.

Phosphorus

Flooding significantly increased the concentration and total uptake of P in shoots grown in all the soils except the Luisiana clay where no significant difference was noted between the two moisture regimes.

Table 5. Concentration of mineral nutrients in 8 week old shoot of two rices grown in four soils under moist and flooded conditions.^a

| Soil | Variety | Treatment | | N | P | K | Ca | Mg | SiO ₂ | Fe | Mn | Zn | Cu |
|----------|---------|-----------------|---|---------|----------|---------|-----------|-----------|------------------|-------|--------|---------|---------|
| | | Moisture regime | % | | | | | | | | | | |
| Luisiana | IR43 | Moist | | 2.99 c | 0.160 ef | 2.74 d | 0.135 cde | 0.450 b | 11.2 cd | 63 f | 827 b | 49.3 a | 16.3 b |
| | | Flooded | | 3.06 c | 0.142 g | 1.66 g | 0.148 bc | 0.274 gh | 10.4 ef | 138 d | 343 f | 24.5 bc | 2.7 f |
| Maahas A | IR46 | Moist | | 3.07 c | 0.164 ef | 2.83 d | 0.150 bc | 0.480 b | 12.1 a | 77 ef | 1127 a | 49.2 a | 18.2 ab |
| | | Flooded | | 3.21 bc | 0.156 fg | 1.70 g | 0.161 b | 0.364 cd | 10.3 ef | 183 c | 417 e | 26.2 bc | 3.8 ef |
| Pila | IR43 | Moist | | 2.50 d | 0.173 e | 3.09 bc | 0.088 ij | 0.305 efg | 10.6 def | 62 f | 33 h | 21.8 cd | 6.8 de |
| | | Flooded | | 1.12 g | 0.201 d | 3.14 b | 0.083 ij | 0.218 i | 11.4 bc | 73 ef | 530 d | 19.0 de | 4.3 def |
| Burabod | IR46 | Moist | | 2.40 d | 0.192 d | 3.16 b | 0.118 fg | 0.332 de | 10.0 fg | 70 ef | 70 h | 15.0 ef | 6.5 de |
| | | Flooded | | 1.16 g | 0.273 b | 2.91 cd | 0.078 j | 0.290 fgh | 12.0 ab | 80 ef | 743 c | 18.7 de | 2.8 f |
| Maahas A | IR43 | Moist | | 2.29 d | 0.203 d | 3.27 ab | 0.149 bc | 0.368 c | 10.0 fg | 73 ef | 57 h | 12.5 f | 10.7 c |
| | | Flooded | | 1.55 f | 0.244 c | 3.15 b | 0.130 def | 0.261 h | 11.1 cd | 102 e | 523 d | 14.3 ef | 4.3 def |
| Pila | IR46 | Moist | | 3.20 bc | 0.246 c | 3.43 a | 0.229 a | 0.536 a | 10.9 cde | 60 f | 67 h | 12.8 f | 12.5 c |
| | | Flooded | | 1.92 e | 0.304 a | 3.43 a | 0.141 cd | 0.332 de | 11.5 abc | 77 ef | 697 c | 11.2 f | 6.3 de |
| Burabod | IR43 | Moist | | 3.35 ab | 0.154 fg | 2.90 d | 0.075 j | 0.315 ef | 10.0 fg | 78 ef | 163 g | 28.5 b | 18.5 ab |
| | | Flooded | | 3.13 bc | 0.282 b | 2.01 f | 0.105 gh | 0.258 h | 11.1 cd | 308 a | 43 h | 18.0 de | 6.5 de |
| Maahas A | IR46 | Moist | | 3.40 ab | 0.165 ef | 2.43 e | 0.095 hi | 0.329 e | 10.0 fg | 85 ef | 177 g | 28.3 b | 20.8 a |
| | | Flooded | | 3.60 a | 0.299 a | 1.97 f | 0.120 efg | 0.259 h | 9.6 g | 275 b | 42 h | 18.5 de | 7.5 d |

^aMean of 3 replications. In a column, means followed by a common letter are not significantly different by DMRT at the 5% level.

Table 6. Total uptake of mineral nutrients by 8 week old shoot of two rices grown in four soils under moist and flooded conditions.^a

| Soil | Variety | Treatments | | N | P | K | Ca | Mg | Fe | Mn | SiO ₂ (g/pot) | Zn | Cu |
|---|---------|------------|--------|-----------|----------|--------|----------|--------|---------|--------|-----------------------------|---------|----------|
| | | Moisture | regime | | | | | | | | | | |
| ----- mg/pot ----- (g/pot) ----- µg/pot ----- | | | | | | | | | | | | | |
| Louisiana | IR43 | Moist | | 574 cde | 30.7 fgh | 525 c | 26.0 de | 86 d | 1.21 d | 15.8 c | 2.15 de | 943 ab | 314 ab |
| | | Flooded | | 946 a | 43.7 ef | 512 cd | 46.1 bc | 85 d | 4.34 bc | 10.9 d | 3.22 c | 767 c | 85 f |
| Maahas A | IR46 | Moist | | 659 bc | 35.2 efg | 609 c | 32.3 d | 103 c | 1.65 d | 24.2 b | 2.61 cd | 1053 a | 390 a |
| | | Flooded | | 998 a | 48.3 e | 528 c | 49.9 b | 113 bc | 5.68 a | 12.9 d | 3.20 c | 810 bc | 119 ef |
| Pila | IR43 | Moist | | 414 gh | 28.8 gh | 512 cd | 14.5 gh | 50 fgh | 1.03 d | 0.5 e | 1.76 efg | 363 de | 114 ef |
| | | Flooded | | 558 cdef | 100.8 c | 1572 a | 41.5 c | 109 bc | 3.64 c | 26.4 b | 5.70 b | 950 ab | 223 cd |
| Burai | IR46 | Moist | | 427 fgh | 34.2 efg | 565 c | 21.1 efg | 59 ef | 1.25 d | 1.2 e | 1.78 efg | 267 def | 116 ef |
| | | Flooded | | 629 bcd | 148.8 a | 1584 a | 42.4 bc | 157 a | 4.36 bc | 40.3 a | 6.54 a | 1020 a | 153 cdef |
| Burabod | IR43 | Moist | | 430 fgh | 38.2 efg | 616 c | 28.1 de | 69 de | 1.38 d | 1.0 e | 1.89 ef | 237 ef | 201 cde |
| | | Flooded | | 743 b | 116.7 b | 1505 a | 62.3 a | 125 b | 4.91 ab | 24.9 b | 5.32 b | 683 c | 213 cd |
| Burabod | IR46 | Moist | | 348 h | 26.8 gh | 374 de | 25.1 def | 58 efg | 0.66 d | 0.7 e | 1.19 g | 140 f | 136 def |
| | | Flooded | | 441 efg | 71.2 d | 799 b | 33.0 d | 78 d | 1.80 d | 16.2 c | 2.69 cd | 263 def | 142 def |
| Burabod | IR43 | Moist | | 429 fgh | 19.7 h | 373 de | 9.6 h | 40 gh | 1.00 d | 2.1 e | 1.28 fg | 363 de | 237 bc |
| | | Flooded | | 515 defg | 46.5 e | 331 e | 17.1 gh | 42 fgh | 5.05 ab | 0.7 e | 1.82 efg | 290 def | 107 ef |
| Burabod | IR46 | Moist | | 529 cdefg | 25.8 gh | 379 de | 14.8 gh | 51 fgh | 1.33 d | 2.7 e | 1.56 efg | 443 d | 325 a |
| | | Flooded | | 538 cdefg | 44.6 ef | 294 e | 17.9 fg | 38 h | 4.06 bc | 0.6 e | 1.45 fg | 277 def | 112 ef |

^aMean of 3 replications. In a column, means followed by a common letter are not significantly different by DMRT at the 5% level.

Although P concentrations in straw under flooding were lower than that under moist conditions of the Luisiana, Maahas A and Pila soils, total P uptake by plants at harvest were significantly higher under flooded regimes of all the four soils. The lower concentrations of P in the straw under flooding observed in the three soils could be attributed partly to the dilution factor and partly to the higher translocation of P from straw to grains. Usually P concentration in panicles is 2 to 3 times that in the straw (Yoshida 1981).

Potassium

Concentration and total uptake of K in 8 week old shoots grown in the acidic soils were higher under moist than under flooded conditions. In the Maahas A and Pila soils, however, K concentration did not vary significantly with moisture regimes; while total K uptake was significantly higher under flooded conditions. It may be recalled here that the concentration of water soluble K in the Luisiana soil was higher under flooded than under moist conditions throughout the growing season (Fig. 15). The significantly lower concentrations of K in the plants grown in the flooded acidic soils therefore might have been caused by probable antagonistic effect of very high concentrations of Fe present in the soil solutions.

While K concentrations in straw in the acidic soils were slightly higher under moist than under flooded conditions, flooding increased straw K concentrations in the Maahas A and Pila soils. Total K uptake in plants at harvest did not vary significantly with moisture regimes in the acidic soils, but in the Maahas A and Pila soils it was significantly higher under flooded than under moist conditions.

Calcium

Shoots grown in the acidic soils had lower concentration and uptake of Ca under moist than under flooded conditions. In the other soils moisture regimes did not have any consistent effect on the Ca concentration, but total uptake was appreciably higher under the flooded conditions.

Calcium concentration in straw as well as total Ca uptake in plants at maturity were markedly higher under flooded than under the moist conditions of all the soils.

Magnesium

Concentration of Mg in shoots was higher under moist than under flooded conditions of all the soils. The moisture regimes had no notable effect on total Mg uptake by shoots in the acidic soils, whereas in the Maahas A and Pila soils flooding significantly increased it.

Table 7. Concentration of mineral nutrients in straw of two rices grown in four soils under moist and flooded conditions.

| Soil | Treatments | | N | P | K | Ca | Mg | SiO ₂ | Fe | Mn | Zn | Cu |
|-----------|------------|-----------------|----------|-----------|---------|-----------|-----------|------------------|-------|--------|----------|----------|
| | Variety | Moisture regime | | | | | | | | | | |
| mg/kg | | | | | | | | | | | | |
| Louisiana | IR43 | Moist | 1.32 b | 0.132 gh | 0.96 gh | 0.110 fg | 0.446 b | 8.6 ef | 95 d | 1200 b | 85.8 a | 9.5 c |
| | | Flooded | 1.23 bc | 0.104 hi | 0.86 h | 0.160 bcd | 0.215 gh | 13.7 b | 202 c | 307 f | 47.5 c | 1.7 j |
| Maahas A | IR46 | Moist | 1.61 a | 0.127 gh | 1.06 fg | 0.130 ef | 0.545 a | 10.4 d | 85 d | 1600 a | 85.5 a | 11.2 ab |
| | | Flooded | 0.84 de | 0.090 i | 0.85 h | 0.155 cde | 0.288 ef | 14.5 ab | 322 b | 357 ef | 57.0 bc | 2.0 hij |
| Pila | IR43 | Moist | 0.64 f | 0.165 ef | 1.91 d | 0.037 j | 0.178 h | 5.9 h | 78 d | 15 h | 19.0 def | 4.0 fg |
| | | Flooded | 0.27 g | 0.148 fg | 2.22 c | 0.075 hi | 0.213 gh | 13.3 bc | 83 d | 448 de | 27.5 de | 1.8 ij |
| Burabod | IR46 | Moist | 0.64 f | 0.217 abc | 1.93 d | 0.060 ij | 0.264 fg | 7.0 gh | 100 d | 28 h | 27.3 de | 5.0 ef |
| | | Flooded | 0.36 g | 0.155 fg | 2.88 a | 0.145 de | 0.309 def | 15.3 a | 105 d | 620 c | 33.0 d | 3.3 ghi |
| Pila | IR43 | Moist | 0.71 ef | 0.223 ab | 2.17 c | 0.185 b | 0.327 cde | 7.9 efg | 75 d | 20 h | 18.0 ef | 5.2 ef |
| | | Flooded | 0.35 g | 0.154 fg | 2.22 c | 0.225 a | 0.208 gh | 12.2 c | 98 d | 458 d | 28.3 de | 2.8 ghij |
| Burabod | IR46 | Moist | 1.14 c | 0.190 cde | 1.95 d | 0.180 bc | 0.362 cd | 7.3 fgh | 68 d | 29 h | 8.0 f | 6.8 d |
| | | Flooded | 0.34 g | 0.172 def | 2.53 b | 0.135 def | 0.370 c | 13.4 bc | 110 d | 518 d | 21.8 def | 2.8 ghij |
| Burabod | IR43 | Moist | 0.78 def | 0.150 fg | 1.36 e | 0.065 i | 0.325 cde | 8.2 efg | 88 d | 200 g | 50.0 c | 9.8 bc |
| | | Flooded | 1.28 bc | 0.237 a | 1.25 e | 0.155 cde | 0.176 h | 14.2 ab | 227 c | 30 h | 18.5 def | 3.5 gh |
| Burabod | IR46 | Moist | 0.70 ef | 0.179 def | 1.38 e | 0.095 gh | 0.375 c | 9.3 de | 98 d | 263 fg | 66.0 b | 12.0 a |
| | | Flooded | 0.94 d | 0.199 bcd | 1.23 ef | 0.145 de | 0.222 gh | 14.7 ab | 458 a | 38 h | 25.2 de | 5.7 de |

^aMean of 3 replications. In a column, means followed by a common letter are not significantly different by DMRT at the 5% level.

Table 8. Total uptake of mineral nutrients by plants (grain plus straw) at harvest in four soils under moist and flooded conditions.

| Soil | Variety | Treatments | | N | K | SiO ₂ | P | Ca | Mg | Fe | Mn | Zn | Cu |
|-----------|---------|-----------------|--|----------|----------|------------------|---------|--------|----------|----------|---------|--------|---------|
| | | Moisture regime | | | | | | | | | | | |
| Louisiana | IR43 | Moist | | 1.05 c | 0.73 ef | 7.71 d | 121 def | 83 def | 330 b | 14.1 cd | 91.1 b | 6.6 a | 1.26 c |
| | | Flooded | | 1.76 a | 0.89 def | 12.82 b | 184 c | 125 bc | 223 cd | 26.3 b | 25.3 ef | 5.2 b | 2.08 b |
| Maahas A | IR46 | Moist | | 1.10 c | 0.71 f | 7.26 d | 95 f | 85 def | 361 b | 8.3 f | 106.2 a | 5.7 b | 0.87 d |
| | | Flooded | | 1.77 a | 0.92 def | 15.81 a | 200 c | 179 a | 306 b | 38.0 a | 32.4 de | 6.7 a | 2.68 a |
| Pila | IR43 | Moist | | 0.42 ij | 0.90 def | 3.31 e | 107 ef | 26 h | 101 g | 8.7 ef | 0.9 h | 1.2 gh | 0.67 de |
| | | Flooded | | 0.49 ghi | 1.54 c | 11.13 bc | 196 c | 59 fg | 190 cde | 16.5 c | 31.2 de | 2.8 de | 1.35 c |
| Buraobod | IR46 | Moist | | 0.34 j | 0.86 def | 4.15 e | 115 def | 27 h | 126 fg | 9.0 def | 1.7 h | 1.5 fg | 0.57 de |
| | | Flooded | | 0.53 gh | 1.68 c | 11.35 bc | 214 c | 81 def | 232 c | 16.7 c | 33.1 de | 2.9 de | 1.60 c |
| Pila | IR43 | Moist | | 0.46 hi | 1.00 d | 4.49 e | 142 d | 92 d | 165 def | 9.1 def | 1.2 h | 1.3 gh | 0.72 de |
| | | Flooded | | 0.83 e | 1.91 b | 12.65 b | 274 b | 193 a | 240 c | 17.5 c | 38.2 d | 3.7 cd | 2.21 b |
| Buraobod | IR46 | Moist | | 0.59 fg | 0.98 de | 3.94 e | 99 f | 90 de | 180 cdef | 5.2 f | 1.8 h | 0.5 h | 0.44 e |
| | | Flooded | | 0.95 d | 2.38 a | 16.39 a | 165 a | 139 b | 421 a | 22.8 b | 48.3 c | 3.7 cd | 2.82 a |
| Buraobod | IR43 | Moist | | 0.66 f | 0.82 def | 6.30 d | 127 def | 45 gh | 210 cde | 13.7 cde | 13.5 g | 3.5 cd | 1.35 c |
| | | Flooded | | 1.31 b | 0.86 def | 10.24 c | 252 b | 104 cd | 160 ef | 22.3 b | 2.8 h | 2.2 ef | 1.45 c |
| Buraobod | IR46 | Moist | | 0.54 gh | 0.81 def | 7.84 d | 139 de | 61 efg | 228 c | 16.0 c | 17.3 fg | 4.0 c | 1.50 c |
| | | Flooded | | 1.25 b | 0.91 def | 12.44 b | 280 b | 93 d | 215 cde | 36.3 a | 3.9 h | 3.0 de | 2.07 b |

^aMean of 3 replications. In a column means followed by a common letter are not significantly different by DMRT at the 5% level.

While no significant influence of moisture regimes was observed on Mg concentrations in straw grown in the Maahas A and Pila soils, in the acidic soils straw had significantly higher concentration of Mg under moist than under flooded conditions. Total Mg uptake by plants at maturity was higher under aerobic conditions of the acidic soils but under submerged conditions of the Maahas A and Pila soils.

Silica

Flooding did not show any consistent effect on the silica concentration in shoots grown in the acidic soils but in the Maahas A and Pila soils submergence increased the silica concentration. Total silica uptake, however, was higher under flooded than under moist conditions of all the soils.

Significantly higher silica concentration in straw as well as total silica uptake in the plants at maturity were obtained under flooded than under moist conditions of all the soils. It will be recalled here that Si solubility in the Luisiana, Maahas A and Burabod soil were appreciably higher under moist than flooded conditions (Fig. 19). The higher silica content in plants observed under the flooded regime therefore might have been due to abundant water supply rather than chemical benefit of flooding.

Iron

Flooding produced significantly higher concentration of Fe in shoots in the acidic soils. The increase due to flooding was not significant in case of near-neutral Maahas A and calcareous Pila soils. Total Fe uptake in the shoots, however, were substantially higher under flooded than that under moist conditions of all the soils.

Influence of the moisture regimes on the concentration of Fe in straw and total Fe uptake in plants at harvest was same as that observed in case of the 8 week old shoots.

It is interesting to note that although the plants grown on the Maahas A and Pila soils contained equally low concentrations of Fe regardless of the moisture regimes, plants in the aerobic Pila soil only showed clear Fe chlorosis (Plate 2). Probably only some active fraction of total Fe in tissue is directly involved in the Fe metabolism in plants and that active Fe fraction might have been deficient in the plants grown in the aerobic calcareous soil.

Manganese

Concentrations and total uptake of Mn in the 8 week old shoots grown in the acidic soils were markedly higher under moist than under the flooded conditions. Contrastingly, in the near-neutral Maahas A and calcareous Pila soils flooding significantly increased the concentrations and uptake of Mn in the shoots.

The moisture regimes exerted soil-specific influences on the Mn concentrations in straw and the total Mn uptake in plants at maturity in the same way as did in the 8 week old shoots.

Zinc

The shoots grown in the acidic soils showed markedly higher concentration and uptake of Zn under moist than under flooded conditions. In sharp contrast, shoots in the near-neutral Maahas A and calcareous Pila soils showed substantially higher Zn concentrations and total uptake under flooded than under the moist conditions.

Zinc concentration in straw and total uptake in plants at harvest were significantly higher under moist than under flooded conditions of the acidic soils. In the Maahas A and Pila soils, flooding increased the concentrations of Zn in straw appreciably and the total Zn uptake significantly.

Copper

In the acidic soils, significantly higher concentration and uptake of Cu were found under FC moisture regime than under flooding. Although moisture regimes showed similar influence on the concentration of Cu in shoots in the Maahas A and Pila soils, the total uptake was found higher under flooded conditions.

Concentrations of Cu in straw were significantly higher under moist than under flooded conditions of all the soils, but total uptake at harvest was remarkably higher under the flooded regimes.

Some important differences in mineral nutrition of rice under the moist (aerobic) and flooded (anaerobic) soil conditions may now be summarized:

- i. P concentrations in plants were lower under moist than under flooded conditions of all soils except the P deficient Ultisol from Louisiana, where no difference was noted between the two moisture regimes.
- ii. Ca concentrations in tissues were consistently lower under moist than under flooded conditions of strongly acidic soils.
- iii. Concentrations of Fe in plants were lower under moist than under flooded conditions of all soils, but this difference was significant only in the acid soils.
- iv. Relative to that under flooded conditions, in the field capacity moisture regime tissue Mn concentrations were very low in the near-neutral and the calcareous soil but very high in the acid soils.

- v. No appreciable difference in SiO_2 concentration in 8 week old plants was noted between the two moisture regimes. But in straw at maturity, SiO_2 concentrations were significantly lower under moist than under flooded conditions of all soils.

Comparison of chemical kinetics of the soils and mineral nutrient contents in plants under moist and flooded conditions suggests that:

- i. lower availability of P in most soils,
- ii. lower availability of Fe and Si in all soils,
- iii. lower availability of Ca in strongly acidic soils,
- iv. lower availability of Mn in near-neutral and calcareous soils, and
- v. excessive solubility of Al and Mn in strongly acidic soils could be important soil chemical factors responsible for poor growth of rice under field capacity moisture regimes.

Growth and Yield of Two Rices in Four Soils under
Moist and Flooded Conditions

Plant height

Growth in plant height of IR43 and IR46 in four soils under moist and flooded conditions are presented in Fig. 23. The figure shows that in the formative stage all the plants, regardless of the cultivars and the moisture regimes, were

Plant height (cm)

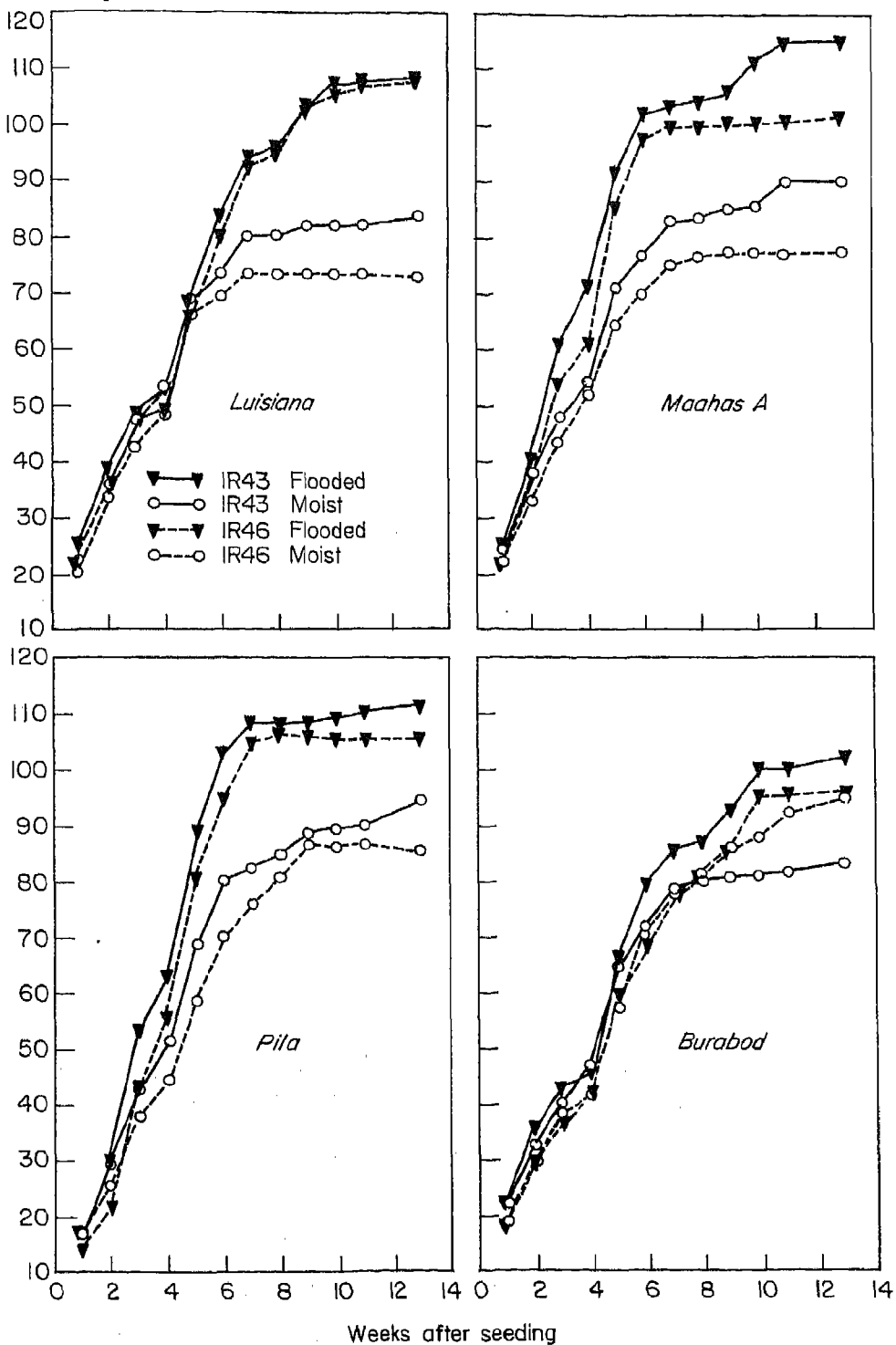


Fig. 23. Plant height of two rices during growth in four soils under moist and flooded conditions.

practically of the same height. Influence of the moisture regimes on the growth of plants in the near-neutral Maahas A and calcareous Pila soils started only after two weeks of seeding. Then the plants grew taller under the flooded than under the moist conditions of these soils. However, this superiority of the flooding treatment on the rice growth started manifestation much later (after 6 weeks) in case of the acidic soils from Luisiana and Burabod. The figure also shows that the IR43 plants were taller than IR46, irrespective of the treatments.

Tillering

Changes in the number of tillers per hill upto 12 weeks were recorded and are presented in Fig. 24. Flooding of the near-neutral Maahas A and the calcareous Pila soils produced more number of tillers in both the cultivars. Contrastingly, in both the acidic soils tillering was higher under the moist than under the flooded conditions. In the Burabod soil, however, flooding started producing more number of tillers than did the aerobic condition from ninth week onwards. Late manifestation of superior tillering of rice under flooded condition over the non-flooded condition of an acid soil had earlier been reported by Senewiratne and Mikkelsen (1961). The acid soil from Luisiana, however, produced consistently more number of tillers under the moist condition.

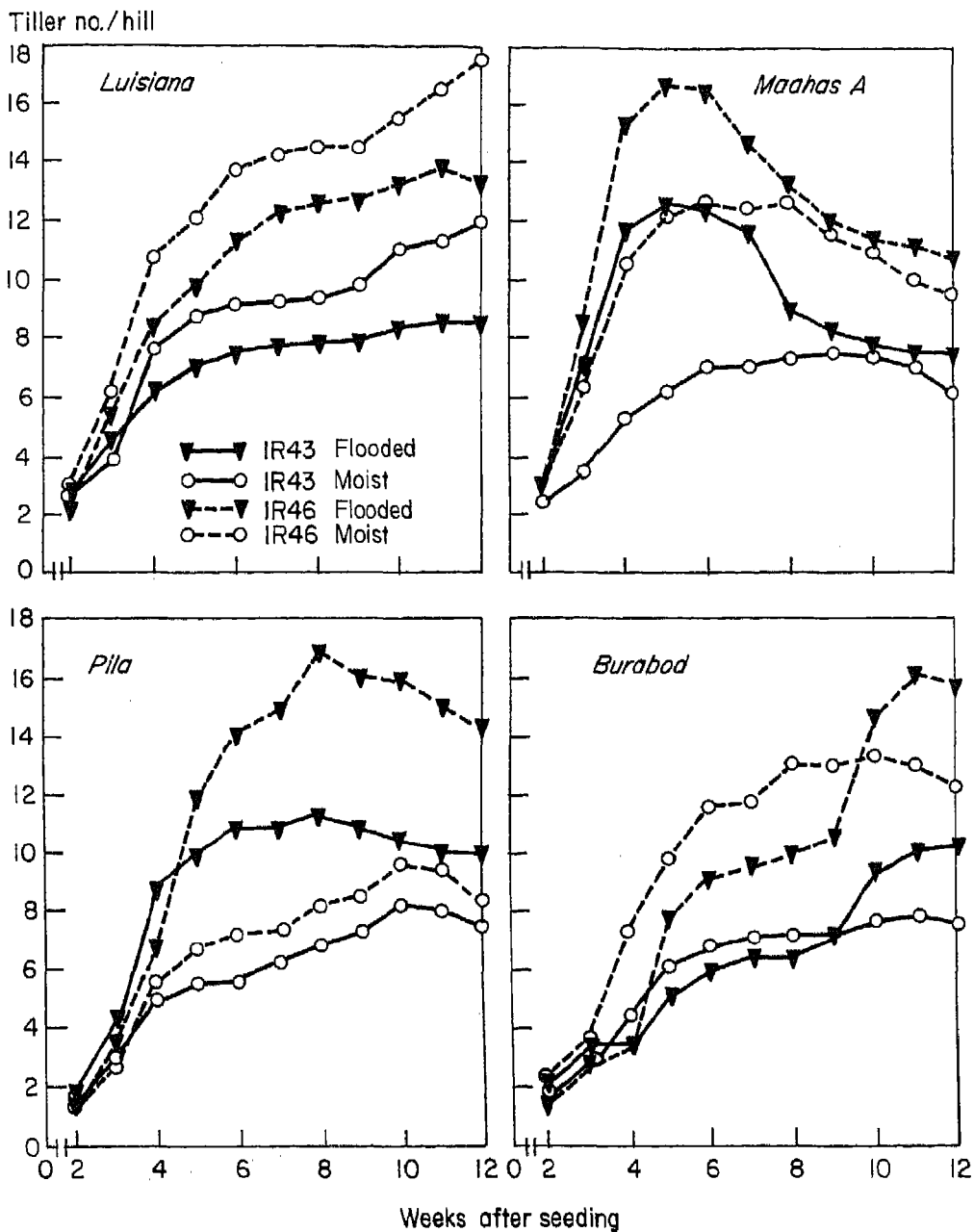


Fig. 24. Tiller number per hill of two rices during growth in four soils under moist and flooded conditions.

Sharp visible difference in the tillers formed under the two different moisture regimes was observed. While the flooded soils produced healthy and succulent tillers spreading out fanwise, the FC moist conditions of the soils produced thin tillers compressed together at the base to give a bushy appearance.

Visual symptoms

Under FC moisture regime, clear chlorotic symptoms typical of Fe deficiency appeared on both the rices in the calcareous Pila soil starting from seedling stage and persisted throughout the growing period (Plate 2). Under flooded conditions of the Pila soil, however, plants grew vigorously with normal green foliage (Plate 3). At the end of the grand vegetative stage, plants growing in the moist Luisiana soil showed mildly chlorotic leaves with light brown lesions along the edges which may have been caused by latent Fe deficiency and/or incipient Mn toxicity. Although no clear foliar symptoms of Al toxicity could be identified, root growth of rice in the moist acid-sulfate (Burabod) soil was found remarkably restricted (Plate 4) apparently due to the toxic concentration (30-70 ppm) of water-soluble Al present under this treatment.



Plate 2. Growth of IR43 in four soils under Field Capacity Moisture Regimes.
(a) Maahas A, (b) Luisiana,
(c) Burabod (Malinao), (d) Pila.



Plate 3. Growth of IR43 in the calcareous Pila soil under (a) Flooded, and (b) Field Capacity Moist Conditions.

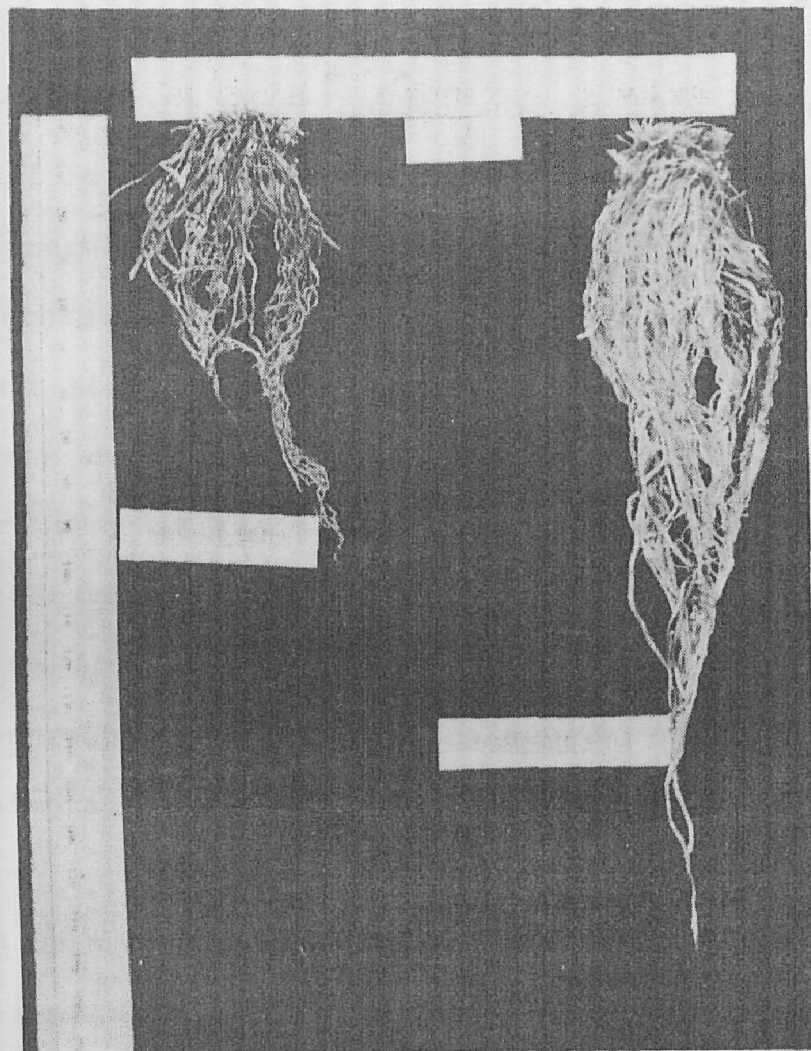


Plate 4. Root growth of 8 week old IR43 in the acid sulfate Burabod (Malinao) soil under (a) Field Capacity Moist, and (b) Flooded conditions.

During the reproductive phase, plants growing in both the Maahas A and Pila soils under flooded conditions showed clear N deficiency symptoms. The incipient chlorotic symptoms exhibited by the plants grown in the moist Maahas soil at this stage were similar to both of Fe deficiency and N deficiency.

In spite of regular watering in every morning to maintain the soil water content around field capacity, plant growing in the moist Luisiana soil apparently suffered from several spells of moisture stress during the post-tillering stage. The very fast draining property of the soil and high temperature in the greenhouse (the minimum and maximum air temperature ranged from 25 to 30 and 32 to 45°C, respectively) during this period might have jointly been responsible for causing several shocks of mild wilting in the plants.

Dry matter yield of 8 week old shoot

Table 9 presents dry matter yield of 8 week old shoots of two rices in four soils under two different moisture regimes. The yields under flooded conditions were significantly higher than under FC moisture regimes of the Luisiana, Maahas A and Pila soils. In case of the Burabod soil, there was no significant difference in yields obtained under the two moisture regimes.

Under flooded conditions, both the cultivars performed equally well in all the soils except the calcareous Pila loam in which IR43 produced significantly higher shoot yield than that

of IR46. Under moist conditions also, IR43 proved significantly superior to IR46 only in the Pila soil; while in the other soils no significant difference in performance was noted between the two cultivars.

Grain yield

Grain yields of IR43 and IR46 under different treatments are given in Table 9. The yield, regardless of the cultivars, was significantly higher under flooded than under the moist conditions of all the soils. Grain yield of rice under FC moisture regimes did not exceed 38% of that under the flooded conditions. In all the flooded soils, IR46 produced significantly higher grain yield than that of IR43. Although IR43 produced higher grain yield than that of IR46 in all the moist soils, the varietal difference was statistically significant only in the calcareous Pila loam.

Straw yield

Straw yields obtained from different treatments are presented in Table 9. Data show that although straw yield was generally higher under flooded than under the moist conditions of all the soils, this difference was not statistically significant in case of the acidic soils from Luisiana and Burabod. The two cultivars did not differ significantly from each other with respect to their straw yields.

Table 9. Yield of two^a rices in four soils under moist and flooded-conditions.

| Soil | Treatment | | Dry matter yield of 8 shoots | Grain yield g/pot | Straw yield |
|----------|-----------|--------------------|------------------------------------|-------------------------|----------------|
| | Variety | Moisture regime | ----- | ----- | ----- |
| Luisiana | IR43 | Moist | 19.2 def | 7.3 fgh | 65.9 bcd |
| | | Flooded | 31.0 c | 59.1 b | 66.4 bcd |
| | IR46 | Moist | 21.5 de | 2.3 gh | 63.6 bcde |
| | | Flooded | 31.1 c | 70.7 a | 75.1 ab |
| Maahas A | IR43 | Moist | 16.6 efgh | 10.6 fg | 43.7 fg |
| | | Flooded | 50.2 ab | 33.3 e | 62.3 cde |
| | IR46 | Moist | 17.8 defg | 4.7 gh | 41.5 g |
| | | Flooded | 54.4 a | 41.7 cd | 51.3 efg |
| Pila | IR43 | Moist | 18.8 defg | 10.6 fg | 42.4 g |
| | | Flooded | 47.8 b | 57.3 b | 73.3 abc |
| | IR46 | Moist | 10.9 h | 0.5 h | 48.4 fg |
| | | Flooded | 23.4 d | 74.7 a | 80.5 a |
| Burabod | IR43 | Moist | 12.8 gh | 14.0 f | 53.3 efg |
| | | Flooded | 16.5 efgh | 36.6 de | 52.1 efg |
| | IR46 | Moist | 15.6 efgh | 10.5 fg | 49.8 fg |
| | | Flooded | 15.0 fgh | 47.3 c | 55.1 def |

^aMean of 3 replications. In a column, means followed by a common letter are not significantly different by DMRT at the 5% level.

Experiment 3

Chemical Kinetics of Four Soils
Under Moist, Wet and Flooded Conditions
in Relation to Growth and Mineral Nutrition of Rice

In the previous experiment (Experiment No. 2) grain yields of rice under FC moisture regimes did not exceed 38 percent of that under flooded soil conditions. Several adverse chemical factors were identified in the aerobic regime of moist soils. However, the observed poor yields cannot be attributed solely to those unfavorable soil chemical factors. It is likely that the FC moisture level fails to meet the complete water requirement of rice crop as has been suggested by several workers (Jana and De Datta 1971). Such poor grain yields as obtained under FC moisture regimes may have been caused by both moisture stress and adverse soil chemical environment. In an attempt to isolate the effect of adverse chemical factors from that of moisture stress on rice growth and to study the chemical environments of aerobic soils with abundant supply of water, the present experiment was conducted.

MATERIALS AND METHODS

This experiment was conducted in the greenhouse in 1986 Dry Season. The soils used for this experiment were collected freshly and stored in air-dry condition for about six months in the greenhouse before use. While the Burabod, Maahas A, and

Pila soils were collected from the same sites as for the previous experiment, the Luisiana soil was sampled from a different site (Barrio: San Pedro, Luisiana) which was selected for a subsequent field experiment. The same procedures as described for the previous experiment were followed to prepare bulk soils for using in the pots and to prepare the samples for chemical analyses. Important properties of the soils are furnished in Tables 3 and 4.

Experimental Factors and Levels

Soils

The following four soils were used:

- S1 - Luisiana soil
- S2 - Maahas A soil
- S3 - Pila soil
- S4 - Burabod soil

Moisture regimes

The following three moisture regimes were studied:

- M1 - Moist (constant field capacity moisture)
- M2 - Wet (moisture level in soil equated thrice daily to that under the flooded regime and constant free drainage maintained. Drained leachate saved everytime and used for next irrigation).
- M3 - Flooded (constant submergence with 3 cm level of standing water).

Cultivar:

IR43 was grown as the test cultivar for this trial.

Experimental Design

For this 4 x 3 factorial experiment, the pots were laid out in a Randomized Complete Block Design with 4 replications.

Greenhouse procedure

Twelve kilogram portions of each soil were thoroughly mixed with reagent grade ammonium sulfate, monocalcium phosphate and potassium chloride to supply N, P and K at the rates of 100, 50 and 50 mg/kg soil, respectively. The fertilized soils were then placed in 16 liter glazed porcelain pots fitted with the drainage tube assembly at the bottom (similar set-up as used for the previous experiment). The pots were then placed in the greenhouse tanks. Soils in all the pots were first brought to the field capacity moisture level by adding required amount of demineralized water. Bright platinum electrodes and tensiometers were installed in each pot in same way as described for the previous experiment.

The recycled saturation extracts were collected as representative soil solutions from all the pots at 0 week. Eight pre-germinated seeds of IR43 were dibbled in each pot after the sampling of 0 week solutions. Throughout the

experiment the moisture level in the moist pots were maintained around field capacity with help of tensiometers and by adding demineralized water whenever necessary.

The 'flooded' pots were maintained saturated for the first 10 days until the seedlings were established well. After first 10 days of seeding, seedlings in each pot (regardless of the moisture regimes) were thinned out to keep four healthy ones and in the 'flooded' pots flooding was imposed to give a 3 cm level of standing water.

The moisture level in soils under the wet regime was maintained around field capacity for first 10 days and thereafter these pots were irrigated thrice daily (at 8 AM, 2 PM and 10 PM), everytime to equate the water level in these pots to that present under the flooded regime. Drain tubes of both the 'moist' and the 'wet' pots were kept open constantly into glass bottles. Drained leachate following an irrigation was collected from the 'wet' pots in the bottles and was used for the next irrigation.

Unlike in the previous experiment, no seedlings growing in the calcareous Pila soil were replaced this time by the healthy ones from the other pots. Two diagonal plants were harvested from each pot at 8 weeks after dibbling for recording dry matter yield and their chemical analyses. Thereafter, a top dressing of nitrogen at the rate of 50 mg N/kg soil was given as urea to all the pots. The remaining two plants in each pot were grown to the maturity and then harvested.

Soil redox potentials in situ were recorded at weekly intervals.

Sampling of soil solutions

From flooded pots, soil solutions were drawn by gravity. The equilibrium saturation extracts were collected as the representative solutions of both the 'moist' and 'wet' soils following the method described by Kundu et al (1987). From all the pots, solutions were collected at fortnightly intervals under anoxic conditions using similar set-up as described for the previous experiment.

Preparation of plant samples for analysis

The 8 week old shoots and straw at harvest were washed, dried and chopped in the same way as detailed in the previous experiment. These samples were then ground by using a UD cyclone mill and stored in the envelopes for analysis.

Plant growth observations and yield data gathered

1. Visual symptoms of any nutritional disorder.
2. Plant height and tiller number at 8 weeks after seeding.
3. Dry matter yield of 8 week old shoots.
4. Grain yield.
5. Straw yield.

RESULTS AND DISCUSSION

Electro-chemical and Chemical Kinetics of the Soil Solutions

Soil solutions, on all the sampling dates, were collected and analyzed from all the treatments and replications. The mean values of analyses for different treatments are furnished in the Tables 25-43 of the Appendix and the results are illustrated graphically in the following pages. Since the FC and the flooded regimes were studied in the previous experiment with the same soils and the results were discussed in detail, no further discussion will be made on the influence of these two water regimes. To discuss the result of the present experiment, emphasis will be given only for comparing the wet regime with the other two regarding their influence on the soil chemical kinetics and rice growth. For convenience, moist and wet regimes will be collectively referred to as non-flooded when comparing them with the flooded regime.

Electro-chemical kinetics

Redox potential (Eh). Changes in Eh of four soils under three different moisture regimes and of the solutions collected therefrom are presented in Fig. 25 and 26, respectively. All the soils got reduced within 2 to 4 weeks after flooding, and

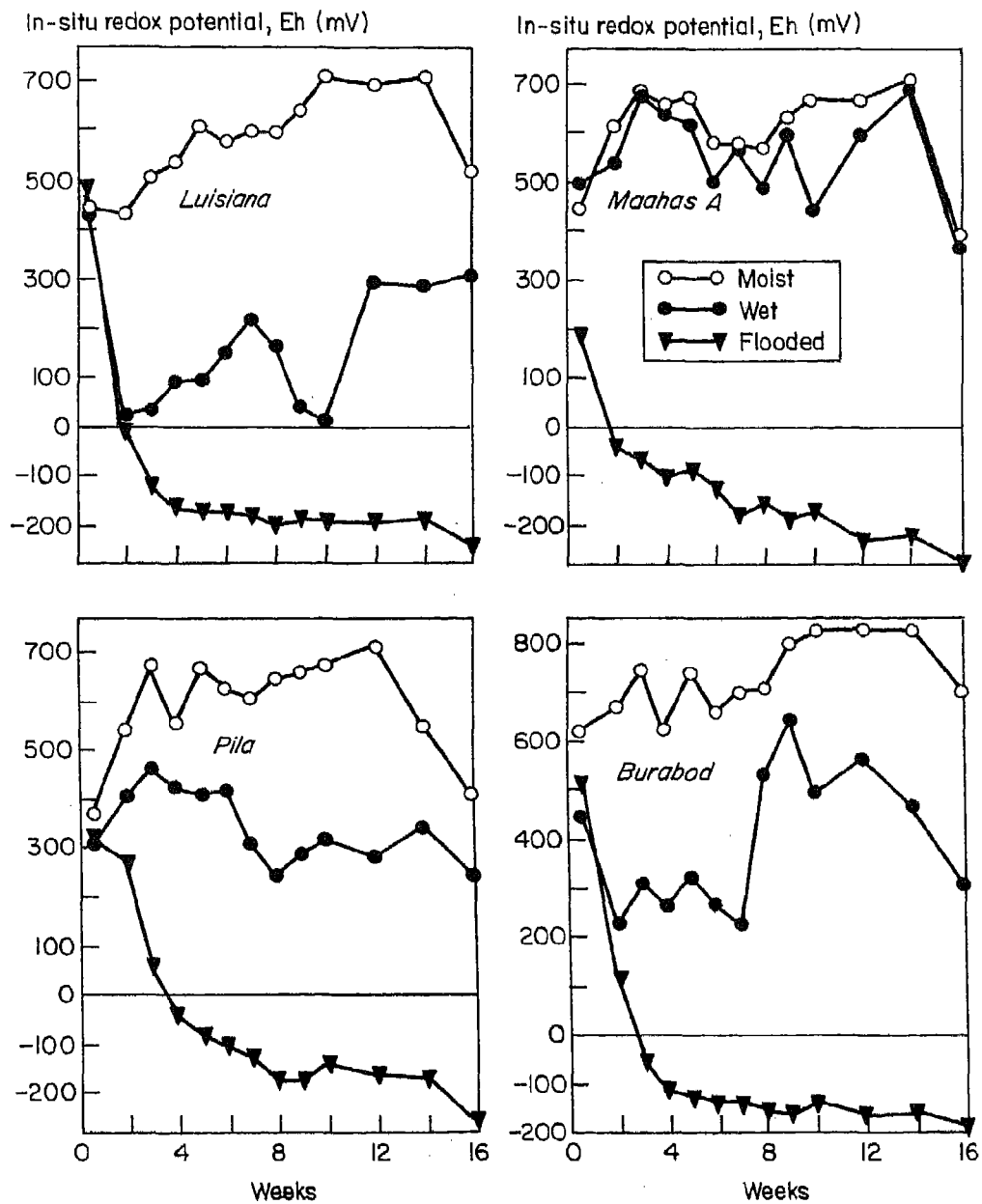


Fig. 25 Kinetics of Eh in four soils under moist, wet and flooded conditions.

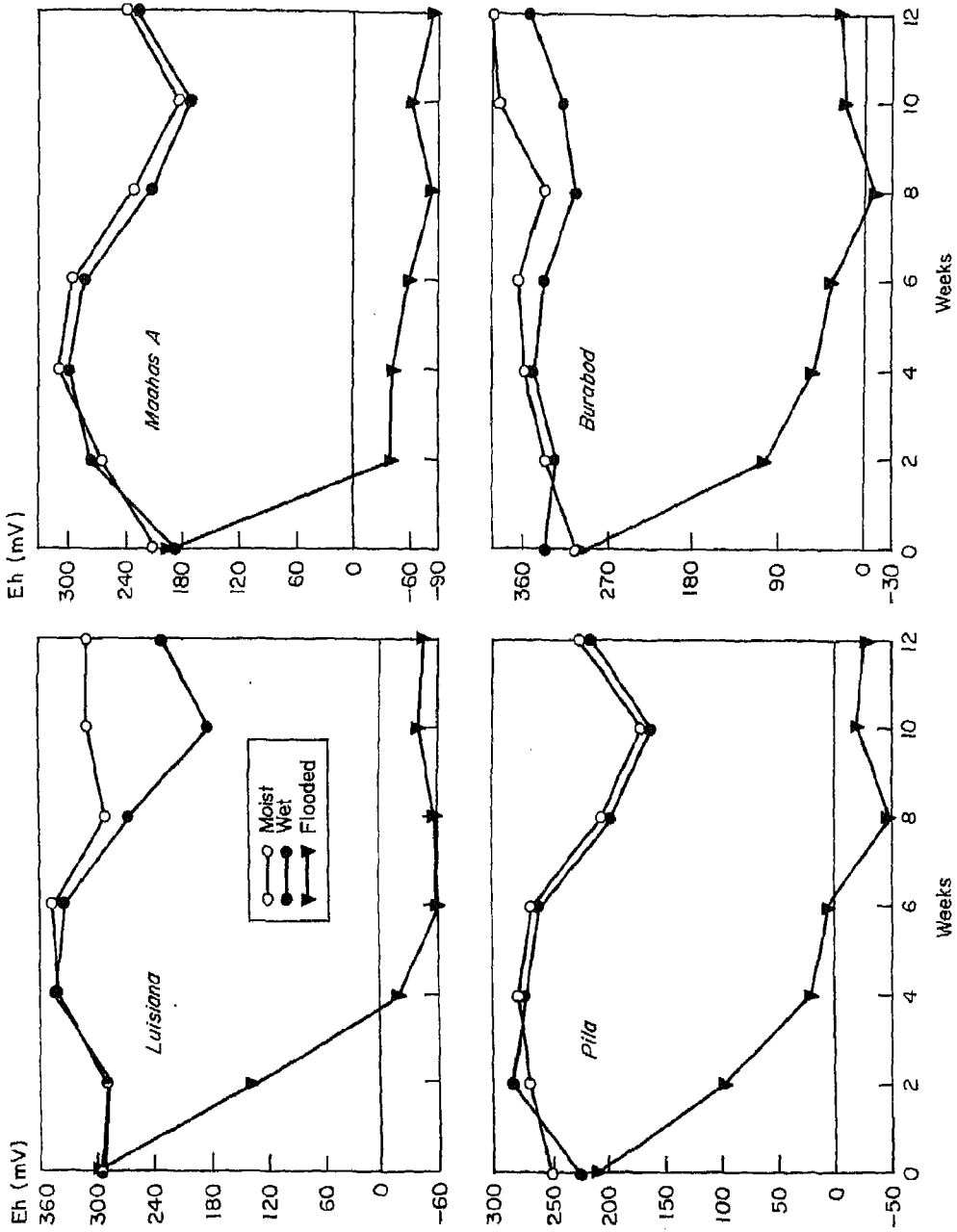


Fig. 26 Kinetics of solution Eh in four soils under moist, wet and flooded conditions.

under the field capacity moisture regimes they indicated oxidized status throughout the experimental period. This observation is in conformity with those of the previous experiment. The soil Eh under wet regimes were lower than that under the moist conditions and indicated moderately reduced status of the Luisiana, Burabod and Pila soils under the wet regimes. Eh of the Maahas A soil, however, did not differ appreciably between the moist and wet regimes.

Measured solution Eh values did not indicate any appreciable difference in redox status of the soils between the moist and wet regimes (Fig. 26). It has been discussed earlier that solution Eh is much more meaningful and reliable index of soil redox condition than the Eh of soil itself (Ponnamperuma 1972). From that point of view, the wet soils were as aerobic as the moist ones under the present experimental conditions.

pH

Figure 27 illustrates the kinetics of solution pH of the soils under three different moisture regimes. While flooding increased pH of the acidic soils and decreased that of the calcareous soil towards neutrality, pH of the non-flooded soils remained within their original ranges throughout the growing season. The initial marked drop in pH of the Maahas A and Pila soils under non-flooded regimes were due to the high degree of

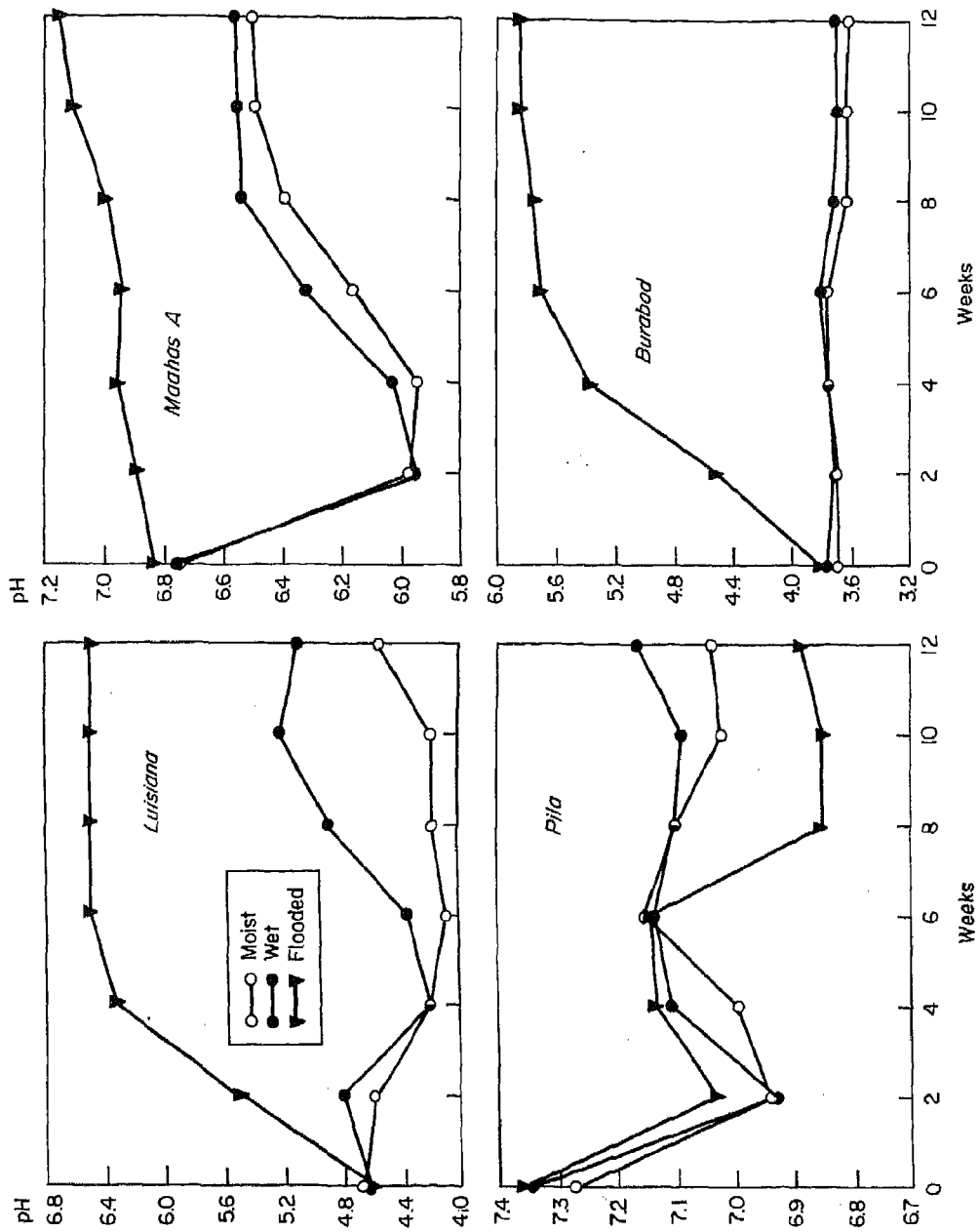


Fig. 27 Kinetics of solution pH in four soils under moist, wet and flooded conditions.

nitrification in them. The NO_3^- -N concentration in the solutions reached from as low as 10-30 ppm at the start to as high as 200-230 ppm after two weeks, under these treatments (Fig. 32).

Marginally higher pH of the non-flooded soils under wet than under the moist regimes were more closely associated with the changes in EC than with the Eh change. The higher pH in the wet soils may be attributed to the decrease in the electrolyte concentration.

Electrical conductivity (EC)

Kinetics of solution EC of the soils under three different moisture regimes are presented in Fig. 28. EC of the Louisiana, Maahas A and Pila soils were higher under flooded than under the non-flooded conditions. Contrastingly, the acid-sulfate soil from Burabod had higher EC under non-flooded than under the flooded condition. This finding is in conformity with that of the previous experiment.

In all the soils, EC was higher under moist than under the wet regime. Washing out of electrolytes due to frequent leaching and their apparent precipitation at the bottom of the receiving bottles might have caused this reduction in EC in the wet soils.

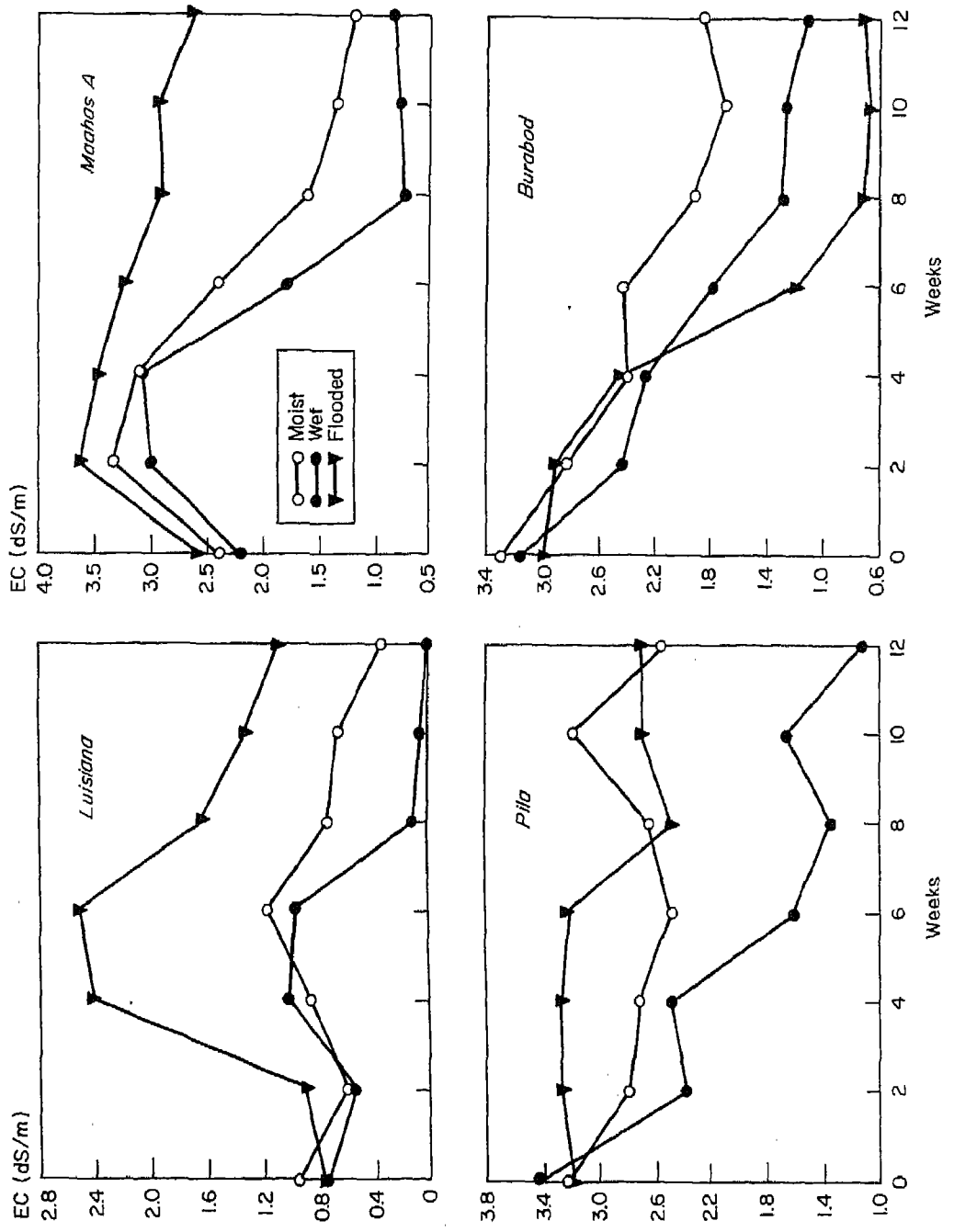


Fig. 28 Kinetics of electrical conductivity in four soils under moist, wet and flooded conditions.

Chemical kinetics

Oxidizable matter. Kinetics of the water-soluble oxidizable matter (Fig. 29) indicates that throughout the growing season, its concentrations in all the four soils were much higher under flooded than under the non-flooded conditions. Under the non-flooded condition, no appreciable difference in the oxidizable matter concentrations was found between the moist and the wet regimes of the soils.

Partial pressure of CO₂ (^PCO₂). Changes in ^PCO₂ in the soils under three different moisture regimes are presented in Fig. 30. The ^PCO₂ increased on flooding to attain a peak of 14 kPa in the Maahas A, 22 kPa in the Pila, 57 kPa in the Luisiana and 72 kPa in the Burabod soils and declined thereafter. Such high values of ^PCO₂ in the flooded acid soils, especially in Burabod soil, might cause CO₂ injury to rice plants (Ponnamperuma 1985, Dent 1986). Under the non-flooded conditions, ^PCO₂ in the Maahas A and Pila soils remained below 4 kPa, whereas in the Luisiana soil it varied between 8 and 28 kPa. The ^PCO₂ were slightly higher under wet than under the moist regimes of Maahas A and Pila soils. In the Luisiana soil, however, this difference in ^PCO₂ between the moist and wet conditions was not consistent.

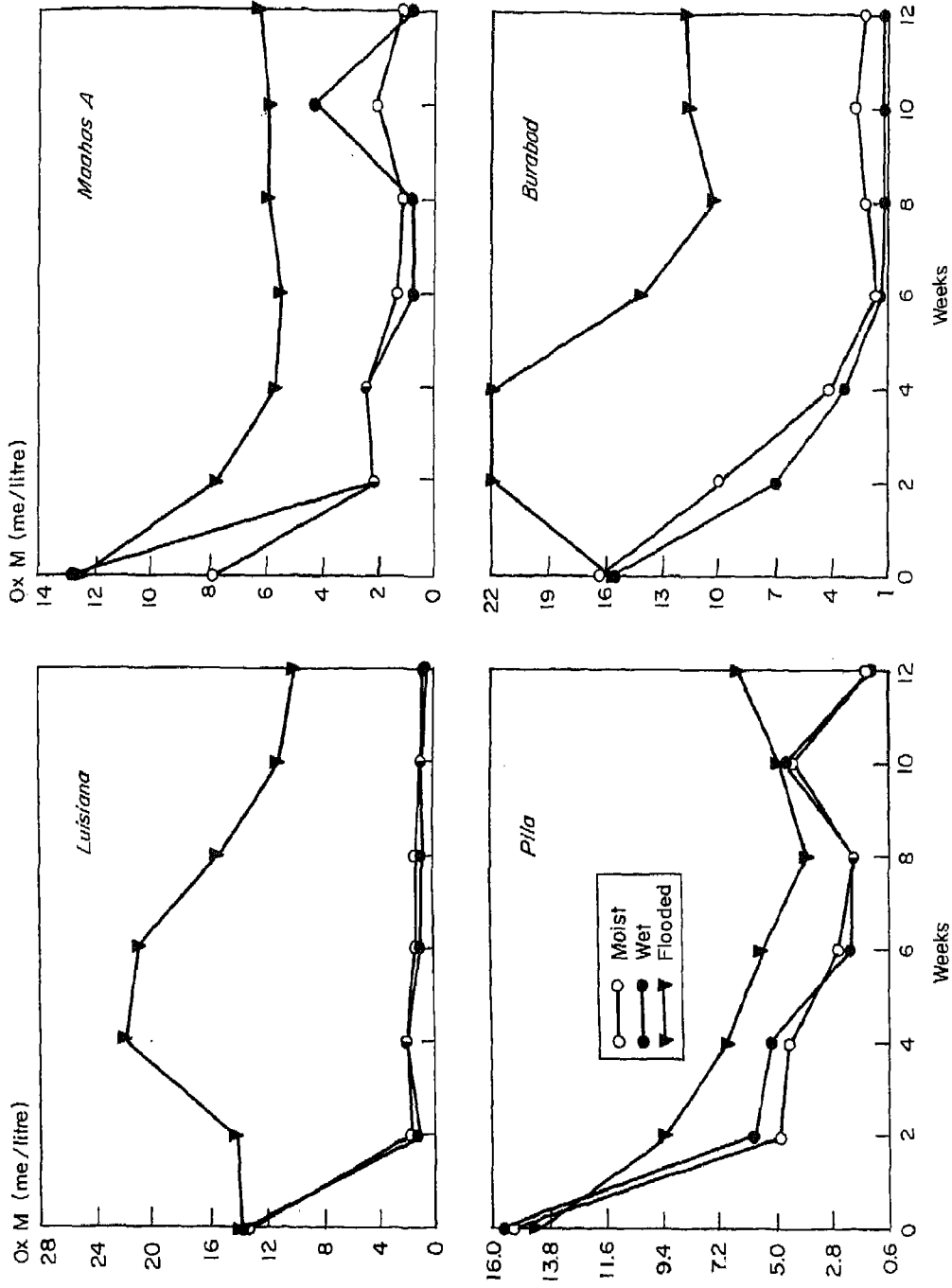


Fig. 29 Kinetics of water-soluble oxidizable matter in four soils under moist, wet and flooded conditions.

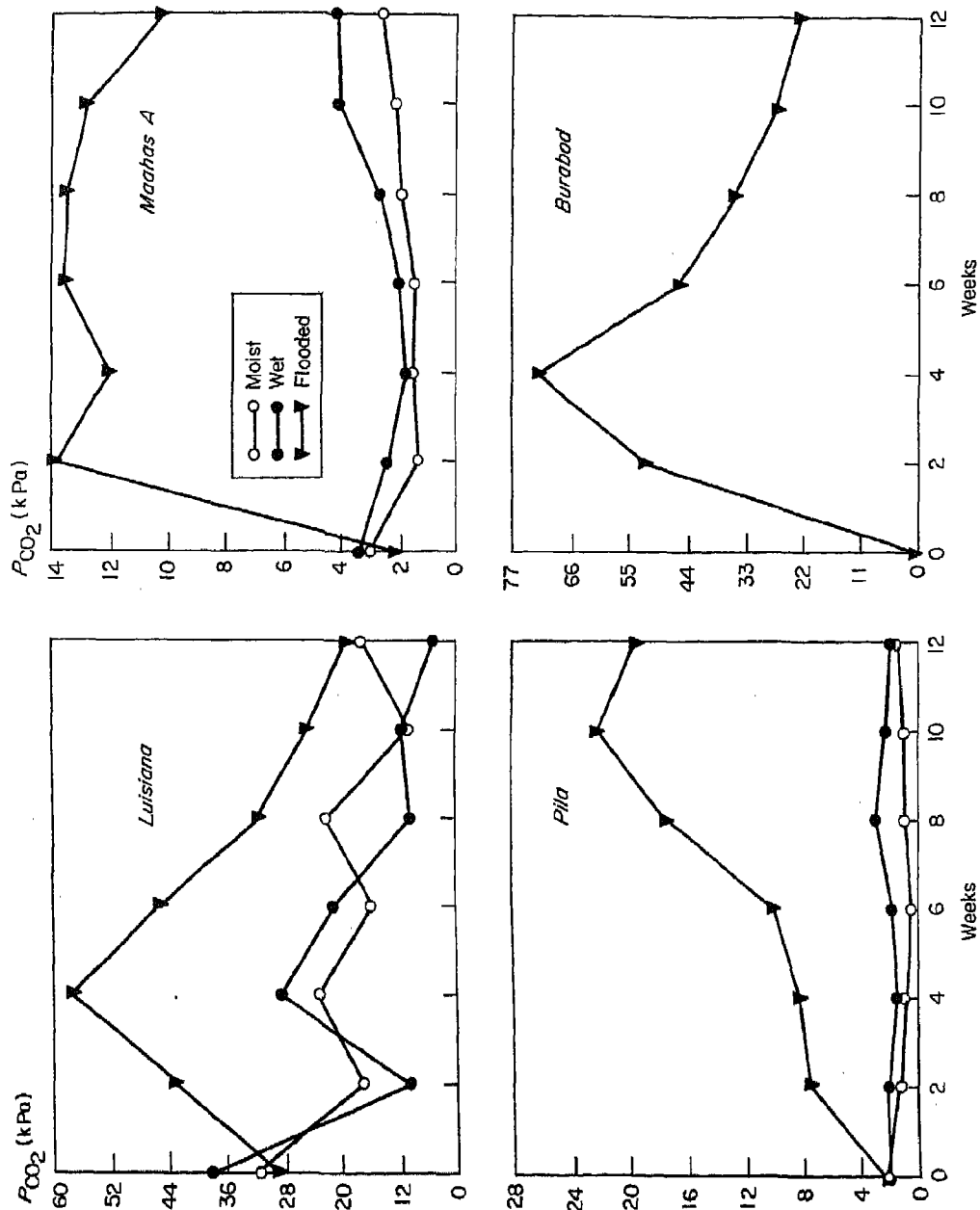


Fig. 30 Kinetics of partial pressure of CO₂ in four soils under moist, wet and flooded conditions.

Nitrogen

Ammonium. Figure 31 shows that the concentrations of water-soluble NH_4^+ -N in Luisiana, Maahas A and Pila soils were much higher under flooded than under non-flooded conditions. In the Burabod soil, however, the average concentrations of NH_4^+ -N during the growing season under the flooded and non-flooded conditions did not differ appreciably.

The moist and wet regimes did not differ appreciably with respect to the concentrations of water-soluble NH_4^+ -N in soils.

Nitrate. Figure 32 illustrates the kinetics of NO_3^- -N concentrations in three soils under three different moisture regimes. Since the concentrations of NO_3^- -N in the Burabod soil were very low irrespective of the moisture regimes (Appendix Table 31), they are not presented here graphically. NO_3^- -N disappeared from all the soils soon after flooding. Under non-flooded conditions, it increased to reach a peak and declined thereafter. The second peak observed in the calcareous Pila soil was due to the topdressing of N at 8 weeks after seeding and virtual absence of plant growth (plants under these treatments were dying of acute Fe chlorosis). Soils under the wet regimes had lower concentration of NO_3^- -N than that under the moist regimes. This lower concentration may be due largely to the higher assimilation by the plants (in case of

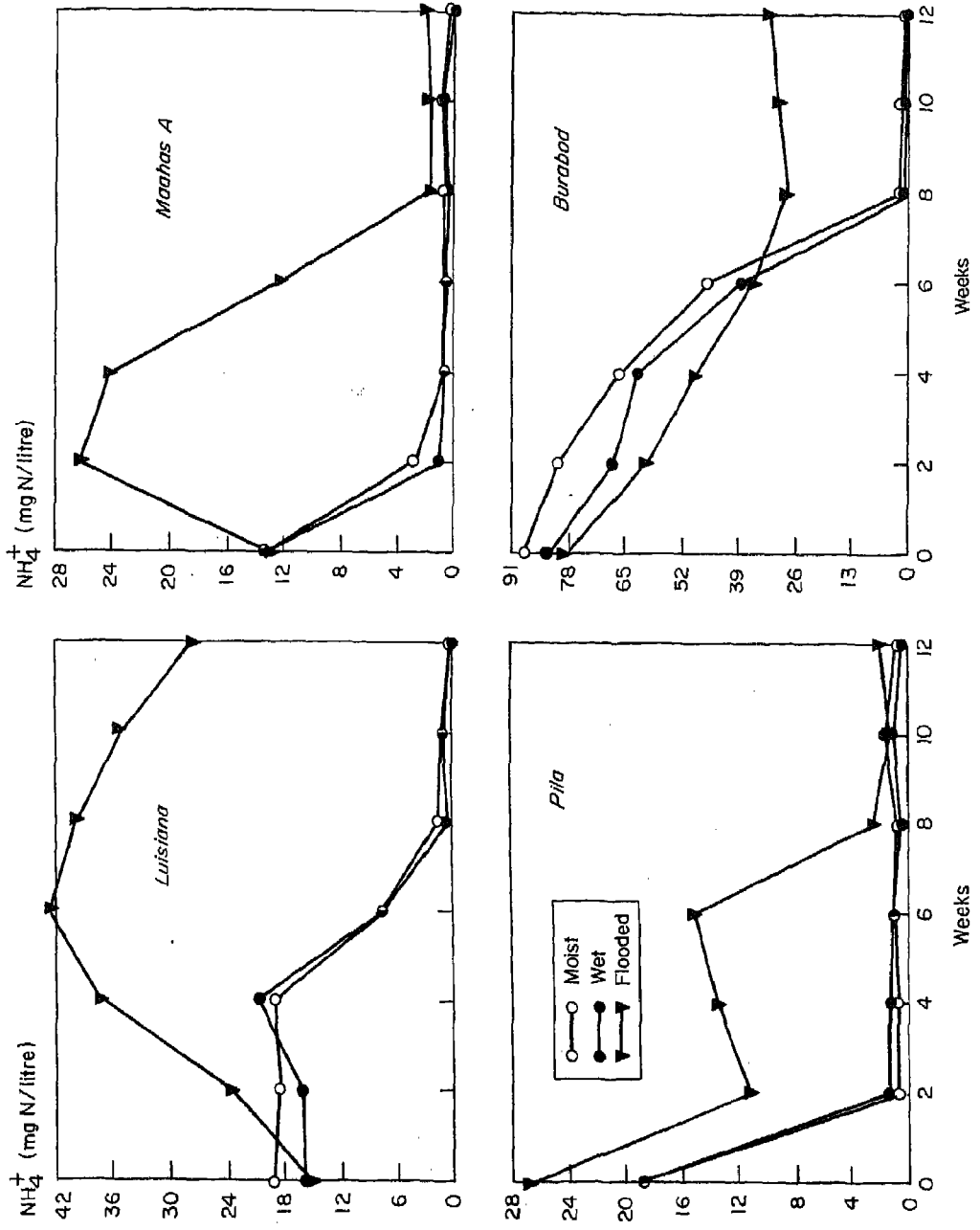


Fig. 31 Kinetics of water-soluble NH_4^+ -N in four soils under moist, wet and flooded conditions.

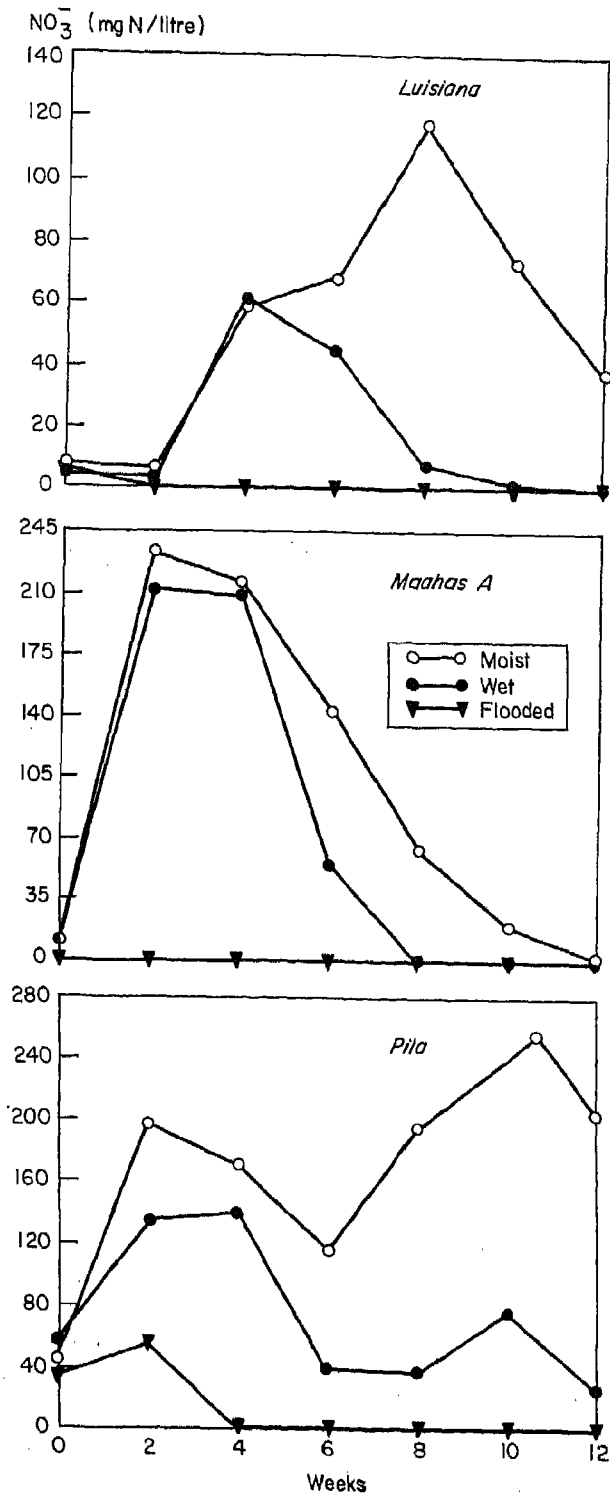


Fig. 32 Kinetics of NO₃⁻-N in the solutions of three soils under moist, wet and flooded conditions.

Luisiana and Maahas A soils), some losses through leaching as well as the denitrification (in the Pila soil) under the wet regimes.

Phosphorus

Changes in concentrations of water-soluble P in four soils under different moisture regimes are shown in Fig. 33. In the Burabod, Maahas A and Pila soils, P concentrations were higher under flooded than under non-flooded conditions. The observed lower concentration of P in the flooded Pila soil beyond 4 weeks and in the flooded Maahas soil beyond 6 weeks may be attributed to the larger assimilation by plants. In fact, plant growth was vigorous under the flooded and almost negligible under the non-flooded condition of the Pila soil. Regardless of the moisture regimes, concentration of water-soluble P was very low in the Luisiana soil and the influence of the moisture regimes was not clear.

No consistent difference in P solubility was found between the moist and wet regimes. In Maahas A and Pila soils, P concentrations under wet regimes were higher than under the moist regimes, whereas in the acidic Luisiana and Burabod soils higher concentrations of P were found under the moist than under wet regimes.

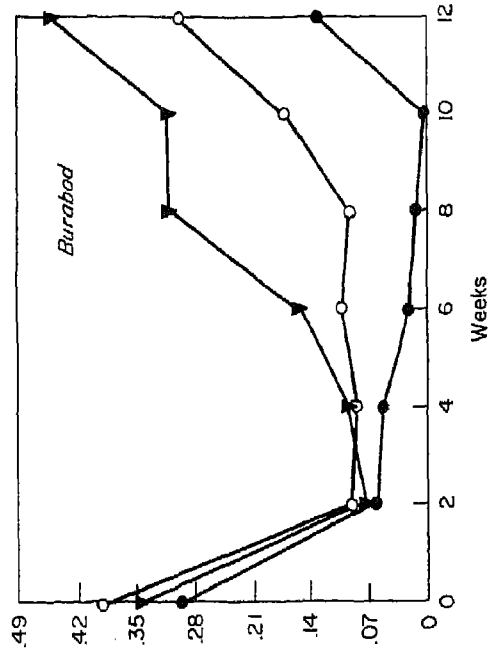
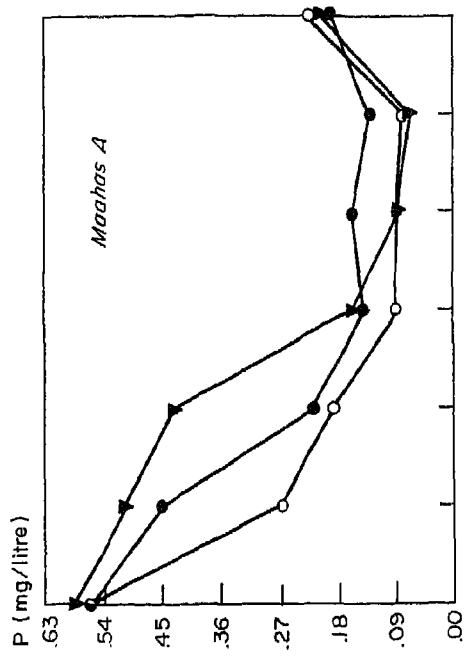
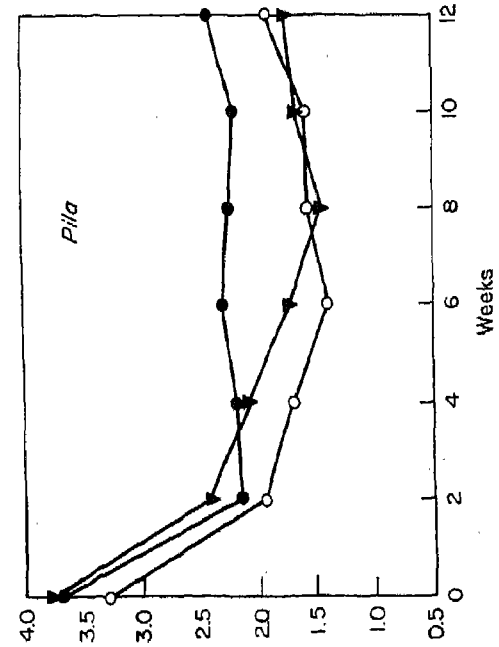
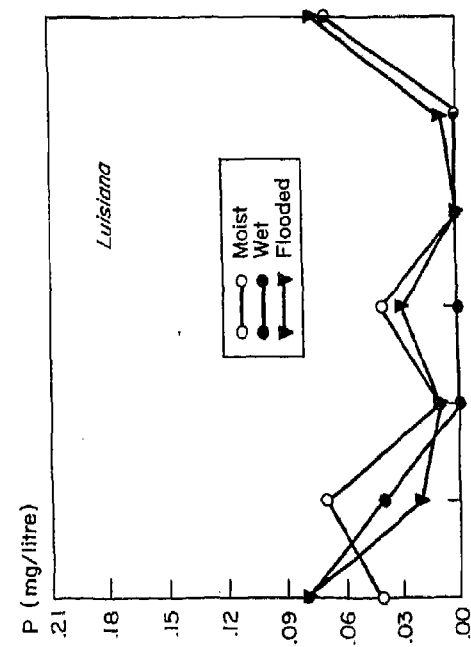


Fig. 33 Kinetics of water-soluble P in four soils under moist, wet and flooded conditions.

Iron

Changes in concentrations of water-soluble Fe in the soils under different moisture regimes throughout the growing season are presented in Fig. 34. On flooding, Fe concentrations increased to reach a peak of about 390 ppm in both the acidic soils within first 4-6 weeks and declined asymptotically thereafter. Peak concentrations of Fe in the flooded Maahas A (40 ppm) and Pila (2.4 ppm) soils reached much later. Under non-flooded conditions, Fe concentrations were very low in all the soils. In the non-flooded Burabod soil, Fe concentration was higher under wet than under the moist regime; whereas in the other soils the moist and wet regimes did not differ notably with respect to their effects on Fe solubility. The observed increase in Fe concentration in the Burabod soil under wet regime might have been due to temporary moderate reduction caused by impeded drainage as well as by the presence of very easily reducible Fe oxides in this soil.

Manganese

Concentrations of water-soluble Mn increased to reach a peak of 45 ppm in the Maahas A, 125 ppm in Luisiana, and 35 ppm in the Pila soil at 2, 4, and 10 weeks after flooding, respectively and declined thereafter (Fig. 35). In the Burabod soil, Mn concentration decreased on flooding. Under non-flooded conditions, concentration of water-soluble Mn were almost

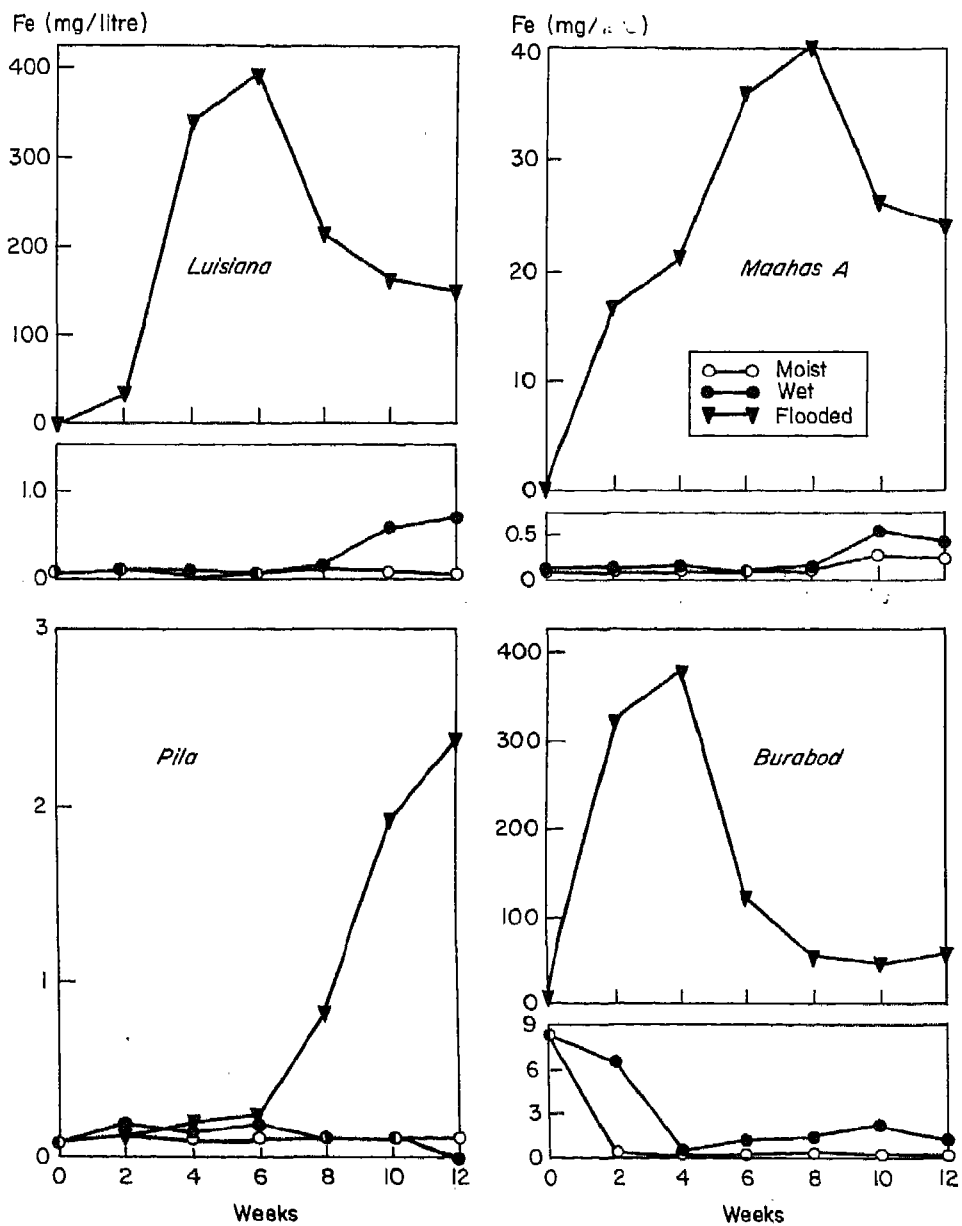


Fig. 34 Kinetics of water-soluble Fe in four soils under moist, wet and flooded conditions.

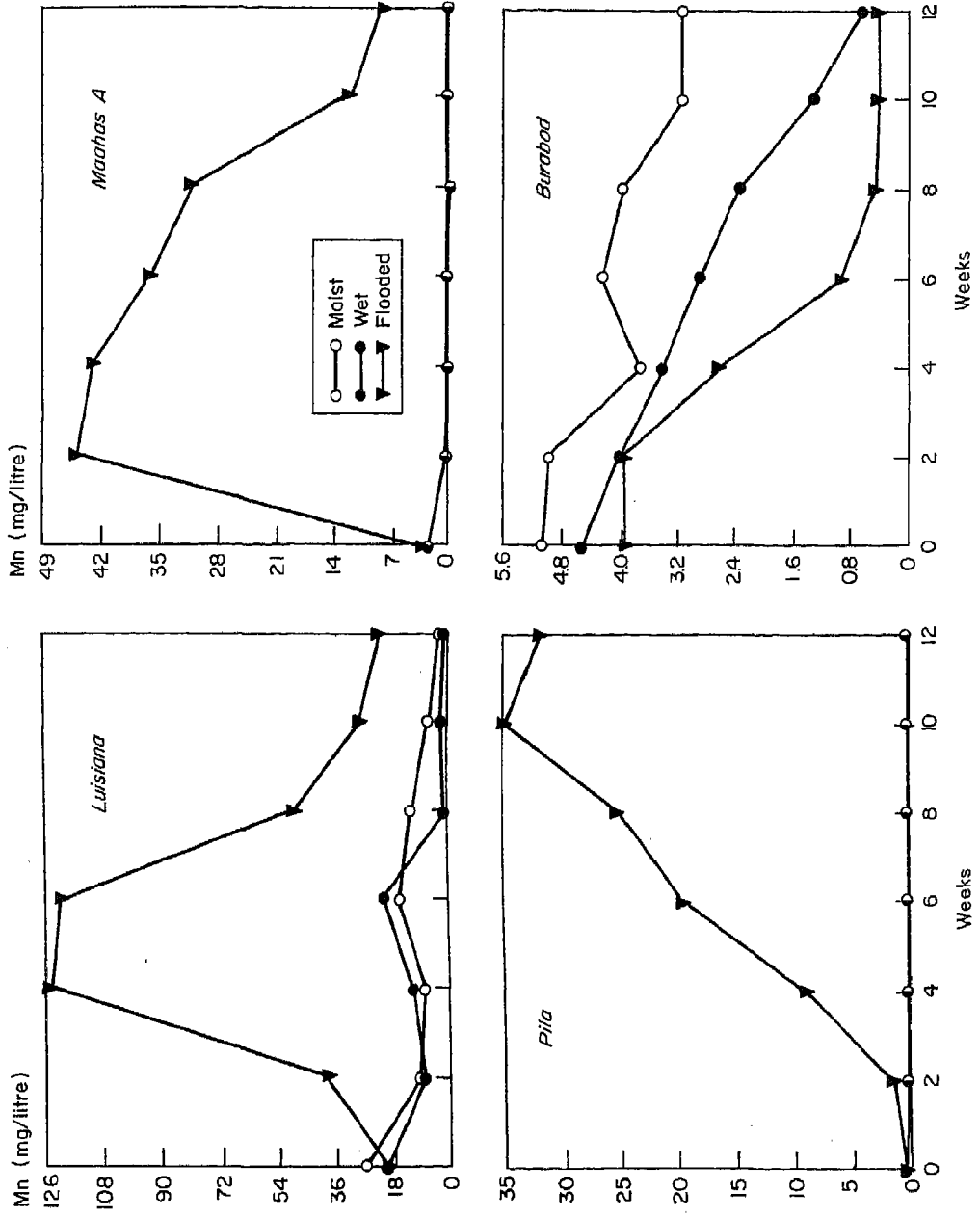


Fig. 35 Kinetics of water-soluble Mn in four soils under moist, wet and flooded conditions.

undetectable in the Maahas A and Pila soils. Although much lower than under the flooded condition, Mn concentration ranged between 2 and 20 ppm in the non-flooded Luisiana soil. No clear difference was noted between the moist and wet regimes with respect to the Mn solubility. In the strongly acidic Burabod soil, solubility of Mn was consistently higher under non-flooded than under the flooded condition. Again, concentration of water-soluble Mn was higher under moist than under wet regime of the Burabod soil, which may be attributed to relatively lower pH of this soil under the moist regime.

Potassium

The kinetics of water-soluble K in four soils under the different moisture regimes are presented in Fig. 36. Concentrations of K in the Luisiana, Maahas A and Pila soils were higher under flooded than under the non-flooded conditions. In case of the Burabod soil, however, the concentration was higher under non-flooded than under flooded condition. This is in conformity with the findings of the previous experiment.

In all the non-flooded soils, K concentration was slightly higher under the moist than under the wet regime. This difference may be attributed to the greater assimilation by the plants growing more vigorously under the wet regime.

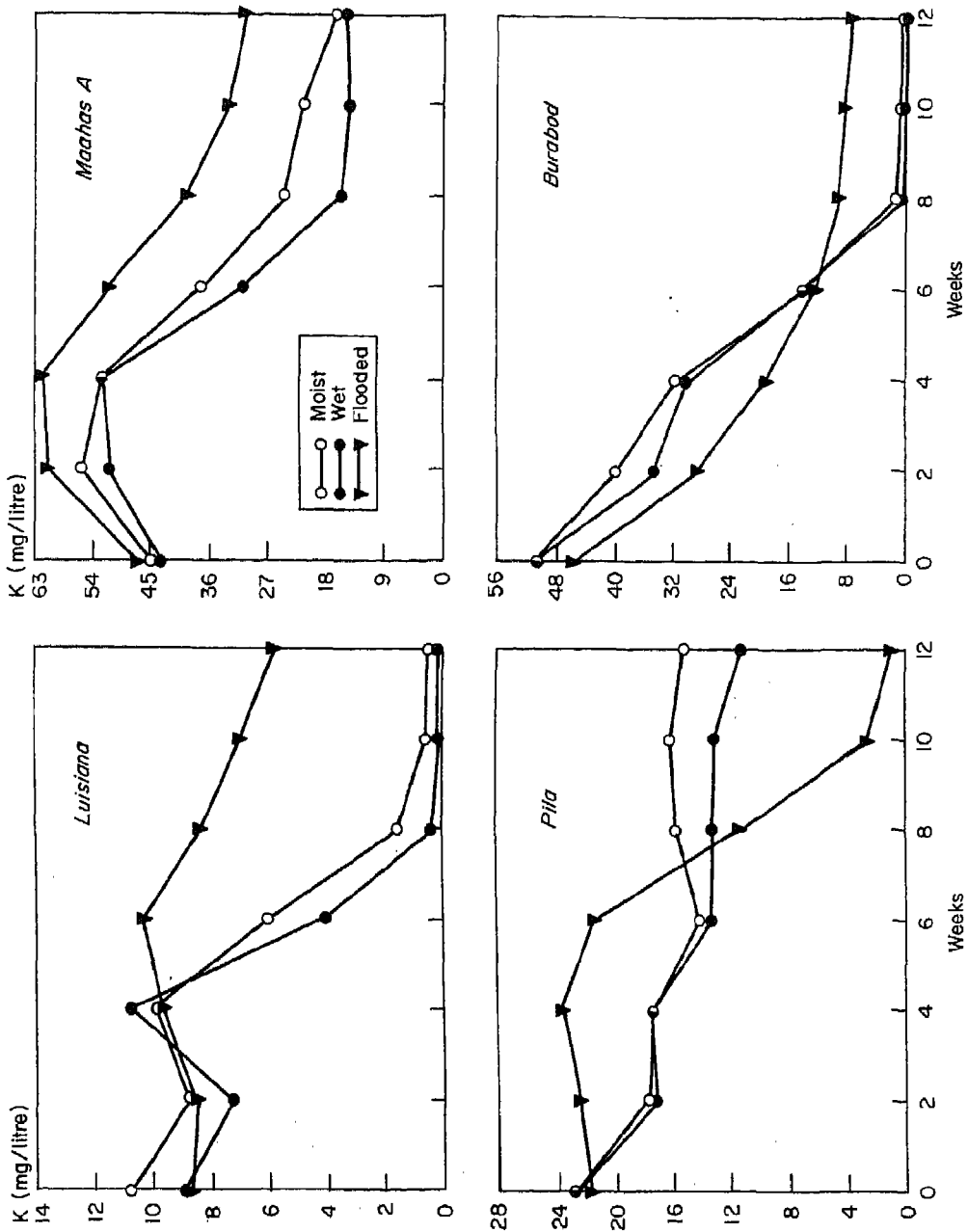


Fig. 36 Kinetics of water-soluble K in four soils under moist, wet and flooded conditions.

Calcium, Magnesium and Sodium

Figure 37, 38 and 39 present the kinetics of water-soluble Ca, Mg and Na in the soils under different water regimes. In the Luisiana, Maahas A and Pila soils, concentrations of these cations were higher under the flooded than under the non-flooded conditions. In the Burabod soil, however, the concentrations were higher under non-flooded than under the flooded conditions, in close agreement with the findings of the previous experiment.

Again, in all the non-flooded soils, the concentrations of Ca, Mg and Na were appreciably higher under moist than under the wet regimes. This may be attributed to washing out of their salts due to frequent leaching and their apparent precipitation at the bottom of the receiving bottles as well as the higher assimilation by growing plants. The observed lower EC in wet than in moist regimes support this contention.

Silicon

Figure 40 illustrates the kinetics of water-soluble Si in the soils under different moisture regimes. The calcareous Pila soil had higher concentration of Si under flooded than under non-flooded conditions. The decreased concentration observed after 6 weeks under the flooded condition could be attributed to the assimilation by growing plants, because plant growth under

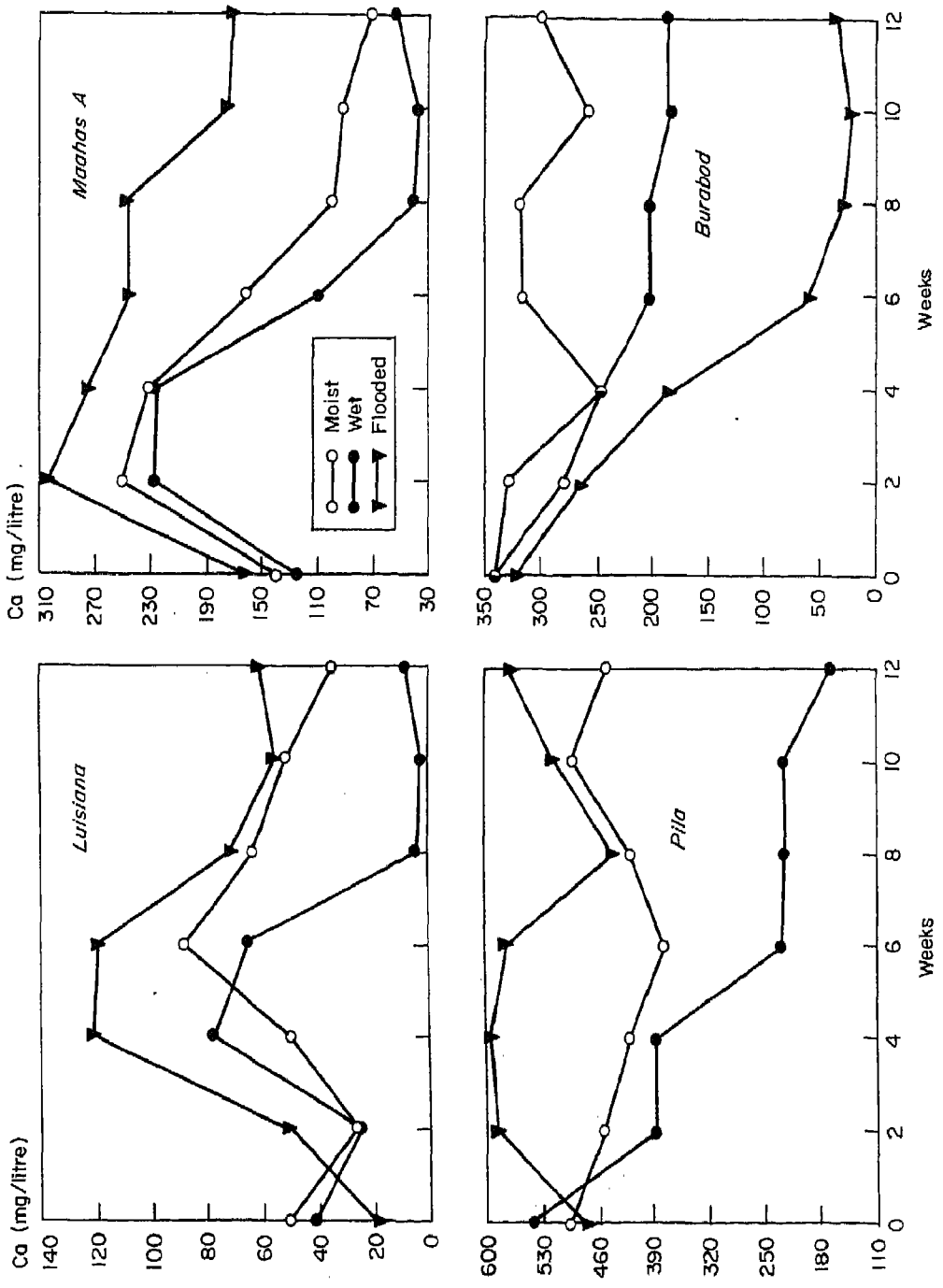


Fig. 37 Kinetics of water-soluble Ca in four soils under moist, wet and flooded conditions.

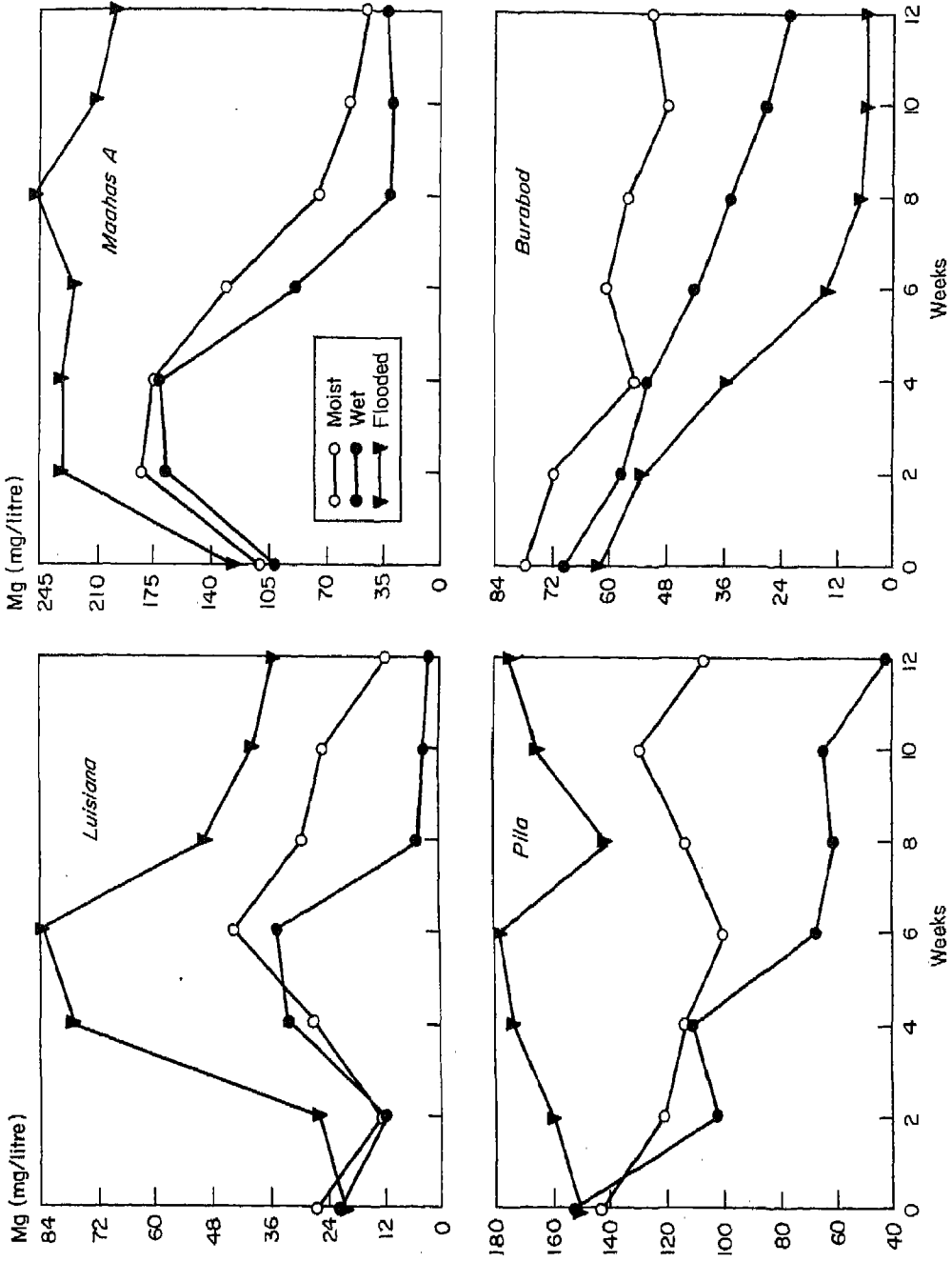


Fig. 38 Kinetics of water-soluble Mg in four soils under moist, wet and flooded conditions.

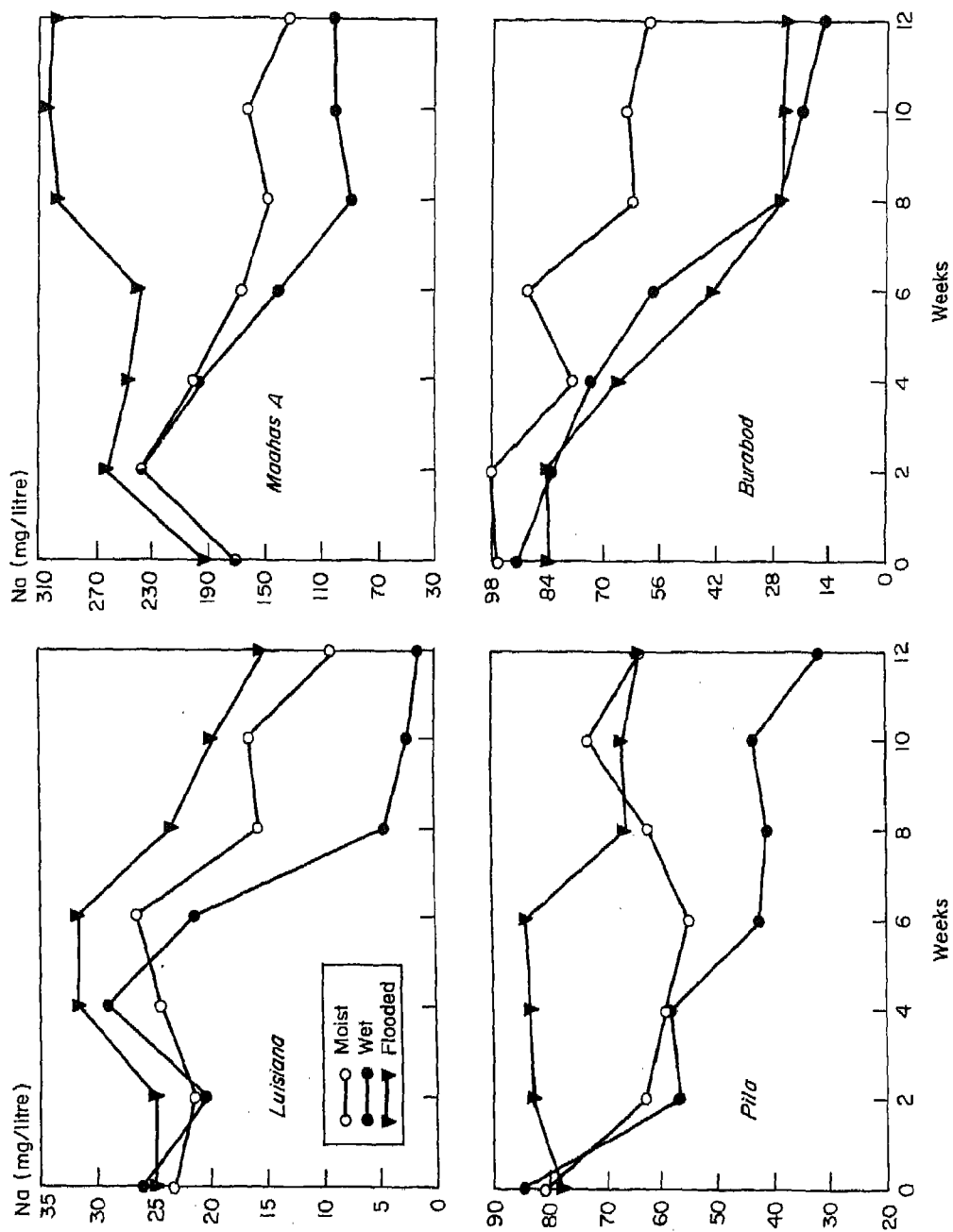


Fig. 39 Kinetics of water-soluble Na in four soils under moist, wet and flooded conditions.

flooded condition was vigorous compared to negligible growth under the non-flooded regime. Under non-flooded conditions, Si solubility was higher in the wet than in moist regime of this soil.

In the Luisiana, Maahas A and Burabod soils, concentrations of Si were found to be higher under non-flooded than under the flooded conditions. No appreciable difference in the solubility of Si was noted between the moist and wet regimes of these soils upto first six weeks. The subsequent lower concentration of Si observed under the wet regime might have been caused by larger uptake by plants growing vigorously under this treatment.

Zinc

As the concentrations of water-soluble Zn in the Maahas A and Pila soils were very low and the moisture regimes did not appear to have any appreciable effect on them (Appendix Table 38), they are not presented graphically. Figure 41 shows that solubility of Zn in the acidic soils from Luisiana and Burabod were higher under non-flooded than under flooded conditions. Again in both the non-flooded soils, Zn concentration was higher under moist than under the wet regimes. This may be attributed to relatively lower pH of these soils and lower assimilation by plants under the moist conditions.

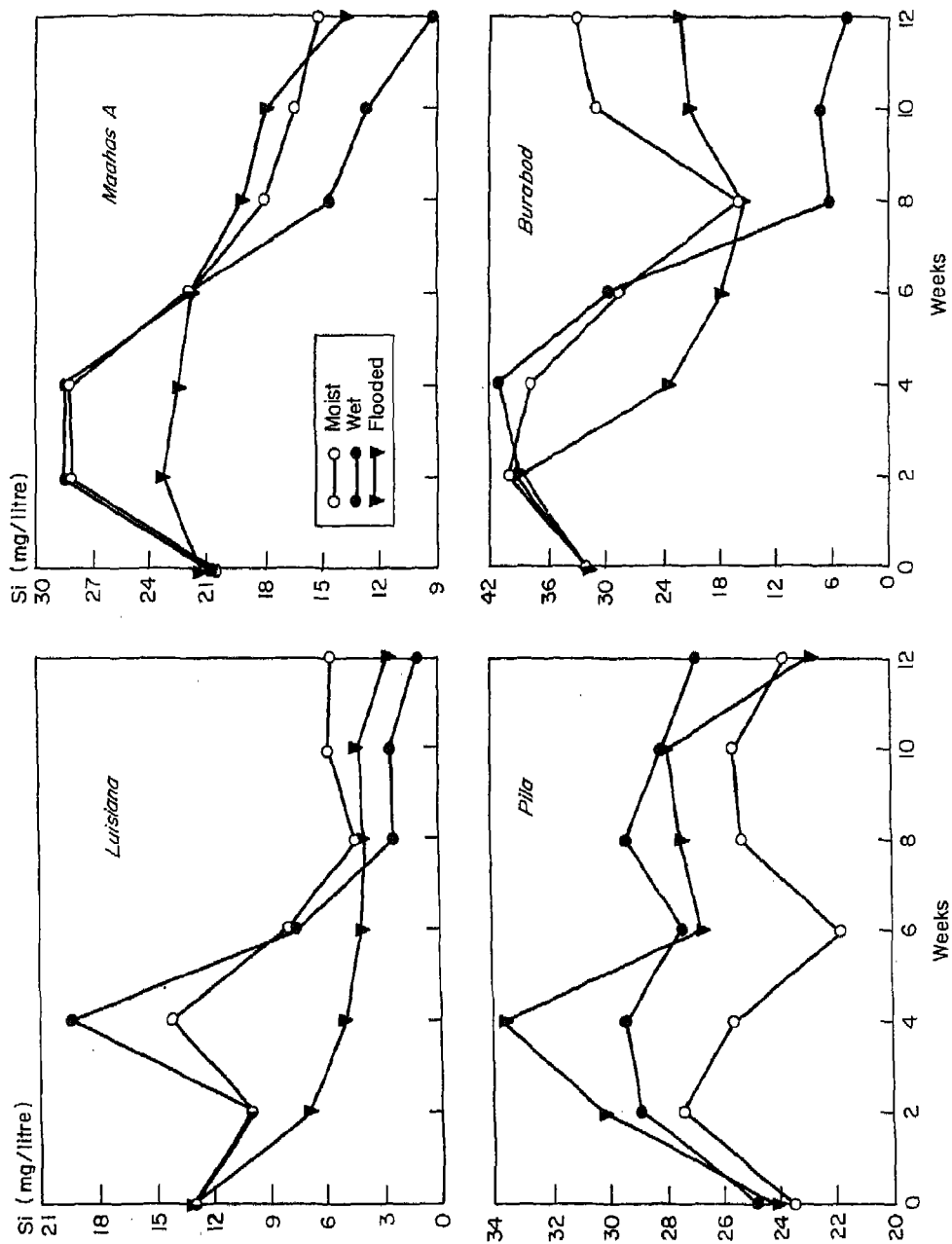


Fig. 40 Kinetics of water-soluble Si in four soils under moist, wet and flooded conditions.

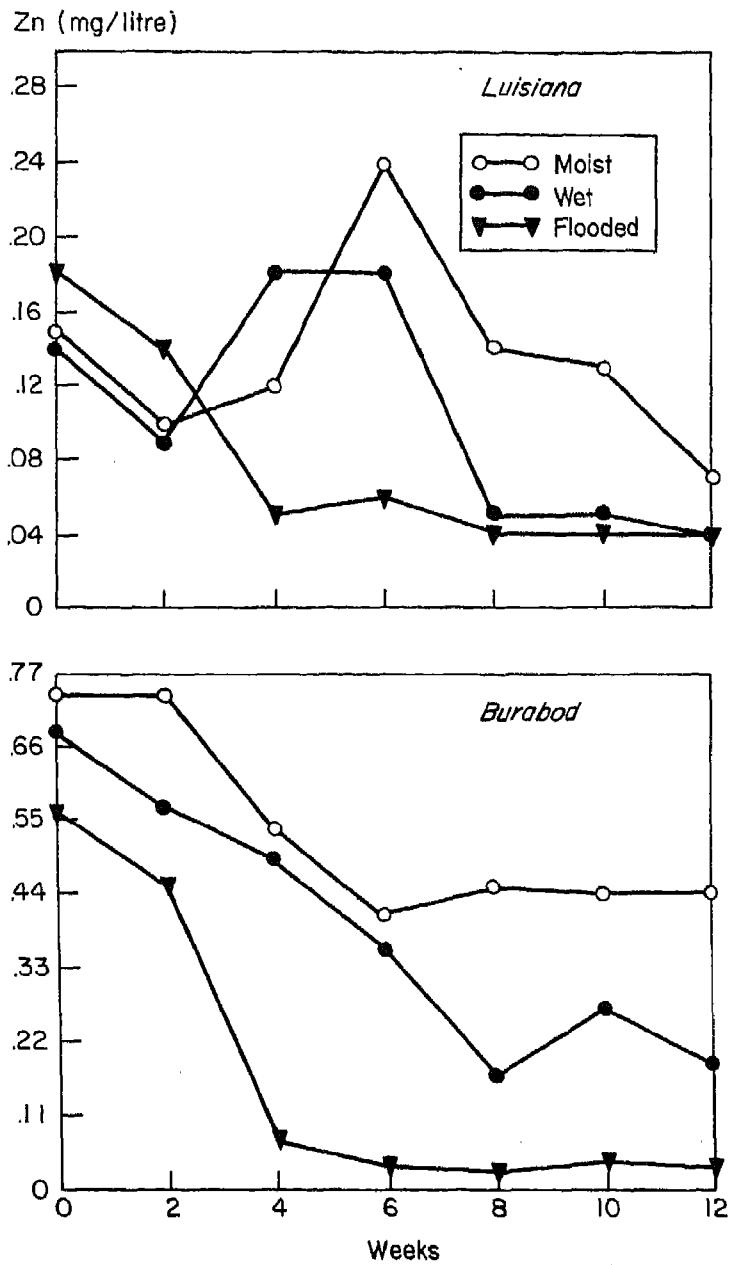


Fig. 41 Kinetics of water-soluble Zn in two soils under moist, wet and flooded conditions.

Copper

Since the concentrations of water-soluble Cu in the Luisiana, Maahas A and Pila soils were very low regardless of the moisture regimes (Appendix Table 39), they are not shown graphically.

The Figure 42 shows kinetics of the concentration of Cu in the Burabod soil. In this acidic soil, solubility of Cu was much lower under flooded than under the non-flooded condition. Under non-flooded condition, again, the solubility was higher under moist than under wet regime. This difference may be attributed to relatively lower pH and lower uptake by plants under the moist regime.

Aluminum

Changes in concentrations of water-soluble Al in the two acidic soils under three different moisture regimes are shown in Fig. 43. The figure indicates that solubility of Al in both the Luisiana and Burabod soils decreased to zero within 2-4 weeks after flooding. Under non-flooded conditions, its concentration ranged between 0.1 and 1.1 ppm in the Luisiana and between 9 and 36 ppm in the Burabod soil. Concentrations under wet regimes were lower than that under the moist regimes, which might be due to relatively higher pH and higher assimilation by plants under the wet regimes.

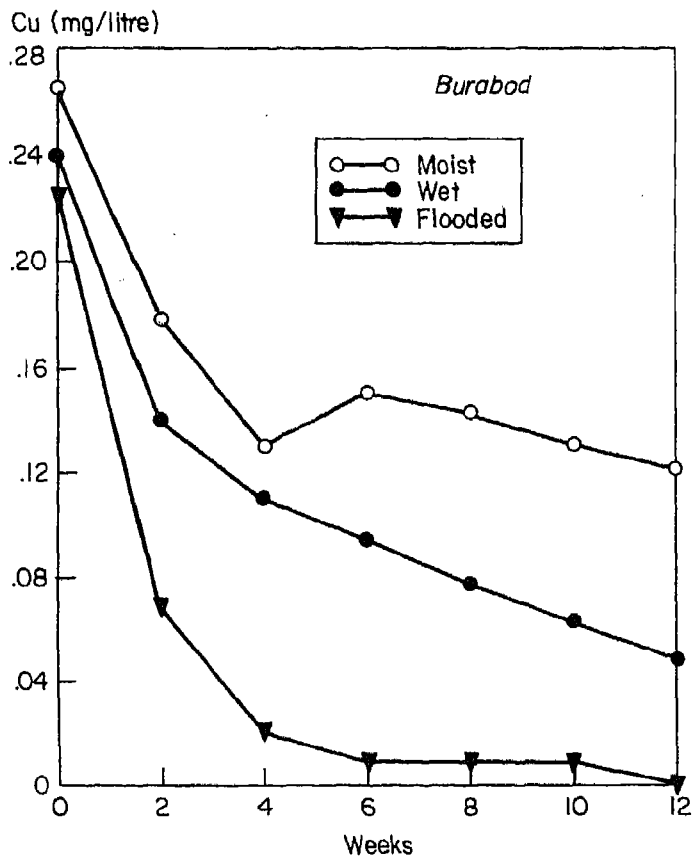


Fig. 42 Kinetics of water-soluble Cu in an acid soil under moist, wet and flooded conditions.

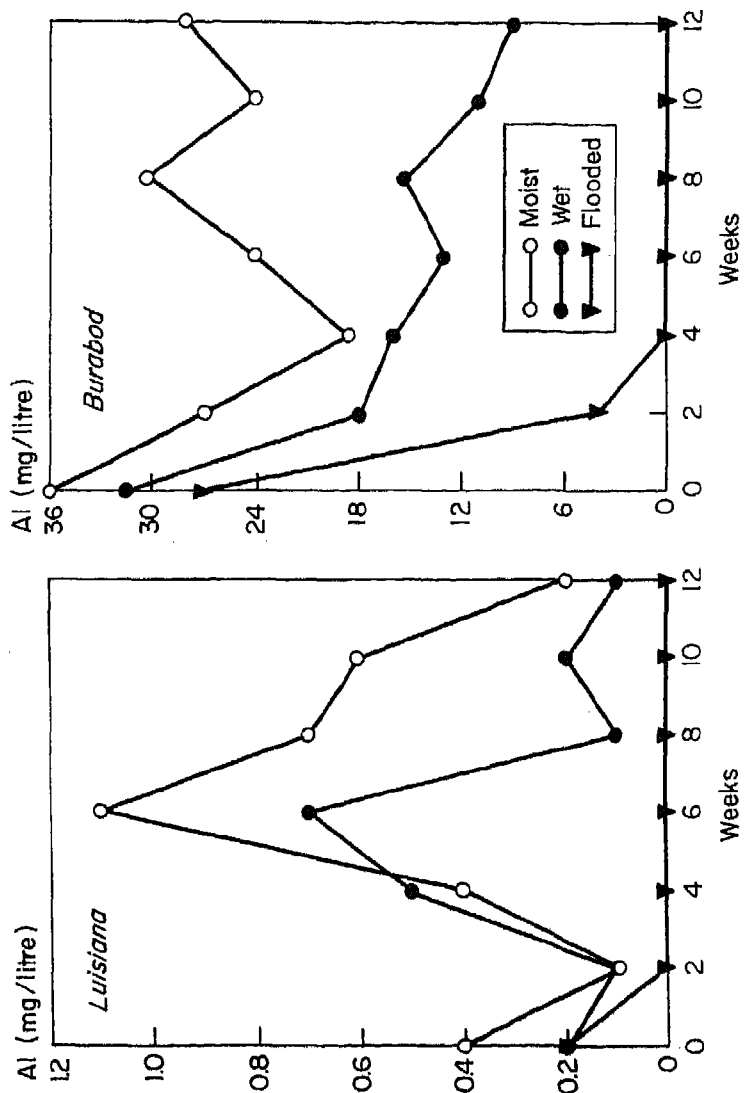


Fig. 43 Kinetics of water-soluble Al in two acid soils under moist, wet and flooded conditions.

To summarize results of the chemical kinetics study: chemical environments of non-flooded soils would not change appreciably with the amount of water supply, as long as they are drained freely. Thus abundant supply of water to typical upland rice fields may not cause any measurable improvement in their chemical regime.

Mineral Nutrition of IR43
Under Three Different Moisture Regimes

Since the plants in the calcareous Pila soil died of severe Fe chlorosis under the moist and wet regimes, they could not be analysed for the mineral constituents. The 8 week old shoots and straw at harvest from the Luisiana, Maahas A and Burabod soils were analyzed for mineral nutrients. Grain samples were also analysed for estimating total uptake of nutrients by the plants at harvest. The concentrations of nutrients in the shoot and straw samples are presented in Tables 10 and 12, respectively. Total nutrient uptake by the shoots and plants at harvest (straw plus grain) are furnished in Tables 11 and 13, respectively.

Total dry matter yields (shoot as well as plant at harvest) under flooded conditions were nearly half of that under the non-flooded conditions in both the strongly acidic Luisiana and Burabod soils. Very high concentration of Fe in soil solutions and excessive uptake of Fe in plants caused Fe toxicity leading

to such poor yields and lower uptake of several other nutrients in these two soils under flooded regimes. In the near-neutral Maahas A soil, however, plants grew normally and gave much higher yield under flooded regime. In this case, concentrations of the nutrients in tissue could be influenced by dilution factor. The results are discussed under the following heads:

Nitrogen

In both the acidic soils (from Luisiana and Burabod), concentrations of N in shoot as well as straw were highest under flooded regimes, followed by the moist and wet regimes. In the near-neutral Maahas A soil, tissue N concentration was highest under the moist regime, followed by wet and flooded regimes.

Scrutiny of total N uptake data indicates that the observed differences in N concentrations in plants under different moisture regimes of the soils were mainly due to differences in total dry matter yields.

Phosphorus

The 8 week old shoots in the Maahas A and Burabod soil had significantly higher concentration of P under flooded than under the non-flooded regimes, but in the Luisiana soil the moisture regimes did not show any effect on tissue P concentration. The moist and wet regimes did not differ appreciably regarding their effects on P availability to plants.

Table 10. Concentration of mineral nutrients in 8 week old shoot of IR43 grown in three soils under moist, wet and flooded conditions.^a

| Soil | Treatment Moisture regime | % | | | | | | | | | | mg/kg | | | | |
|-----------|---------------------------------|--------|---------|--------|---------|---------|------------------|--------|--------|--------|-------|-------|--|--|--|--|
| | | N | P | K | Ca | Mg | SiO ₂ | Na | Fe | Mn | Zn | Cu | | | | |
| Louisiana | Moist | 3.18 b | .169 e | 3.3 b | .248 a | .499 c | 6.59 d | 163 e | 138 d | 1475 b | 44 ab | 29 c | | | | |
| | Wet | 3.12 b | .178 e | 2.7 cd | .254 a | .639 ab | 7.00 d | 275 d | 173 c | 1838 a | 40 b | 33 b | | | | |
| | Flooded | 3.44 a | .168 e | 2.5 de | .243 a | .249 g | 5.23 e | 450 b | 233 b | 1900 a | 25 cd | 11 f | | | | |
| Maahas A | Moist | 3.01 b | .218 c | 4.2 a | .210 bc | .427 d | 11.01 b | 150 e | 148 cd | 54 f | 25 cd | 19 de | | | | |
| | Wet | 2.23 d | .221 bc | 4.1 a | .170 d | .377 e | 12.39 a | 163 e | 162 cd | 48 f | 20 d | 20 d | | | | |
| | Flooded | 1.95 e | .257 a | 4.2 a | .153 d | .258 g | 9.95 c | 350 c | 171 c | 725 c | 20 d | 16 de | | | | |
| Buraobod | Moist | 3.45 a | .201 d | 2.8 c | .215 b | .602 b | 9.41 c | 188 e | 170 c | 369 e | 50 a | 36 ab | | | | |
| | Wet | 2.56 c | .196 d | 2.4 e | .197 c | .662 a | 9.75 c | 438 b | 180 c | 520 d | 51 a | 39 a | | | | |
| | Flooded | 3.56 a | .231 b | 2.4 e | .222 b | .329 f | 4.98 e | 1713 a | 630 a | 94 f | 30 c | 15 e | | | | |

^aMean of 4 replications. In a column, means followed by a common letter are not significantly different by DMRT at the 5% level.

P concentration in straw was found to be significantly lower under flooded than under non-flooded, and under wet than the moist regimes of all the soils. This lower concentration of P in the flooded Maahas A could be attributed to the dilution in plants, since total uptake was highest under the flooded regimes, followed by the wet and moist regimes (Table 13). Significantly lower total P uptake under the flooded regimes of both the acidic soils were probably caused by an antagonistic interaction of P with very high concentration of Fe. Straw in both the acidic soils under flooded regime had toxic concentrations of Fe.

Potassium

Concentration and total uptake of K in 8 week old shoots in the acidic Luisiana and Burabod soils were lowest under flooded and highest under the moist regimes. In the near-neutral Maahas A soil, K concentration in shoot did not vary with the moisture regimes, but total uptake was significantly higher under the flooded condition.

Very high concentrations of Fe and Mn present in the solution might have adversely affected the K availability to plants in the flooded acid soils. Data on total K uptake by plants at maturity also suggest significantly lower availability of K to plants in these acid soils under flooded regime. Total

Table 11. Total uptake of mineral nutrients by 8 week old shoot of IR43 grown in three soils under moist, wet and flooded conditions.^a

| Soil | Treatment | | N | K | SiO ₂ | P | Ca | Mg | Na | Fe | Mn | Zn | Cu |
|----------|-----------------|---------|--------|--------|------------------|---------|----------|---------|---------|--------|---------|--------|----|
| | Moisture regime | g/pot | | | | | | | | | | | |
| Luisiana | Moist | 0.82 b | 0.84 c | 1.70 d | 43.4 c | 63.9 bc | 129.2 c | 4.21 ef | 3.52 de | 38.1 b | 1.12 ab | 748 b | |
| | Wet | 1.02 a | 0.87 c | 2.28 c | 57.9 b | 82.9 a | 208.8 a | 8.95 cd | 5.62 b | 59.9 a | 1.30 a | 1055 a | |
| | Flooded | 0.49 de | 0.36 f | 0.74 e | 23.8 d | 34.4 fg | 35.2 f | 6.36 de | 3.29 e | 27.0 c | 0.35 c | 148 e | |
| Maahas A | Moist | 0.61 c | 0.85 c | 2.22 c | 44.0 c | 42.1 ef | 85.8 e | 3.02 f | 2.98 e | 1.0 e | 0.50 c | 372 d | |
| | Wet | 0.58 cd | 1.06 b | 3.22 b | 57.2 b | 44.3 e | 97.8 de | 4.19 ef | 4.19 cd | 1.2 e | 0.52 c | 515 c | |
| | Flooded | 0.90 b | 1.93 a | 4.58 a | 118.5 a | 70.5 b | 118.6 cd | 16.12 b | 7.88 a | 33.3 b | 0.92 b | 715 b | |
| Burabod | Moist | 0.89 b | 0.71 d | 2.43 c | 51.7 bc | 55.2 cd | 155.1 b | 4.80 ef | 4.39 c | 9.5 d | 1.29 a | 934 a | |
| | Wet | 0.64 c | 0.59 e | 2.44 c | 49.3 bc | 49.2 de | 165.9 b | 10.96 c | 4.52 c | 13.0 d | 1.28 a | 972 a | |
| | Flooded | 0.41 e | 0.28 f | 0.59 e | 26.9 d | 25.8 g | 38.4 f | 20.10 a | 7.27 a | 1.1 e | 0.35 c | 167 e | |

^aMean of 4 replications. In a column, means followed by a common letter are not significantly different by DMRT at the 5% level.

uptake data further indicates no consistent difference in K availability between the moist and wet regimes of the acid soils.

Calcium

Concentrations of Ca in 8 week old shoot did not differ markedly with moisture regimes in the acidic soils. The significantly lower total uptake in the shoots as well as mature plants in these flooded soils were closely associated with poor dry matter yield and very high concentration of Fe in the tissues.

In the near-neutral Maahas A soil, however, total Ca uptake by the shoots as well as plants at harvest were significantly higher under flooded than under non-flooded regimes. The concentrations in tissues were largely influenced by the dilution factor.

Examination of concentration and total uptake data does not indicate any consistent difference in Ca availability between the moist and wet regimes.

Magnesium

Concentrations of Mg in the shoots as well as straw were significantly lower under flooded than under the non-flooded regimes of all the soils. No consistent difference in Mg concentrations was noted between the moist and wet regimes.

Table 12. Concentration of mineral nutrients in straw of IR43 grown in three soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | % | | | | | | | mg/kg | | | |
|----------|------------------------------|--------|---------|--------|---------|--------|------------------|---------|--------|--------|------|--|
| | | N | P | K | Ca | Mg | SiO ₂ | Na | Fe | Mn | Cu | |
| Luisiana | Moist | 1.59 c | .167 b | 1.4 d | .348 b | .867 a | 11.33 f | 1188 e | 184 de | 2650 b | 19 c | |
| | Wet | 0.95 d | .077 f | 1.6 cd | .425 a | .662 b | 12.60 e | 2200 cd | 218 cd | 3463 a | 20 c | |
| | Flooded | 2.29 a | .094 de | 1.5 d | .269 c | .224 d | 11.99 ef | 2400 c | 390 b | 1963 c | 12 e | |
| Maahas A | Moist | 0.99 d | .179 b | 2.7 b | .201 ef | .339 c | 11.94 ef | 88 f | 136 e | 80 f | 14 d | |
| | Wet | 0.60 e | .102 d | 3.9 a | .185 f | .359 c | 18.21 a | 138 f | 216 cd | 105 f | 18 c | |
| | Flooded | 0.51 f | .088 ef | 3.9 a | .230 de | .207 d | 16.47 b | 1088 e | 261 c | 800 d | 19 c | |
| Burabod | Moist | 1.02 d | .198 a | 1.8 c | .227 de | .642 b | 12.31 ef | 1950 d | 173 de | 558 e | 22 b | |
| | Wet | 0.60 e | .081 ef | 1.5 d | .244 cd | .605 b | 15.49 c | 5250 b | 209 d | 700 d | 29 a | |
| | Flooded | 2.08 b | .129 c | 1.5 d | .267 c | .243 d | 14.50 d | 6750 a | 1375 a | 81 f | 12 e | |

^aMean of 4 replications. In a column, means followed by a common letter are not significantly different by DMRT at the 5% level.

Total uptake data suggest that the observed lower concentration of Mg under the flooded regime of the Maahas A soil was due to mere dilution in plants, whereas in the acidic Luisiana and Burabod soils it was due to restricted availability of Mg to plants.

Silica

Concentrations of crude silica in 8 week old shoots were lower under flooded than under non-flooded regimes of all the soils. Total uptake in shoots were significantly higher in the Maahas A and significantly lower in both the Luisiana and Burabod soils under flooded than under the non-flooded conditions. Very high concentrations of Fe in the flooded acid soils may have adversely affected the silica uptake, and in the flooded Maahas A soil the observed lower concentration of SiO_2 in shoots was caused by mere dilution in tissue.

In all the soils, SiO_2 concentration in straw was highest under the wet regime, followed by the flooded and moist regimes. Unlike in shoots, SiO_2 concentration in straw was higher under flooded than under moist regimes. This could be attributed partly to greater uptake of SiO_2 by the plants during the reproductive stage when solution Fe concentration went down considerably.

Table 13. Total uptake of mineral nutrients by IR43 (grain plus straw) at harvest in three soils under moist, wet and flooded conditions.^a

| Soil | Treatment Moisture regime | N | K | SiO ₂ | P | Ca | Mg | mg/pot | | | |
|----------|---------------------------------|---------|---------|------------------|--------|-------|-------|--------|---------|-------|--------|
| | | | | | | | | Na | Fe | Mn | Cu |
| Luisiana | Moist | 1.87 bc | 1.36 e | 11.1 d | 220 c | 315 b | 805 a | 107 e | 26.3 de | 242 b | 2.7 e |
| | Wet | 1.92 b | 1.64 d | 14.3 c | 256 b | 349 a | 618 b | 178 c | 51.4 b | 305 a | 7.1 b |
| | Flooded | 2.11 a | 1.05 f | 8.8 e | 133 d | 164 d | 166 e | 144 d | 39.0 c | 124 c | 2.3 e |
| Maahas A | Moist | 1.24 e | 2.60 c | 12.1 d | 221 c | 192 d | 342 d | 9 f | 19.5 e | 8 f | 2.0 ef |
| | Wet | 1.23 e | 2.90 b | 16.3 b | 265 b | 128 e | 323 d | 11 f | 35.8 cd | 9 f | 5.1 c |
| | Flooded | 1.79 c | 4.32 a | 22.0 a | 409 a | 229 c | 320 d | 107 e | 80.8 a | 86 d | 8.8 a |
| Burabod | Moist | 1.33 e | 1.55 de | 11.3 d | 245 bc | 182 d | 541 c | 154 cd | 22.4 e | 46 e | 3.7 d |
| | Wet | 1.44 d | 1.43 de | 15.7 bc | 260 b | 180 d | 515 c | 370 a | 40.5 c | 57 e | 7.6 b |
| | Flooded | 1.33 e | 0.69 g | 6.3 f | 107 e | 98 f | 110 f | 245 b | 56.9 b | 4 f | 1.5 f |

^aMean of 4 replications. In a column, means followed by a common letter are not significantly different by DMRT at the 5% level.

Significantly higher concentration of SiO_2 in tissues under the wet than under moist regimes implicate that excess moisture rather than soil reduction, brought on by flooding, favors higher uptake of SiO_2 by rice plants.

Sodium

Sodium concentrations in shoots as well as straw were significantly higher under flooded than under the non-flooded regimes of all the soils. The concentration was again higher under wet than under moist regimes, the difference being nonsignificant in the Maahas A soil.

Total uptake of Na by the shoots and plants at harvest in the Maahas A soil were significantly higher under flooded than under the non-flooded conditions. No significant difference was found between the moist and wet regimes in this respect.

Iron

Concentrations of Fe in shoots and straw were higher under flooded than under non-flooded conditions of all the soils, the difference being significant only in the acidic Louisiana and Burabod soils. The wet regimes generally showed higher concentration of Fe in tissue than the moist regimes did, but the difference was non-significant in most cases.

Total uptake of Fe in shoot as well as plants at harvest were also significantly higher under flooded than under the non-flooded regimes of the Maahas A and Burabod soil. In the Luisiana soil, it was lower under flooded than under the wet regime because of very poor dry matter yield under the flooding treatment.

Manganese

Manganese concentrations in the shoots as well as straw were significantly higher under non-flooded than under flooded conditions of the acidic soils, with the single exceptional behavior of the 8 week old shoot in the Luisiana soil. It will be recalled here that the peak concentration of water-soluble Mn (125 ppm) in the submerged Luisiana soil occurred at 4-6 weeks after flooding and it sharply declined thereafter (Fig. 35). Comparable or even higher Mn concentration in 8 week old plants in flooded Luisiana soil is therefore not surprising. In the near-neutral Maahas A soil, concentrations of Mn in both shoots and straw were significantly higher under flooded than under non-flooded regimes; and there was no difference between the moist and wet regime in this regard.

Zinc

Concentrations of Zn in the 8 week old shoots were significantly higher under non-flooded than under the flooded regimes of the Luisiana and Burabod soils. In the near-neutral Maahas A soil, this difference between the flooded and non-flooded regimes was not significant. Under non-flooded conditions, the moist and wet regimes did not differ significantly regarding their influence on Zn availability to plants.

Copper

Copper concentrations in shoots as well as straw in both the acidic (Luisiana and Burabod) soils were significantly higher under non-flooded than under flooded regimes. In the Maahas A soil, however, no significant difference in tissue Cu concentration was noted between the flooded and non-flooded conditions. Concentrations of Cu in tissues did not show consistent difference between the moist and wet regimes.

Results of the mineral nutrition study indicate that in soils with unrestricted drainage, frequent and abundant supply of water over field capacity would markedly increase the SiO_2 concentration in rice plants but would not appreciably affect the tissue concentrations of other mineral nutrients including P, Fe and Mn.

Growth and Yield of IR43 in Four
Soils Under Three Moisture Regimes

Visual symptoms

Under both the moist and wet regimes of the non-flooded calcareous soil, unmistakably clear symptoms of Fe chlorosis appeared on plants starting from the seedling stage (Plate 5). Due to the severe chlorosis: plants under these treatments could not develop properly, did not tiller normally, failed to flower and got withered ultimately. The same soil under flooded conditions produced healthy plants with normal growth and development (Plate 6).

Growth of plants in both the acidic soils (Luisiana and Burabod) were markedly arrested under flooded conditions. Plant height as well as tillering were remarkably lower under flooded than under the non-flooded conditions. Clear symptoms of Fe toxicity started appearing on the plants grown in the flooded Burabod soil from early tillering phase and persisted throughout the growth period (Plate 7). Plants growing in the flooded Luisiana soil, however, did not exhibit any specific toxicity symptoms except the dark green leaves, stunted growth, markedly poor tillering and spindly culms. Mature straw analysis showed toxic concentration of Fe in tissue.

Rice growth in the near-neutral Maahas A soil was best under flooded regimes, followed by the wet and moist regimes (Plate 8).

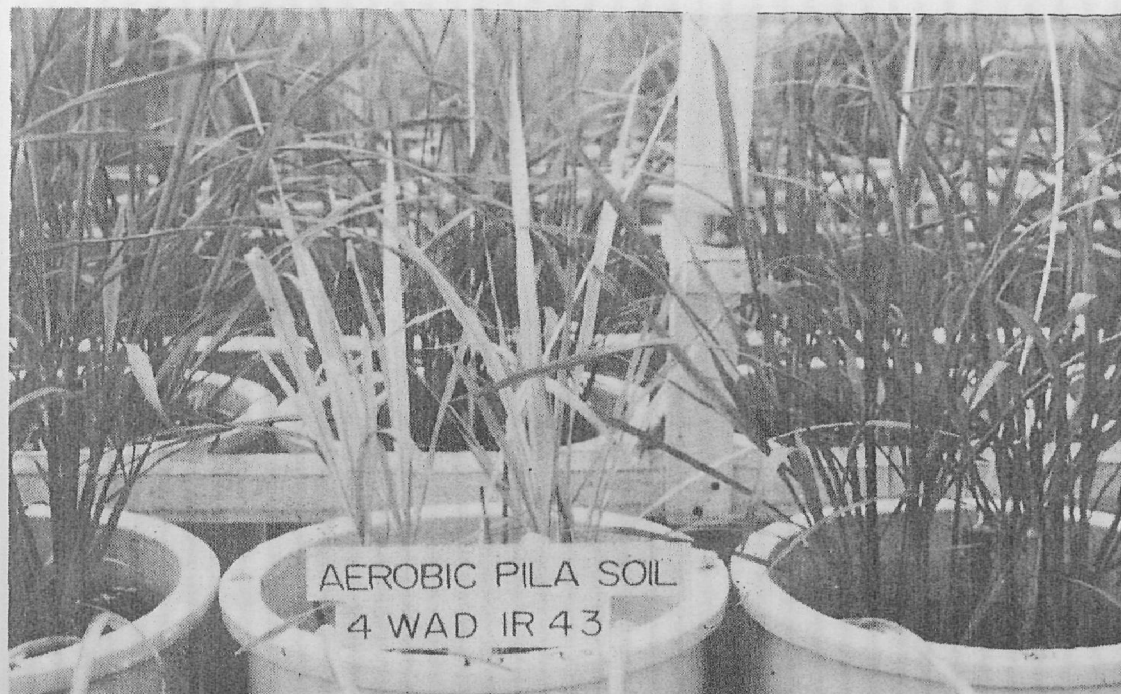


Plate 5. Acute iron chlorosis exhibited by IR43 in the calcareous Pila soil under aerobic (both Moist and Wet) conditions.



Plate 6. Growth of IR43 in the calcareous Pila soil under (a) Flooded, (b) Wet and (c) Moist conditions.



Plate 7. Growth of IR43 in the acid-sulfate Burabod (Malinao) soil under (a) Flooded, (b) Moist, and (c) Wet conditions.

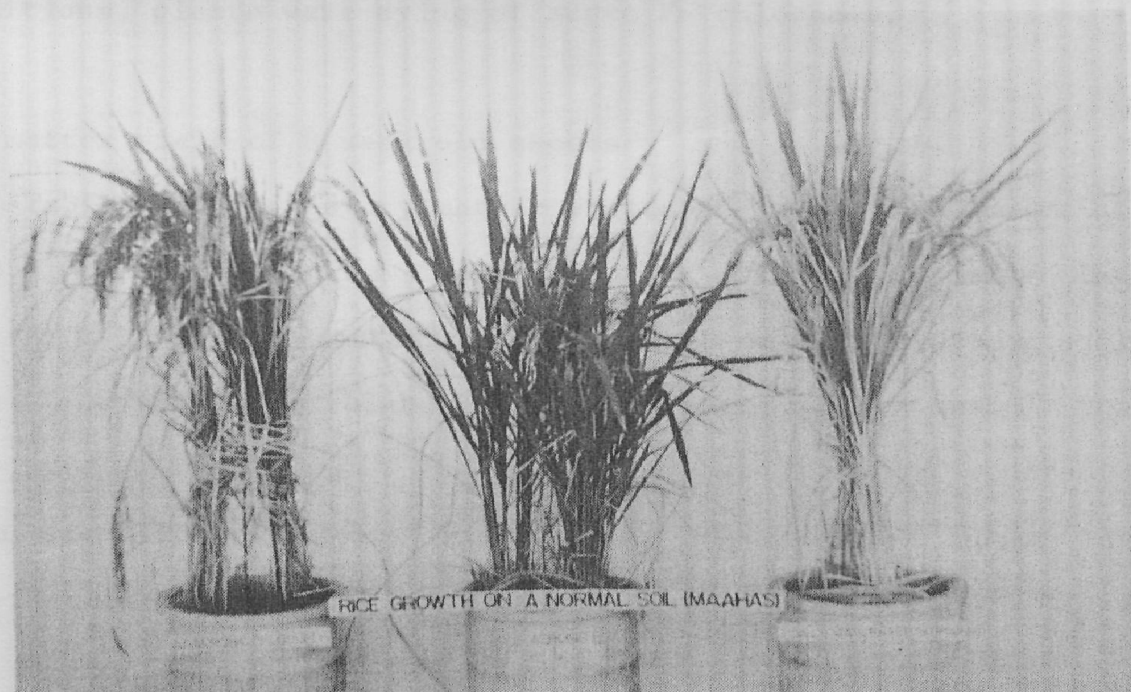


Plate 8. Growth of IR43 in the near-neutral Maahas A soil under (a) Flooded, (b) Moist, and (c) Wet conditions.

Plant height and tiller number

Height and tiller number of plants were recorded at 8 weeks after seeding. The results are presented in Table 14.

Both height and tillering of plants were higher under flooded than under non-flooded conditions of the near-neutral Maahas A and the calcareous Pila soils. In the acidic soils, however, both the growth measurement were lower under flooded than under non-flooded conditions. In the Luisiana, Burabod and Maahas A soils, the growth (in terms of both height and tiller number) was higher under wet than under the moist regimes. However, in the calcareous Pila soil no growth difference was noted between the moist and the wet regimes; under both the conditions, plants were dying of acute Fe chlorosis.

Dry matter yield of 8 week old shoots

Table 14 presents dry matter yields of 8 week old shoots of IR43 in four soils under three different moisture regimes. The yields in the near-neutral Maahas A and calcareous Pila soil were significantly higher under flooded than under the non-flooded conditions. The acidic soils, in sharp contrast, gave significantly lower yield under flooded than under the non-flooded regimes.

Table 14. Growth and dry matter yield of 8 week old IR43 in four soils under moist, wet and flooded conditions.^a

| Soil | Treatment | | Plant height (cm) | Tiller number per pot | Dry matter yield of shoot (g/pot) |
|----------|-----------------|--|-------------------|-----------------------|-----------------------------------|
| | Moisture regime | | | | |
| Luisiana | Moist | | 94 e | 27 a | 25.8 c |
| | Wet | | 104 bc | 25 a | 32.6 b |
| | Flooded | | 94 e | 12 d | 14.2 ef |
| Maahas A | Moist | | 96 de | 18 bc | 20.2 d |
| | Wet | | 105 bc | 19 b | 26.0 c |
| | Flooded | | 112 a | 28 a | 46.1 a |
| Pila | Moist | | 58 g | 6 e | 2.2 g |
| | Wet | | 59 g | 6 e | 1.4 g |
| | Flooded | | 109 ab | 15 cd | 15.6 e |
| Burabod | Moist | | 91 e | 28 a | 25.8 c |
| | Wet | | 101 cd | 20 b | 25.1 c |
| | Flooded | | 85 f | 14 d | 11.7 f |

^aMean of 4 replications. In a column, means followed by a common letter are not significantly different by DMRT at the 5% level.

While shoot yields in the Luisiana and Maahas A soils were significantly higher under wet than under moist regimes, no significant difference was found between these two moisture regimes with respect to their effects on shoot yields in the Burabod and Pila soils.

Grain yield

Table 15 shows that in the near-neutral Maahas A soil, grain yield was significantly higher under flooded than under the non-flooded conditions. Again, the wet regime gave significantly higher yield than in the moist regime. Compared to that obtained under flooded regime, yields were 20 and 67 percent under the moist and wet regimes, respectively.

While grain yield was normal under flooded condition of the calcareous Pila soil, non-flooded (moist and wet) regimes failed to produce any grain. Since comparable amounts of water were made available to plants under the wet and flooded regimes and the soils under these two regimes were found to be aerobic and anaerobic respectively, the yield difference between the two treatments could apparently be attributed to the difference in soil chemical environments. Data show that apparent contributions of the unfavorable chemical environments of aerobic Maahas A and Pila soils to yield reduction in IR43 were 33 and 100 percent, respectively.

Like the other growth parameters, grain yields in both the strongly acidic soils were very poor under the flooded regimes presumably because of Fe toxicity. The non-flooded wet regime produced highest grain yield in both the acidic soils.

Straw yield

In the near-neutral Maahas A and calcareous Pila soils, straw yields were much higher under flooded than under non-flooded conditions (Table 15). Contrastingly, in both the strongly acidic soils it was significantly higher under non-flooded than under flooded conditions.

While the moist and wet regimes produced equally low amounts of straw in the calcareous Pila soil, the moist regime gave higher yield of straw than did the wet regime in all other soils.

The grain:straw ratio (data not shown) was lowest under the moist regime of all the soils. It was highest under flooded regimes in the Maahas A and Pila and under the wet regime in both the strongly acidic soils.

Table 15. Grain and straw yield of IR43 in four soils under moist, wet and flooded conditions.^a

| Soil | Treatment | Grain yield ----- g/pot ----- | Straw yield ----- |
|----------|--------------------|---|-------------------------|
| | Moisture regime | | |
| Luisiana | Moist | 28.6 f | 89.1 b |
| | Wet | 92.8 b | 80.1 c |
| | Flooded | 34.2 e | 59.7 f |
| Maahas A | Moist | 22.9 g | 94.8 ab |
| | Wet | 74.8 d | 67.5 e |
| | Flooded | 111.5 a | 97.5 a |
| Pila | Moist | 0.0 h | 6.0 h |
| | Wet | 0.0 h | 6.2 h |
| | Flooded | 97.0 b | 72.4 de |
| Burabod | Moist | 35.0 e | 78.6 cd |
| | Wet | 81.1 c | 70.1 e |
| | Flooded | 23.3 g | 35.8 g |

^aMean of 4 replications. In a column, means followed by a common letter are not significantly different by DMRT at the 5% level.

Experiment 4

Chemical Kinetics of Six Soils
Under Moist, Wet and Flooded Conditions in
Relation to Growth and Mineral Nutrition of Rice

In the previous experiment, chemical environments of four non-flooded soils under moist and wet regimes were studied by analyzing their equilibrium solutions collected by the recycling method. The Eh and other analyses of the soil solutions did not show any appreciable difference between the two regimes, although in situ soil Eh values were much lower under the wet regime (indicative of a moderately reduced condition). If the soils under the wet regimes had been moderately reduced, soil solutions could have been oxidized during the recycling process. This could have caused the soil solution analyses to be similar under both moist and wet regimes. In order to exclude such a possibility, a new method of collecting unaltered equilibrium solutions of unsaturated soils was developed (described in Appendix).

The purposes of the present experiment were to employ this refined method of collecting equilibrium solutions from the soils under the wet regime, and to compare their chemical environments with those under the moist and flooded regimes. In addition to the four soils used in the previous experiment, two new soils (one moderately acidic and a near-neutral) were included for the present investigation.

MATERIALS AND METHODS

Soils from Luisiana (San Pedro), Maahas A, Pila, Burabod, Rotonda (Koronadal, South Cotabato) and Maahas B (Block F6, IRRI Farm, Maahas) were used in this experiment conducted in 1986 Wet Season. The Maahas A, Pila and Burabod soils were used from the lots collected for the previous experiment (Experiment 3). The Rotonda and Maahas B soils were obtained from the greenhouse stocks. These samples had been collected from the respective fields about 2 years back, dried and stored in the bins.

As no stock of the Luisiana soil used for the last experiment was available, it was collected again from the same field after harvesting of the previous season's crop.

The Maahas A, Pila and Luisiana soils happened to get moistened by rain and incidentally they were stored indoors in the moist state for several months before using.

General properties of the Rotonda and Maahas B soils are furnished in Tables 3 and 4. Soil preparation, greenhouse set-up, analyses of soils, soil solutions and plants were done following the same procedures as described earlier for the previous experiment. Amount of soils taken in each pot and their fertilization were also same as that in the last experiment.

Experimental factors and levels

Soils:

Six soils used for the experiment were

- S1 - Luisiana soil
- S2 - Maahas A soil
- S3 - Pila soil
- S4 - Burabod soil
- S5 - Rotonda (Koronadal, South Cotabato) soil
- S6 - Maahas B (Block F6, IRRI Farm, Maahas) soil

Moisture regimes

The following three moisture regimes which have been described in detail for the previous experiment were studied:

- M1 - Moist
- M2 - Wet
- M3 - Flooded

Cultivar:

IR43 was grown as the test cultivar for this trial.

Experimental design

For this 6 x 3 factorial experiment the pots were laid out in a Randomized Complete Block Design with 3 replications.

Sampling of soil solutions

Soil solutions from the flooded pots were drawn by gravity. The equilibrated saturation extracts were collected as the representative soil solutions of the moist soils following the procedure described by Kundu et al (1987). The unaltered equilibrium solutions of the wet soils were collected after keeping them saturated for 8-12 hours (Appendix, p.). Solutions from all the pots were collected at fortnightly intervals in the sampling flasks deaerated previously with nitrogen gas.

Establishment of plants

Eight pre-germinated seeds were dibbled in each pot immediately after the sampling of 0 week soil solutions. At about 10 days after dibbling, seedlings in each pot were thinned out to keep four healthy ones. Because of severe chlorosis, seedlings in the non-flooded calcareous soil were very poor and were getting withered in several pots. These very poor and dying plants were replaced by the healthy seedlings from other pots within first 2-3 weeks.

Preparation of plant samples for analysis

Shoots sampled at 8 weeks after dibbling and straw harvested at maturity were washed with mild detergent solution and subsequently with demineralized water. After drying the

washed samples at 60°C temperature for 2-3 days, they were chopped with a stainless steel scissors and ground by using a stainless steel mill (Cristy and Norris Beater Cross Grinder). The ground samples were then stored in envelopes and redried before analysis.

Plant growth observations and yield data collected

1. Visual symptoms of any nutritional disorder.
2. Plant height and tiller count of 8 week old plants.
3. Dry matter yield of 8 week old shoots.
4. Grain yield.
5. Straw yield.

RESULTS AND DISCUSSION

Electro-chemical and Chemical Kinetics of the Soil Solutions

Soil solutions were collected from all the pots at fortnightly intervals upto first 10 weeks and were analyzed for Eh, pH, EC, oxidizable matter, NH_4^+ -N, NO_3^- -N, P, Fe, Mn, Si and Zn. Mean values of the solution analyses from different treatments are given in Tables 50-61 of the Appendix. The results are presented graphically in the following pages and discussed hereunder. For convenience, moist and wet regimes will be collectively referred to as non-flooded when comparing them with the flooded regime.

Electrochemical kinetics

Redox potential (Eh). Figures 44 and 45 show the kinetics of soil Eh and solution Eh, respectively of six soils under three different water regimes. On flooding, all other soils except Maahas A got reduced in first 2 weeks. Reduction of the Maahas A soil was delayed considerably. This delay could be attributed to the very high content of NO_3^- (about 400 ppm as N) present initially in this soil. Presence of a high content of NO_3^- is known to retard the fall of Eh in soils (Ponnamperuma 1985).

In all the soils, Eh were much higher and positive under the non-flooded regimes. Differences between the moist and wet regimes were generally not appreciable in terms of solution Eh, but were marked in terms of soil Eh. This is in conformity with the observations made in the previous experiment. Since for this experiment unaltered solutions of the wet soils were collected by following an improved method, the observed non-appreciable difference in solution Eh between the two moist and wet regimes can not be discounted. Results of both the previous and the present experiments indicate that redox status of non-flooded soils are virtually same under the moist and wet regimes.

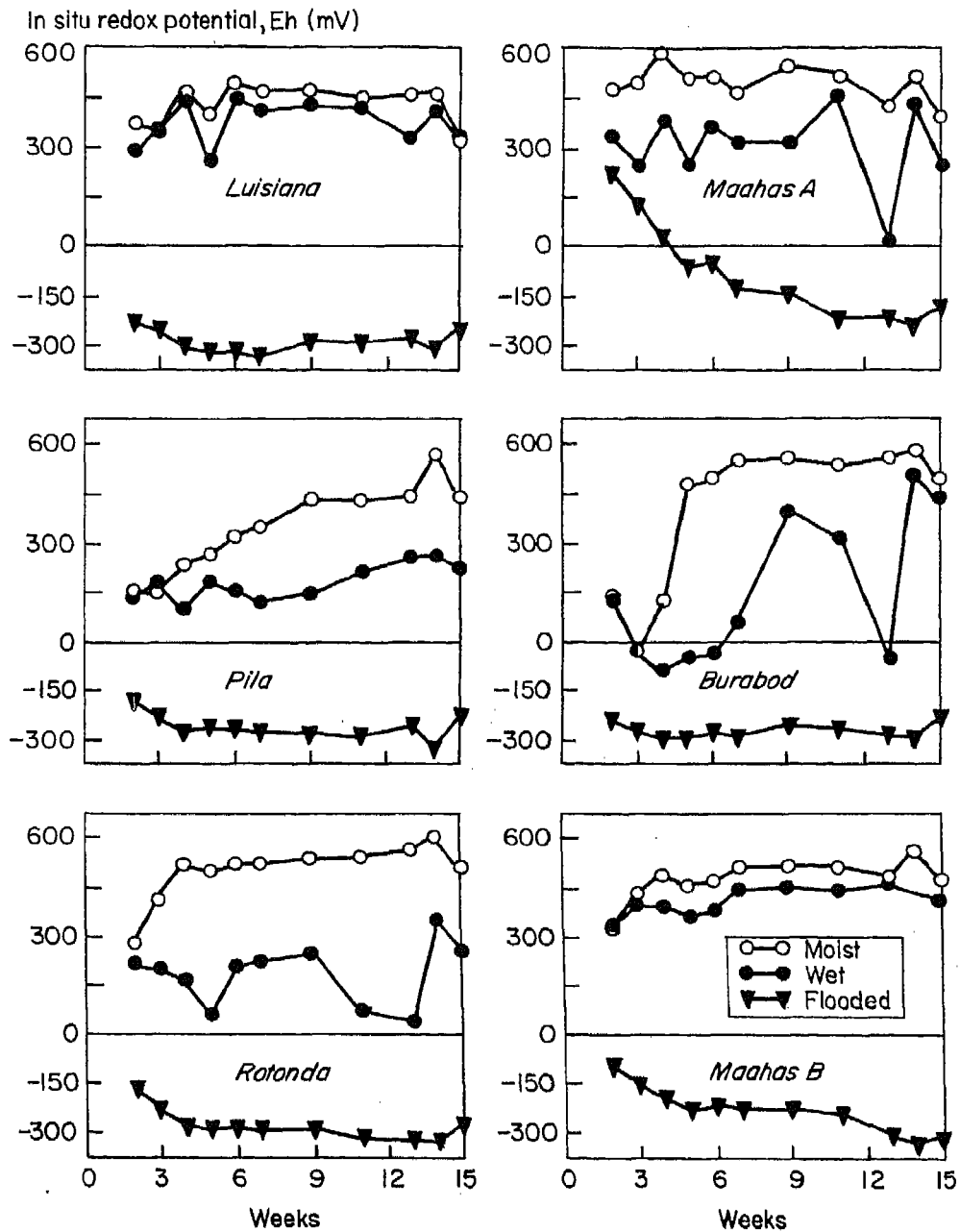


Fig. 44 Kinetics of Eh in six soils under moist, wet and flooded conditions.

It has earlier been discussed that unlike solution Eh, soil Eh (especially Eh of non-flooded soils) are not very reproducible, sensitive and meaningful measurement of their redox status. Eh of wet soils in situ were found to vary greatly from zone to zone to give sometimes both positive and negative values in the same pot. Those readings were averaged to report the soil Eh. The measured Eh of wet soils in situ could be greatly influenced by probable presence of some reduced microsites. On the otherhand, Eh of the equilibrium solutions of these soils did not show any marked variation even with replications.

Scrutiny of Figs. 44 and 45 reveals that under the wet regimes the Rotonda and Burabod soil underwent moderate reduction through a major part of the season and the Luisiana soil got moderately reduced once at 2 weeks after seeding. The periods of moderate reduction in these soils strikingly coincided with that of the impeded drainage encountered in the present experiment.

From these observations it could be concluded that (i) the redox status of non-flooded soils does not vary appreciably with moisture supply as long as drainage is free, (ii) in case of impeded drainage, soils get moderately reduced at higher than field capacity moisture regime, and (iii) under non-flooded wet regime, some anaerobic or reduced microsites could exist in soils.

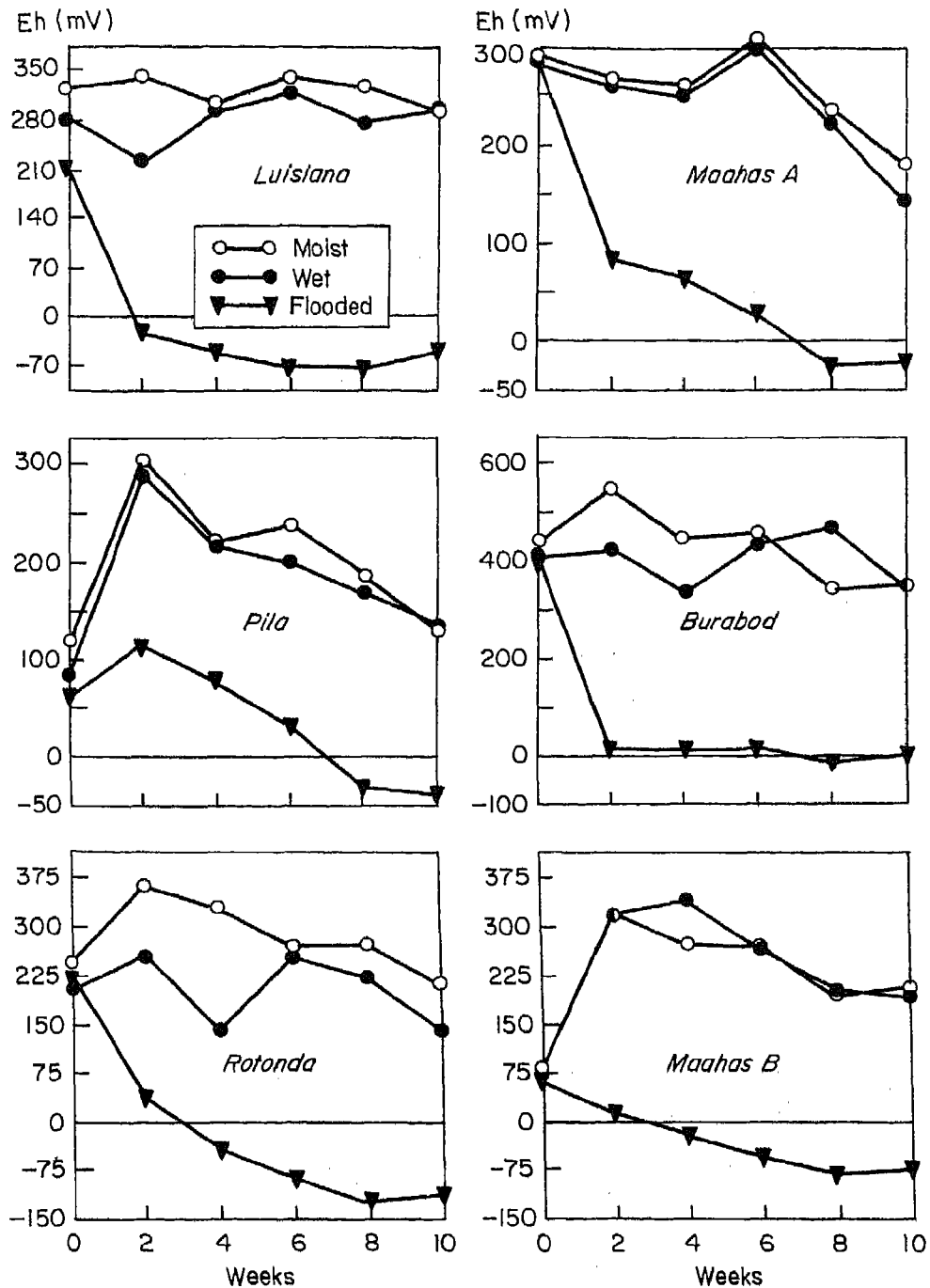


Fig. 45 Kinetics of solution Eh in six soils under moist, wet and flooded conditions.

pH. Changes in solution pH of six soils under three different moisture regimes are shown in Fig. 46. Conforming to the observations made in the previous experiments, flooding increased pH of all the acidic soils and decreased that of the calcareous soil towards neutrality. Solution pH of non-flooded Maahas A, Burabod, Rotonda and Maahas B soils remained within their original ranges throughout the season. The initial marked drop in pH of the Maahas A, Rotonda and Maahas B soils under non-flooded regimes were closely associated with high degree of nitrification in them.

The initial high pH of the non-flooded Luisiana soil in the present study caused some uneasiness at the time of solution analysis. Measurement of pH (1:1) of the air-dried soil (sampled before starting this experiment) showed a value of 5.1. It will be recalled here that this soil was freshly collected from Luisiana following completion of a field experiment there. Among the different treatments included in the field experiment, one was liming. Although the soil was carefully sampled from the control (non-limed) plots, probably it was contaminated with traces of lime coming from the nearby limed plots. The high pH observed initially was probably due to dissolution of free lime traces in the leachate and the subsequent drop in pH, to reach a value around 4.4, could be due largely to the pH-buffering action of the soil and partly to the high degree of nitrification. The sharp decline in pH of the non-flooded Pila

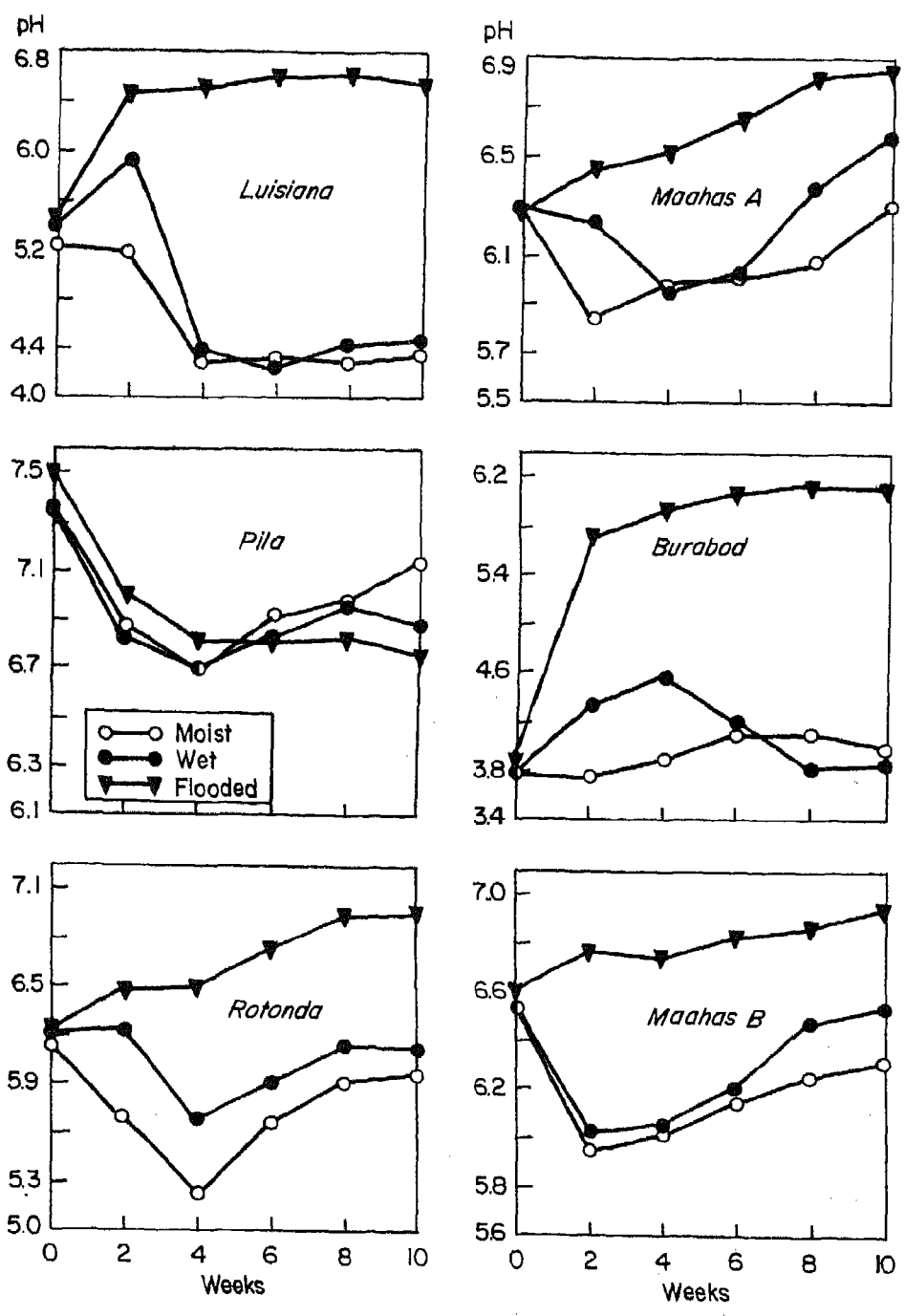


Fig. 46 Kinetics of solution pH in six soils under moist, wet and flooded conditions.

soil was associated with very high degree of nitrification in it. The NO_3^- -N concentration increased from as low as 20 ppm to as high as 1300 ppm in first four weeks and it never came down below 70 ppm.

In agreement with that in the previous experiment, pH of non-flooded soils under wet regime were marginally higher than that under the moist regimes. This small increase in pH in the Maahas A, Rotonda and Maahas B soils could partly be attributed to the decrease in EC under the wet regimes. In the Burabod soil, however, the observed increase in pH was more closely associated with the drop in Eh under the wet regime.

Electrical conductivity (EC). Kinetics of solution EC of six soils under different water regimes are presented in Fig. 47. EC of the Rotonda soil was higher under flooded than under non-flooded regimes. In the Burabod soil, it was higher under non-flooded than under flooded conditions. These observations are in line with those of the previous experiments. However, appreciably higher EC of the Luisiana, Maahas A, Pila and Maahas B soils under non-flooded than under flooded regimes are in sharp contrast to the earlier findings. Presence of very high concentrations of NO_3^- in these soils under non-flooded conditions could account for such higher EC as observed. The unusually high contents of nitrate of the Luisiana, Maahas A and Pila soils were probably the results of very high rate of mineralization occurred in these soils which

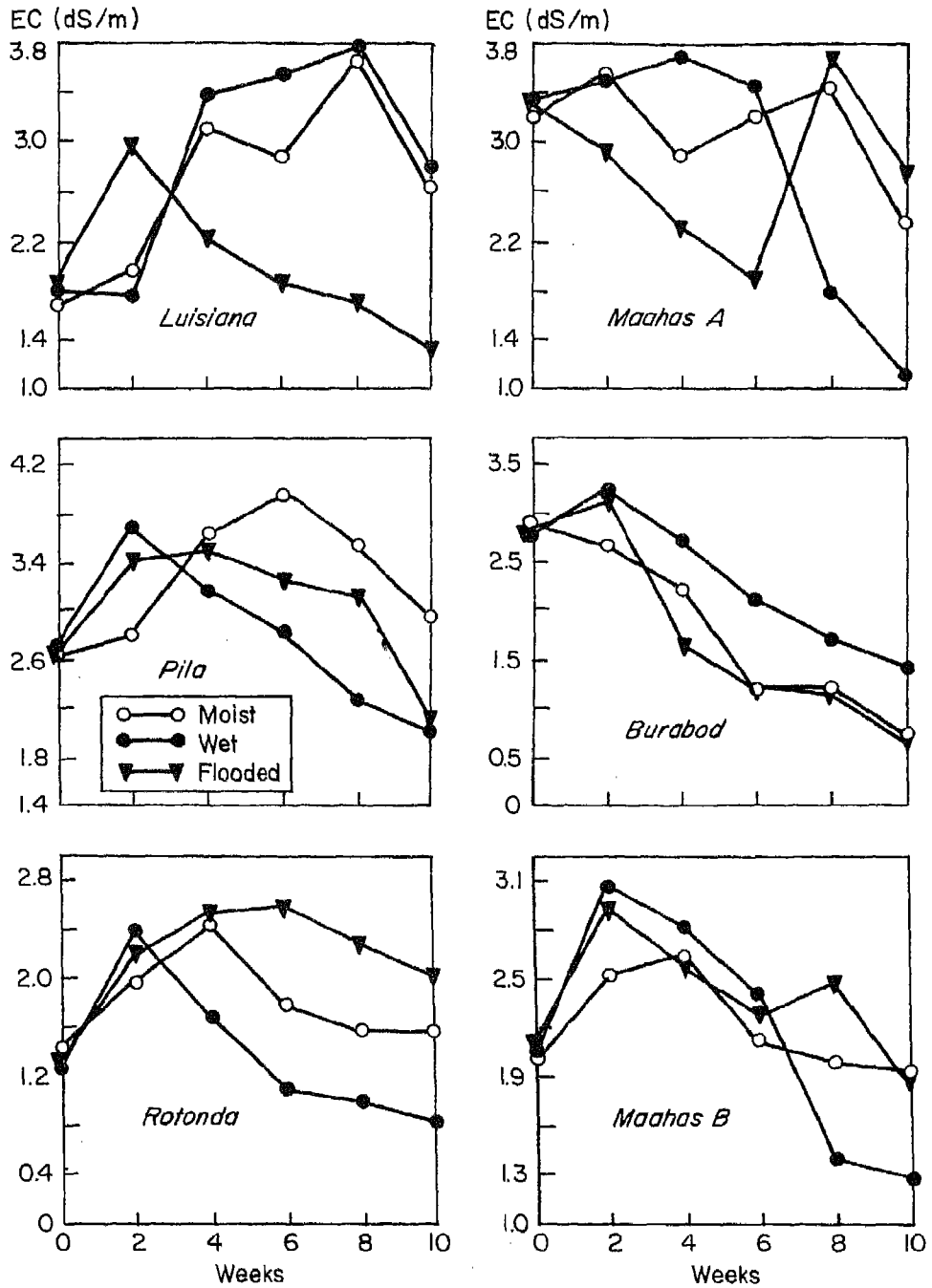


Fig. 47 Kinetics of electrical conductivity in six soils under moist, wet and flooded conditions.

had been stored indoors in moist state for several months. After 8 weeks, the Maahas A soil recorded higher EC under flooded than under the non-flooded conditions, which could be attributed to sharp decline in the NO_3^- concentration under non-flooded and substantial increase in Fe and Mn concentrations under the flooded regimes. The observed EC kinetics of Maahas B soil under flooded and non-flooded conditions could be explained in similar way.

The differences in EC between the moist and wet regimes were not consistent in all the soils.

Chemical kinetics

Oxidizable matter. Kinetics of water-soluble oxidizable matter in six soils (Fig. 48) show that, throughout the season, its concentrations in all the soils were much higher under flooded than under non-flooded regimes. No appreciable differences in the concentrations of oxidizable matter were found between the moist and wet regimes of the soils. These findings compared favorably with those of the previous experiment.

Nitrogen. Ammonium: Changes in solution NH_4^+ -N in six soils under different water regimes are illustrated in Fig. 49. It shows that NH_4^+ -N concentrations in the Luisiana, Maahas A, Pila, Rotonda and Maahas B soils were much higher under

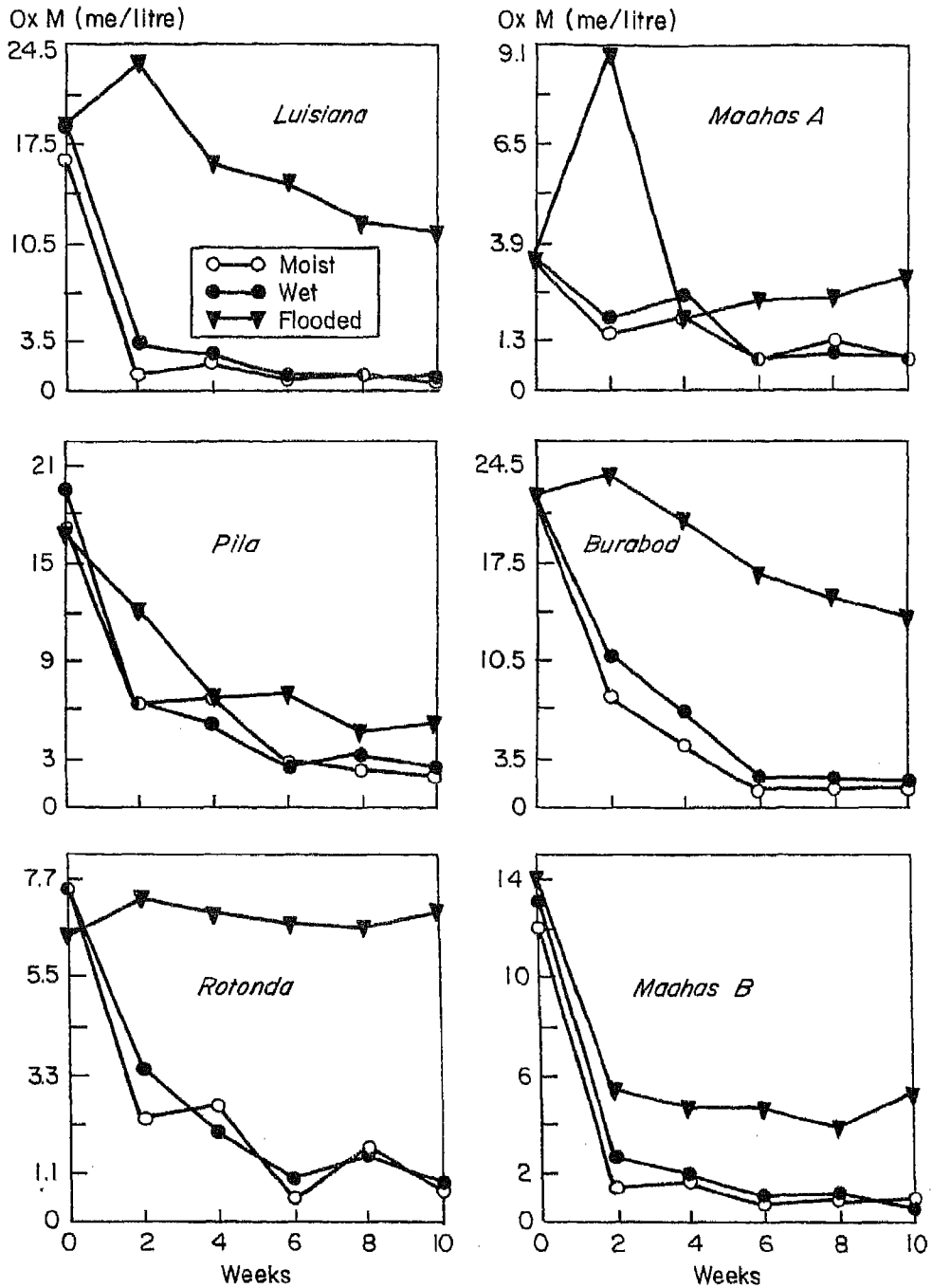


Fig. 48 Kinetics of water-soluble oxidizable matter in six soils under moist, wet and flooded conditions.

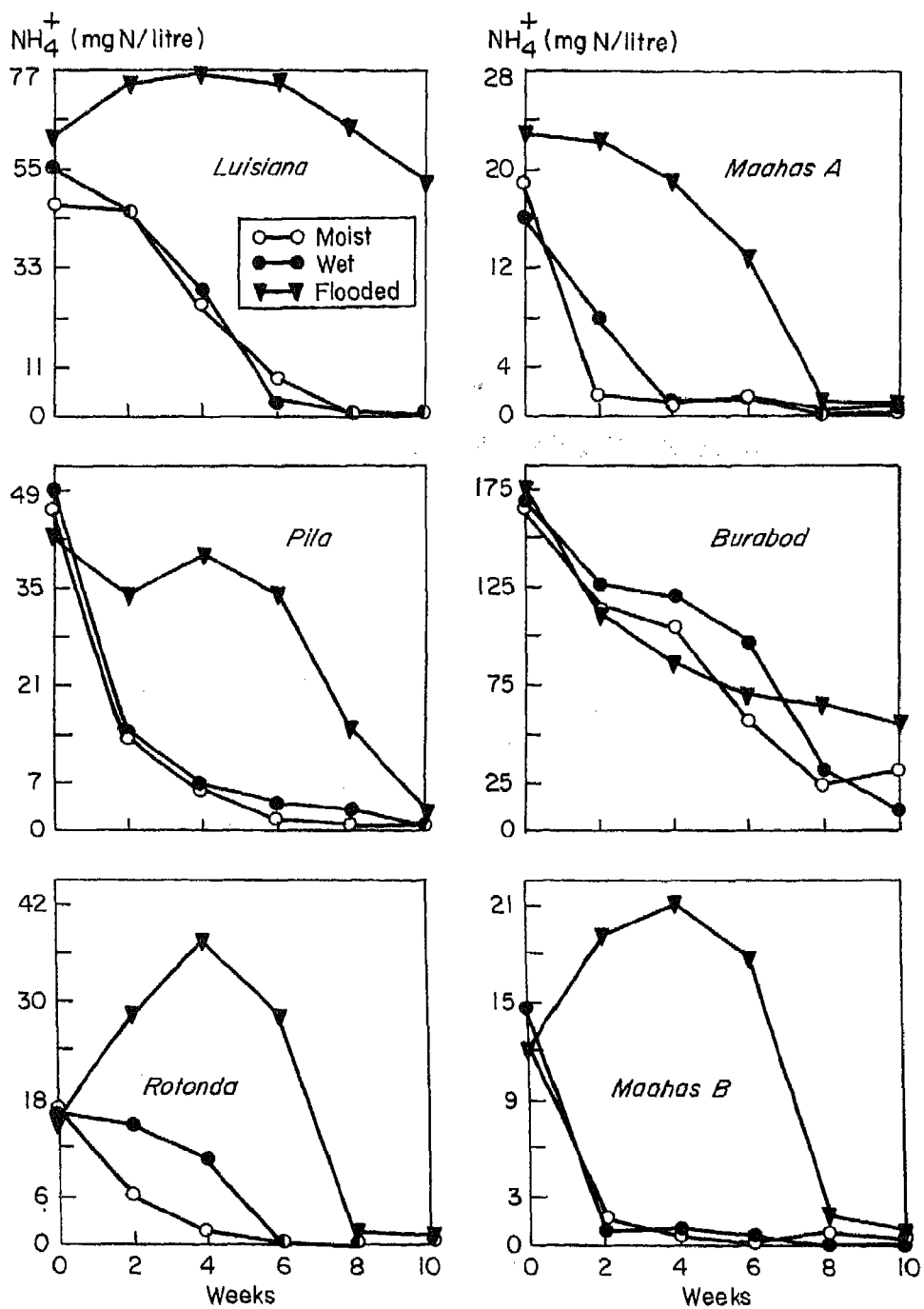


Fig. 49 Kinetics of water-soluble NH_4^+ -N in six soils under moist, wet and flooded conditions.

flooded than under the non-flooded conditions. In the Burabod soil, the moisture regimes did not differ remarkably from each other with respect to their effects on NH_4^+ -N concentration.

In non-flooded Rotonda and Burabod soils, higher concentrations of NH_4^+ -N observed under wet than under moist regimes were associated with the moderately reduced status of these soils under the wet conditions. In the other soils, no marked differences in NH_4^+ -N concentrations were found between the moist and wet regimes.

Nitrate: Kinetics of NO_3^- -N in soils under three different moisture regimes are presented in Fig. 50. Since nitrate concentrations in the Burabod soil were very low, regardless of the moisture regimes, they are not presented graphically. In conformity with the findings of the previous experiments, under non-flooded conditions, NO_3^- -N concentrations increased sharply with time to reach a peak in 4-6 weeks and declined thereafter. Compared to those observed in the previous experiments, NO_3^- -N concentrations in non-flooded Luisiana, Maahas A and Pila soils in the present case were very high which could be attributed to the enhanced mineralization presumably occurred in these soils as they had been stored indoors in moist state for several months.

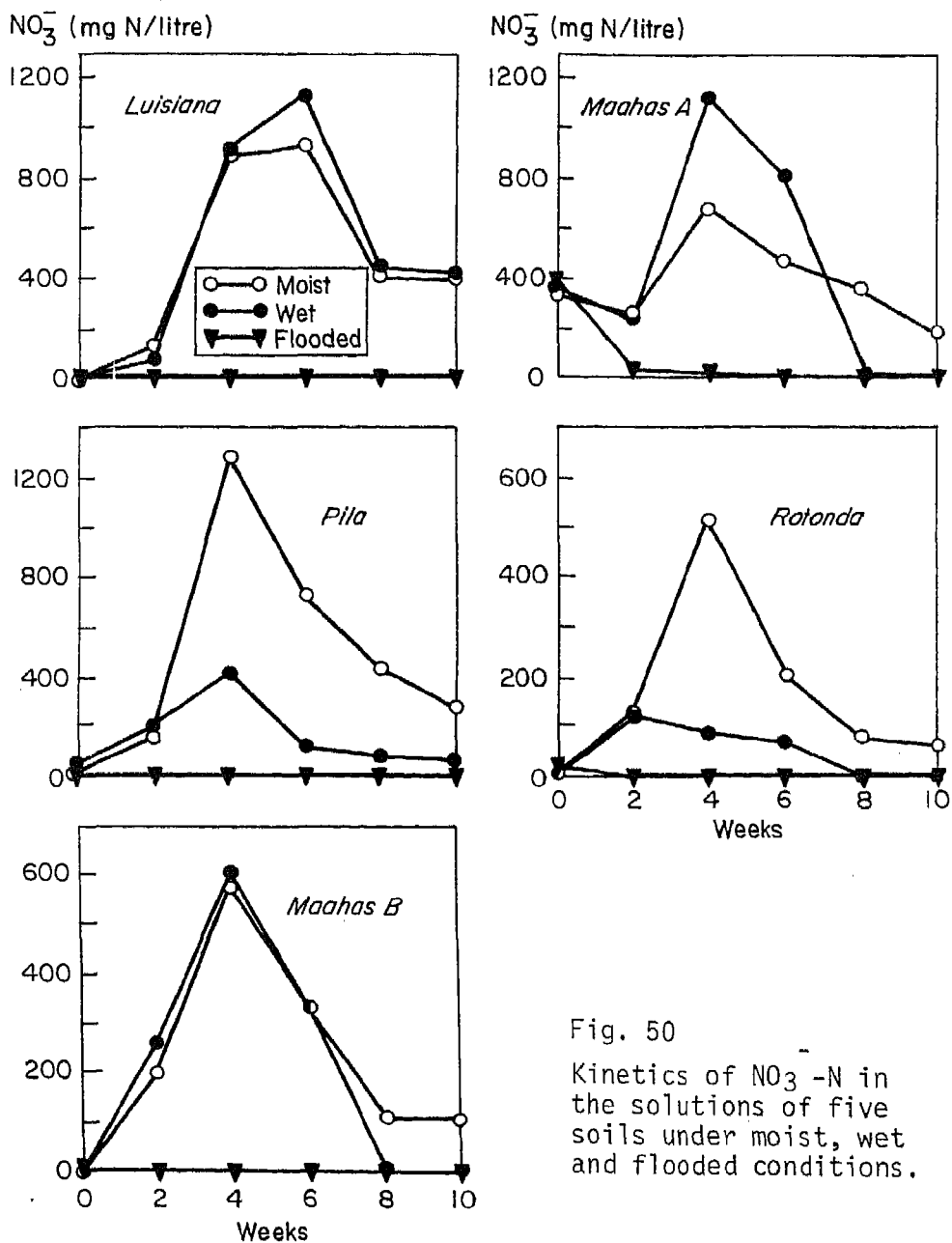


Fig. 50
Kinetics of NO_3^- -N in the solutions of five soils under moist, wet and flooded conditions.

Nitrate-N disappeared from all the soils soon after flooding. Unlike in the previous experiments, disappearance of NO_3^- -N from the flooded Maahas A soil was slow because of a very high (above 300 ppm) amount of NO_3^- -N initially present in the present case.

Phosphorus: Changes in concentrations of water-soluble P in six soils under different moisture regimes are presented in Fig. 51. Concentrations of P in the Burabod, Rotonda and Maahas B soils were convincingly higher under flooded than under non-flooded regimes. Apparently lower P concentrations after 4 weeks in the Maahas A and Pila soils do not indicate lower P solubility under the flooded regimes, because plant growth and P assimilation by plants were several times higher under the flooded than under the non-flooded regimes. Starting from the fourth week onwards, P concentration in the Luisiana soil was very low and the flooded regime maintained lower concentration of P than that under the non-flooded regimes. At 2 weeks after the start, however, P concentration was remarkably higher under non-flooded than under the flooded regime. The P kinetics in this soil was found to be closely associated with pH changes. The pH range of 5 to 6 gave the highest solubility of P in it. At pH below 4.5 and above 6.4, P solubility decreased dramatically. The lower solubility of P under non-flooded conditions at pH <4.5 could be attributed to its fixation by Al. And under the flooded condition, the decreased solubility could

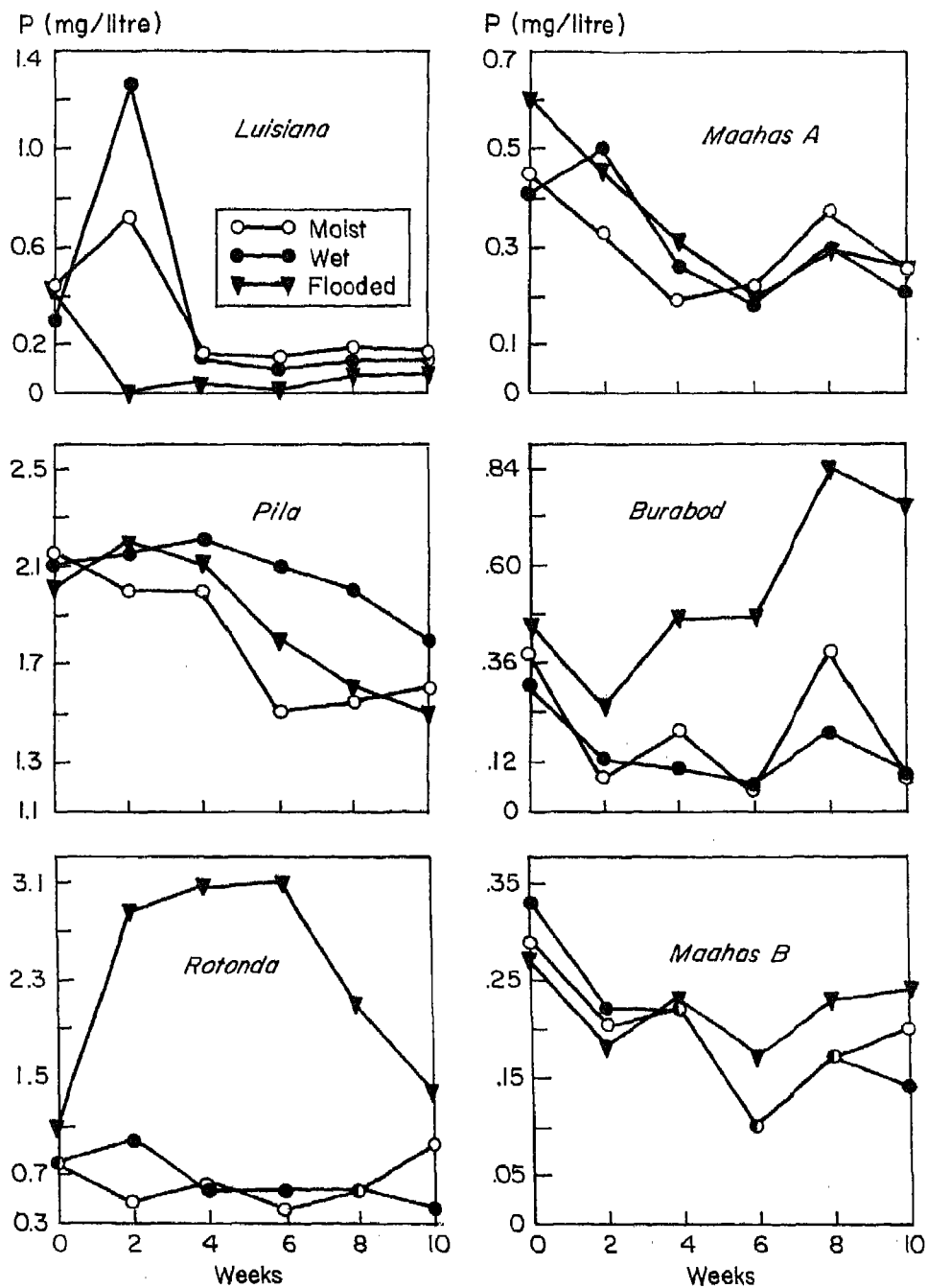


Fig. 51 Kinetics of water-soluble P in six soils under moist, wet and flooded conditions.

be due to precipitation of P on Fe^{2+} . Khalid et al (1977) also noted lower solubility of P under reduced than under the aerobic conditions of some soils.

The moist and the wet regimes did not differ appreciably with respect to their effect on P solubility in most soils, except the calcareous Pila loam in which P concentration was notably higher under wet than under the moist regime.

Iron: Figure 52 illustrates the kinetics of water-soluble Fe in six soils under three different water regimes. Iron concentration increased to reach a peak of about 260 ppm in the Luisiana and about 330 ppm in the Burabod soil at two weeks after flooding and declined thereafter. The decline was very sharp and it brought the Fe concentration to a very low level within 4 weeks in the Burabod soil. Compared to that observed in the previous experiment, peak concentration of Fe in flooded Luisiana soil was considerably lower (260 ppm against the 390 ppm found in the previous experiment) which could be attributed to the presence of some lime traces as contaminant in it.

Peak concentrations of Fe in flooded Maahas A (10 ppm), Pila (3 ppm), Rotonda (62 ppm) and Maahas B (54 ppm) soils were lower and attained much later. Considerably smaller peak of Fe concentration (10 ppm against the 40 ppm found in the previous experiment) observed in flooded Maahas A soil in the present

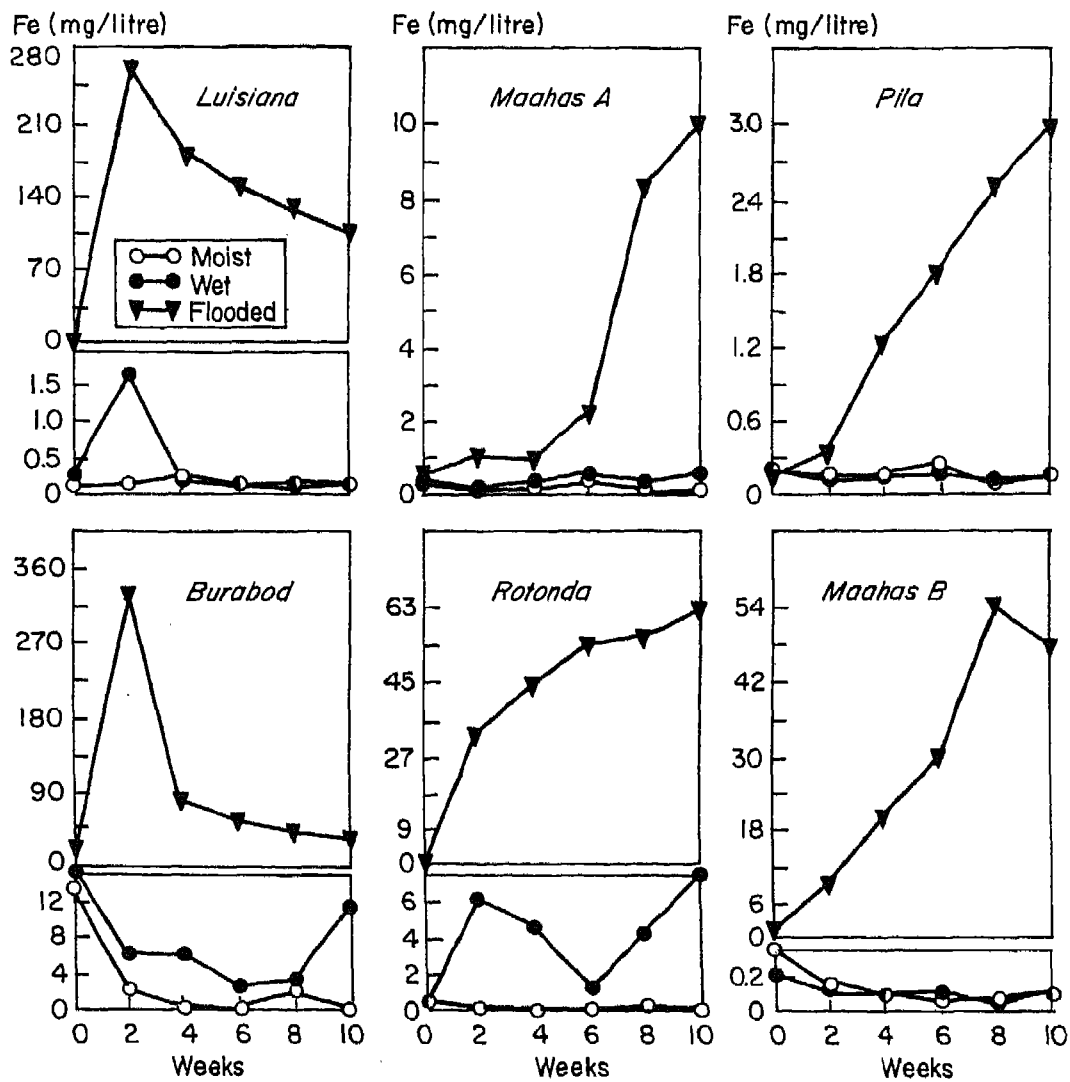


Fig. 52 Kinetics of water-soluble Fe in six soils under moist, wet and flooded conditions.

experiment may be attributed to the delayed and lower degree of reduction caused by presence of very high content of NO_3^- in it.

Iron concentrations under non-flooded conditions were much lower than that under flooded conditions of all the soils. In the non-flooded Burabod and Rotonda soils, Fe concentrations were higher under wet than under moist regimes. In the Luisiana soil, wet regime registered appreciably higher concentration of Fe than did the moist regime only at 2 weeks after start. These observed higher concentrations of Fe in the wet regimes were closely associated with moderate reduction of these soils, brought by impeded drainage. In the other soils, no remarkable difference in Fe solubility was found between the moist and wet regimes.

Manganese: Kinetics of water-soluble Mn in soils under various water regimes are shown in Fig. 53. Under flooded conditions, concentrations of Mn increased with time to reach a peak of about 154 ppm in the Luisiana, 50 ppm in Maahas A, 34 ppm in Pila, 42 ppm in Rotonda and 44 ppm in Maahas B soils and declined thereafter. In the flooded Burabod soil, however, Mn concentration decreased steadily with time. These observations are in conformity with those of the previous experiments.

Under non-flooded conditions, Mn concentrations were extremely low in the near-neutral Maahas A and Maahas B, and calcareous Pila soil. In the strongly acidic Burabod and

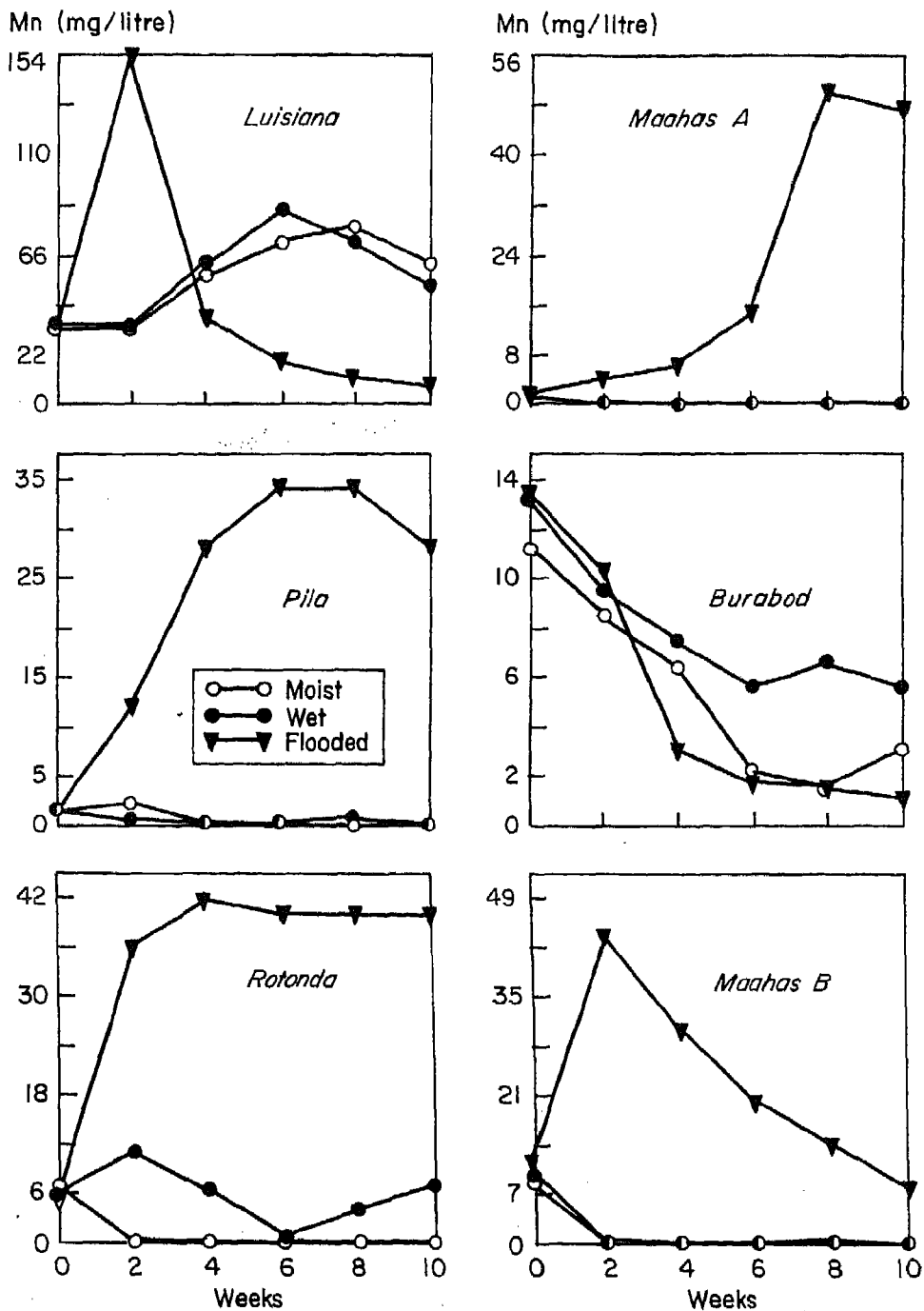


Fig. 53 Kinetics of water-soluble Mn in six soils under moist, wet and flooded conditions.

Luisiana soils, however, Mn concentrations were quite appreciable. In fact, starting from the fourth week onwards, Mn solubility in these two acidic soils were higher under non-flooded than under the flooded regimes. Compared to that observed in the previous study, Mn concentration in the non-flooded Luisiana soil in the present case was about 4 fold (upto about 84 ppm) which could cause potential Mn toxicity problem. It will be recalled here that for the present study, fresh sample was collected from the same field (San Pedro, Luisiana) but after one cropping season (1985 wet season). In the non-flooded Luisiana, Maahas A, Pila and Maahas B soils Mn solubility under the moist and wet regimes did not differ appreciably. However, in the Burabod and Rotonda soils, Mn solubility in the wet regimes were remarkably higher than that in the moist regimes. This increase could be attributed to the moderately reduced status of these soils under the wet regime.

Silicon: Changes in concentrations of Si in six soils under different water regimes are shown in Fig. 54. In conformity with the findings of the previous experiment, Si concentrations in the Burabod, Luisiana and Maahas A soils were appreciably lower under flooded than under the non-flooded regimes. The difference in Si concentrations between flooded and non-flooded regimes were not so well-marked in the Pila, Rotonda and Maahas B soils. It should be mentioned here that in the calcareous Pila soil, total dry matter yield of rice

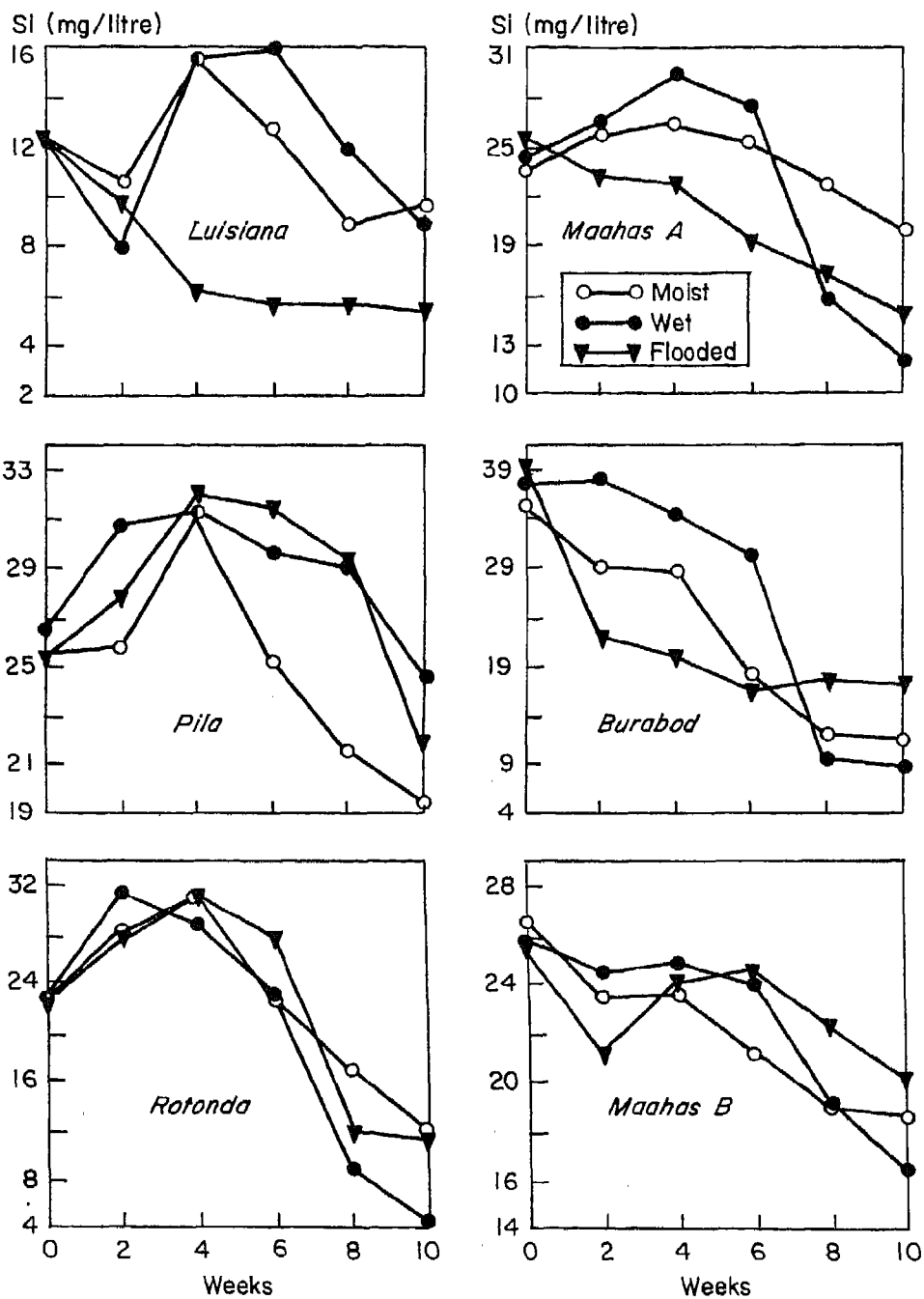


Fig. 54 Kinetics of water-soluble Si in six soils under moist, wet and flooded conditions.

at harvest was about 4 times under flooded than under the non-flooded conditions. Taking into account such a big difference in Si assimilation by plants under the two water regimes, it could be concluded that Si availability in the Pila soil was higher under flooded than under non-flooded regime.

Under non-flooded conditions, no consistent differences in Si solubility were found between the moist and wet regimes of soils except Pila and Burabod soils in which solubilities were higher in the wet regimes.

Zinc: Since concentrations of water-soluble Zn in the Maahas A, Pila, Rotonda and Maahas B soils were very low regardless of the water regimes, they are not presented graphically. Figure 55 illustrates kinetics of Zn in the Luisiana and Burabod soils under different water regimes. In both the soils, Zn concentrations were markedly higher under non-flooded than under flooded conditions. No appreciable difference in Zn solubility was found between the moist and wet regimes of the soils.

The important conclusions from this chemical kinetics study are:

1. in spite of frequent and abundant supply of water, soils would remain aerobic as long as the drainage is unrestricted.

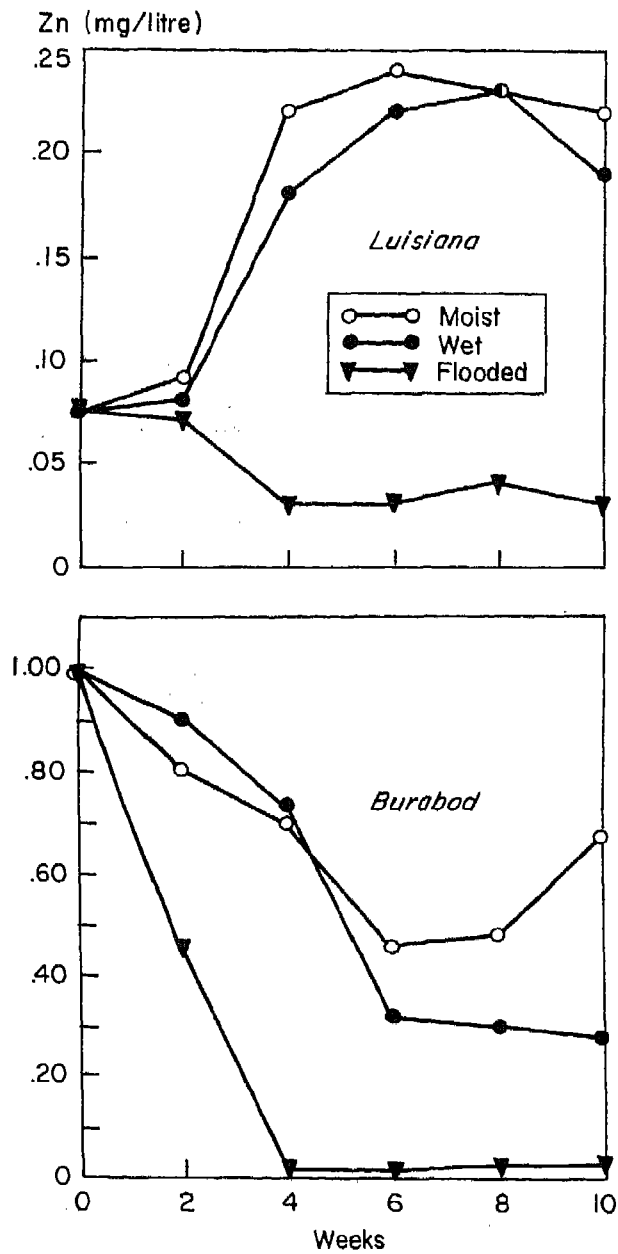


Fig. 55 Kinetics of water-soluble Zn in two soils under moist, wet and flooded conditions.

2. the recycling method may safely be used for collecting equilibrium solutions of soils under the wet regimes.
3. chemical environments of the wet (adequately watered but well-drained) soils would not differ measurably from those of the continuously field capacity moist soils.
4. lower solubility of P in most soils,
lower solubility of Fe in all soils,
lower solubility of Mn in near-neutral and high pH soils, and
excessive solubility of Mn in strongly acidic soils could be some of the important factors limiting growth of rice under both moist and wet regimes.

Mineral Nutrition of IR43 in Six Soils
Under Three Different Moisture Regimes

Concentrations of mineral nutrients in the 8 week old shoots and in straw at harvest are presented in Tables 16 and 17, respectively and are discussed below.

Nitrogen. N concentrations in 8 week old shoot as well as straw grown in the Luisiana and Burabod soils were significantly higher under flooded than under the non-flooded conditions. Plants grown in the other four soils had significantly higher N

Table 16. Concentration of mineral nutrients in 8 week old shoot of IR43 grown in six soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | N | P | K | % | Ca | Mg | SiO ₂ | Na | Fe | Mn | Zn | Cu |
|----------|---------------------------------|---------|----------|-----------|-----------|----------|----------|------------------|--------|--------|---------|--------|----|
| | | | | | | | | | | | | | |
| Luisiana | Moist | 3.34 de | .216 ghi | 3.96 ab | .138 bc | .234 def | 7.64 ef | 62 fg | 65 de | 1117 b | 46 ab | 24 b | |
| | Wet | 3.05 ef | .198 ij | 3.86 abcd | .141 b | .283 bc | 9.20 bcd | 68 efg | 59 e | 1653 a | 42 bc | 22 b | |
| | Flooded | 3.74 bc | .235 fg | 2.91 e | .163 a | .235 def | 7.36 ef | 329 c | 102 b | 1014 c | 27 fg | 9 g | |
| Maahas A | Moist | 3.27 de | .235 fg | 4.00 ab | .122 cdef | .282 bc | 9.32 bcd | 75 efg | 66 de | 48 i | 32 def | 14 def | |
| | Wet | 2.77 fg | .249 f | 4.28 a | .109 ef | .271 bc | 12.36 a | 79 efg | 51 e | 52 i | 30 defg | 20 bc | |
| | Flooded | 2.12 i | .255 ef | 3.89 abc | .106 fg | .199 g | 9.89 bc | 127 e | 62 de | 800 d | 27 fg | 16 cde | |
| Pala | Moist | 3.47 cd | .252 ef | 3.57 bcd | .175 a | .270 bc | 9.63 bcd | 72 efg | 71 cde | 92 hi | 25 fg | 16 cde | |
| | Wet | 3.27 de | .301 bc | 3.45 cd | .175 a | .257 cde | 9.90 bc | 103 ef | 69 cde | 153 gh | 24 fg | 15 de | |
| | Flooded | 3.45 cd | .341 a | 3.40 d | .171 a | .265 cde | 9.47 bcd | 330 c | 73 cde | 559 e | 23 g | 12 efg | |
| Burabod | Moist | 3.70 bc | .208 hij | 3.86 abcd | .120 def | .300 b | 8.56 cde | 98 efg | 86 bcd | 399 f | 52 a | 35 a | |
| | Wet | 3.86 b | .228 gh | 2.61 ef | .129 bcd | .373 a | 8.22 de | 560 b | 110 b | 461 f | 51 a | 36 a | |
| | Flooded | 4.18 a | .300 bc | 2.40 f | .142 b | .257 cde | 6.41 f | 1380 a | 293 a | 158 gh | 28 efg | 12 efg | |
| Rotonda | Moist | 3.08 e | .282 cd | 4.08 a | .135 bcd | .255 cde | 9.32 bcd | 60 fg | 68 cde | 157 gh | 36 cde | 16 cde | |
| | Wet | 2.23 hi | .270 de | 3.87 abc | .124 cde | .251 cde | 10.19 b | 51 fg | 63 de | 243 g | 28 efg | 16 cde | |
| | Flooded | 2.51 gh | .306 b | 3.85 abcd | .124 cde | .231 ef | 9.33 bcd | 214 d | 93 bc | 616 e | 22 g | 10 fg | |
| Maahas B | Moist | 3.17 de | .173 k | 3.92 abc | .129 bcd | .268 bcd | 8.16 de | 69 efg | 70 cde | 35 i | 37 cd | 15 de | |
| | Wet | 2.37 hi | .189 jk | 3.89 abc | .092 gh | .256 cde | 11.53 a | 38 g | 56 e | 30 i | 28 efg | 17 cd | |
| | Flooded | 2.70 g | .270 de | 4.04 ab | .084 h | .217 fg | 10.22 b | 198 d | 73 cde | 413 f | 23 g | 10 fg | |

^aMean of 3 replications. In a column, means followed by a common letter are not significantly different by DMRT at the 5% level.

concentrations under moist than under the wet and flooded regimes which could be attributed to the differences in total dry matter production.

Phosphorus. P concentrations in 8 week old shoots were higher under flooded than under non-flooded regimes of all the soils. However, the difference was statistically significant in the Pila, Burabod, Rotonda and Maahas B soils. There were no significant differences in tissue P concentrations between moist and wet regimes of all the soils, except Pila in which it was higher under the wet regime.

In straw, P concentrations were higher under the flooded conditions of Luisiana, Maahas A, Burabod and Maahas B soils, and the increase was statistically significant only in the Burabod soil. The water regimes in the Rotonda soil did not show any significant effect on P concentration in straw. The observed higher concentration of P in straw in Pila soil under the moist regime could be due to poor dry matter yield as well as very low translocation of P from straw to grains. Grain yield in Pila soil was lowest under the moist regime. In most cases, there were no significant differences in P concentrations in straw between the moist and wet regimes.

Table 17. Concentration of mineral nutrients in straw of IR43 grown in six soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | % | | | | | | | | | | mg/kg | | | |
|----------|------------------------------|---------|------------|----------|----------|----------|------------------|--------|----------|---------|---------|-------|--|--|--|
| | | N | P | K | Ca | Mg | SiO ₂ | Na | Fe | Mn | Zn | Cu | | | |
| Luisiana | Moist | 1.84 c | .119 cdef | 3.52 bc | .357 a | .387 b | 9.37 hij | 122 h | 67 defgh | 3390 b | 97 c | 17 bc | | | |
| | Wet | 1.62 cd | .125 bcde | 4.11 a | .369 a | .445 a | 12.86 cde | 139 h | 56 efgh | 4730 a | 113 b | 21 b | | | |
| | Flooded | 2.39 b | .154 b | 1.81 e | .177 cde | .191 ef | 6.38 k | 1114 d | 224 b | 1397 c | 34 efgh | 3 h | | | |
| Maahas A | Moist | 1.43 de | .124 bcde | 3.65 abc | .159 def | .285 cd | 10.74 fgh | 138 h | 66 defgh | 201 h | 31 fgh | 9 ef | | | |
| | Wet | 0.89 fg | .106 defg | 3.32 bc | .126 f | .257 d | 16.84 a | 151 h | 59 efgh | 156 h | 32 efgh | 8 efg | | | |
| | Flooded | 0.73 g | .130 bcde | 3.12 cd | .151 ef | .210 e | 15.20 b | 363 f | 74 def | 1278 cd | 43 de | 6 fgh | | | |
| Pila | Moist | 1.74 c | .188 a | 3.55 bc | .260 b | .298 cd | 12.98 cd | 141 h | 38 h | 78 h | 18 i | 14 cd | | | |
| | Wet | 1.35 e | .150 bc | 3.48 bc | .212 c | .283 cd | 14.00 bc | 149 h | 50 efgh | 130 h | 17 i | 12 de | | | |
| | Flooded | 0.93 fg | .136 bcd | 2.74 d | .272 b | .212 e | 13.21 cd | 1387 c | 72 defg | 612 f | 17 i | 4 gh | | | |
| Burabod | Moist | 2.41 b | .088 fg | 1.80 e | .147 ef | .308 c | 8.87 ij | 326 fg | 96 d | 851 e | 109 b | 27 a | | | |
| | Wet | 1.74 c | .097 efg | 1.26 f | .175 cde | .403 b | 9.75 ghi | 3825 b | 149 c | 882 e | 135 a | 28 a | | | |
| | Flooded | 2.72 a | .201 a | 1.58 ef | .126 f | .144 g | 7.82 jk | 5647 a | 589 a | 102 h | 25 hi | 4 gh | | | |
| Rotonda | Moist | 1.38 e | .145 bc | 3.85 ab | .195 cd | .280 cd | 10.78 fgh | 122 h | 51 efgh | 464 g | 36 efgh | 9 ef | | | |
| | Wet | 0.99 f | .135 bcd | 3.65 abc | .168 de | .209 e | 12.22 def | 206 gh | 54 efgh | 858 e | 52 d | 8 efg | | | |
| | Flooded | 0.79 fg | .128 bcde | 3.23 cd | .209 c | .168 efg | 10.30 ghi | 471 ef | 95 d | 1243 d | 41 ef | 3 h | | | |
| Maahas B | Moist | 1.35 e | .085 g | 3.65 abc | .156 ef | .267 cd | 11.23 efg | 140 h | 41 gh | 91 h | 38 efg | 8 efg | | | |
| | Wet | 0.82 fg | .120 bcdef | 3.14 cd | .086 g | .170 efg | 13.14 cd | 139 h | 47 fgh | 62 h | 28 ghi | 5 fgh | | | |
| | Flooded | 0.75 g | .143 bc | 3.30 bc | .139 ef | .151 fg | 14.08 bc | 527 e | 79 de | 671 f | 39 efg | 3 h | | | |

^aMean of 3 replications. In a column, means followed by a common letter are not significantly different by DMRT at the 5% level.

Potassium. K concentrations in 8 week old shoots were significantly lower under flooded than under non-flooded regimes of the Luisiana and Burabod soils. In the other soils, K concentrations in plants did not vary significantly with the moisture regimes. These results confirm those of the previous experiment.

While concentrations of K in straw were significantly lower under flooded regimes of the Luisiana and Pila soils, it did not vary remarkably with the moisture regimes of the Maahas A, Maahas B, Burabod and Rotonda soils.

Calcium. Ca concentration in 8 week old shoot grown in the Luisiana soil was significantly lower under non-flooded than under flooded condition. It will be mentioned that plants in the early tillering stage showed symptoms similar to that of Ca deficiency in the non-flooded Luisiana soil and recovered from it in the later stage. Straw analysis revealed significantly higher Ca concentration under the non-flooded conditions. No significant difference in tissue Ca concentrations was found between moist and wet regimes of the soil.

In the other soils, moisture regimes did not show any remarkable variation in the Ca concentrations in plants.

Magnesium. Generally, Mg concentrations in plants (8 week old shoot as well as straw) were higher under non-flooded than under flooded regimes of all the soils and this difference was remarkable in the straw. No consistent differences in tissue Mg concentrations were found between moist and wet regimes of the soils.

Silica. Concentrations of crude SiO_2 in plants (8 week old shoot as well as straw) were significantly higher under wet and flooded than under the moist regimes of the Maahas A and Maahas B soils. In the strongly acidic Luisiana and Burabod soils, it was lowest under the flooded and highest under the wet regimes. This confirms the findings of the previous experiment.

Although statistically insignificant, SiO_2 concentrations in plants were higher under wet than under moist and flooded regimes of the Pila and Rotonda soils.

The observed higher concentrations of SiO_2 in plants under wet regimes of most of the soils imply that supply of abundant moisture rather than soil reduction brought on by flooding chiefly contributes to higher silica uptake in rice.

Sodium. Na concentrations in shoots as well as straw were significantly higher under flooded than under non-flooded conditions of all the soils. The tissue Na concentration was

higher under wet than under moist regime of the Burabod soil. In the other soils, however, wet and moist regimes did not differ in this respect.

Iron. Flooding significantly increased concentrations of Fe in 8 week old shoots in the Luisiana and Burabod soils, and in straw in the Luisiana, Burabod, Rotonda and Maahas B soils. In the other soils, increases in tissue Fe concentrations due to flooding were not statistically significant. These observations confirm the findings of the previous experiments. No significant differences in Fe concentrations in tissue were found between moist and wet regimes of the soils.

Manganese. The observed significantly higher Mn concentrations in plants (shoot as well as straw) in the Luisiana and Burabod soils under non-flooded than under flooded conditions are in conformity with the results of the previous experiments. In the other soils, flooding significantly increased Mn concentrations in tissues. Of these four non-flooded (Maahas A, Pila, Rotonda and Maahas B) soils, the moderately acidic Rotonda produced plants with significantly higher concentration of Mn, than did the other soils with higher pH. No significant differences in tissue Mn concentrations were found between the moist and wet regimes of most soils.

Zinc and copper. Plants (shoot as well as straw) growing in the acidic Luisiana, Burabod and Rotonda soils generally had significantly higher Zn and Cu concentrations under non-flooded than under flooded regimes. In the near-neutral Maahas A and Maahas B, and the calcareous Pila soils, moisture regimes did not have any remarkable influence on Zn and Cu concentrations in plants. Generally no significant differences in Zn and Cu concentrations in tissue were found between moist and wet regimes of the soils.

Mineral nutrient analyses in plants suggest that regardless of the amount and frequency of water supply, in well-drained or aerobic regimes rice plants suffer from:

1. lower availability of P, Fe and Na in all soils;
2. lower availability of Mn in soils of pH >6; and
3. toxic concentration of Mn in strongly acidic soils with high active Mn content.

These analyses also confirm that:

1. availability of SiO_2 to rice is low under field capacity moisture regime, but it increases markedly with abundant supply of water even when soils remain aerobic, and
2. total Fe content in tissue is not a satisfactory index of Fe availability to rice, especially in near-neutral and high pH soils (concentrations of total Fe in chlorotic plants were not significantly lower than that in the normal green plants in calcareous Pila soil).

Growth and Yield of IR43 in Six Soils
Under Three Different Moisture Regimes

Visual symptoms

Since the seedlings growing in the non-flooded (both moist and wet) calcareous soil were suffering from acute Fe chlorosis, they were replaced within first 3 weeks by healthy seedlings raised on normal soils. The transplanted seedlings also started showing moderate chlorotic symptoms soon after their establishment. Under flooded condition of the same soil, seedlings raised by direct seeding looked poor during first 2 weeks, but they recovered and grew normally thereafter without showing Fe chlorosis symptoms.

In the tillering stage, plants in the non-flooded Louisiana soil showed poor growth with complex symptoms of chlorosis and bleaching on young leaves. However, the plants recovered from it gradually with time. Under flooded condition, plants grew vigorously in this soil; but foliage remained dark green even at maturity and the grains did not mature uniformly.

Although no clear specific toxicity symptoms appeared on foliage, growth of plants was severely arrested in the flooded Burabod soil.

In the moderately acidic Rotonda and near-neutral Maahas A and Maahas B soils, growth was highest under the flooded regimes, followed by the wet and moist regimes (Plates 9 and 10).

Plant height and tiller number

Plant heights and tiller number per pot (of two 8 week old plants) under different treatments are presented in Table 18. In the Luisiana, Maahas A, Pila, Rotonda and Maahas B soils, plant height and tiller number were higher under flooded than under non-flooded conditions. In the acid-sulfate soil from Burabod, however, both the growth measurement were significantly lower under flooded than under non-flooded regimes. Plant height and tiller number were higher under wet than under moist regimes of all the soils.

Dry matter yield of 8 week old shoot

Table 18 presents dry matter yield of 8 week old shoots of IR43 in six soils under three different moisture regimes. The yields were significantly higher under flooded than under non-flooded regimes of the Luisiana, Maahas A, Pila, Rotonda and Maahas B soils. In the acid-sulfate soil from Burabod, however, flooded condition produced lowest yield. Yields were higher under wet than under moist regimes of all the soils.



Plate 9. Growth of IR43 in the moderately acidic Rotonda soil under (a) Moist, (b) Wet, and (c) Flooded conditions.

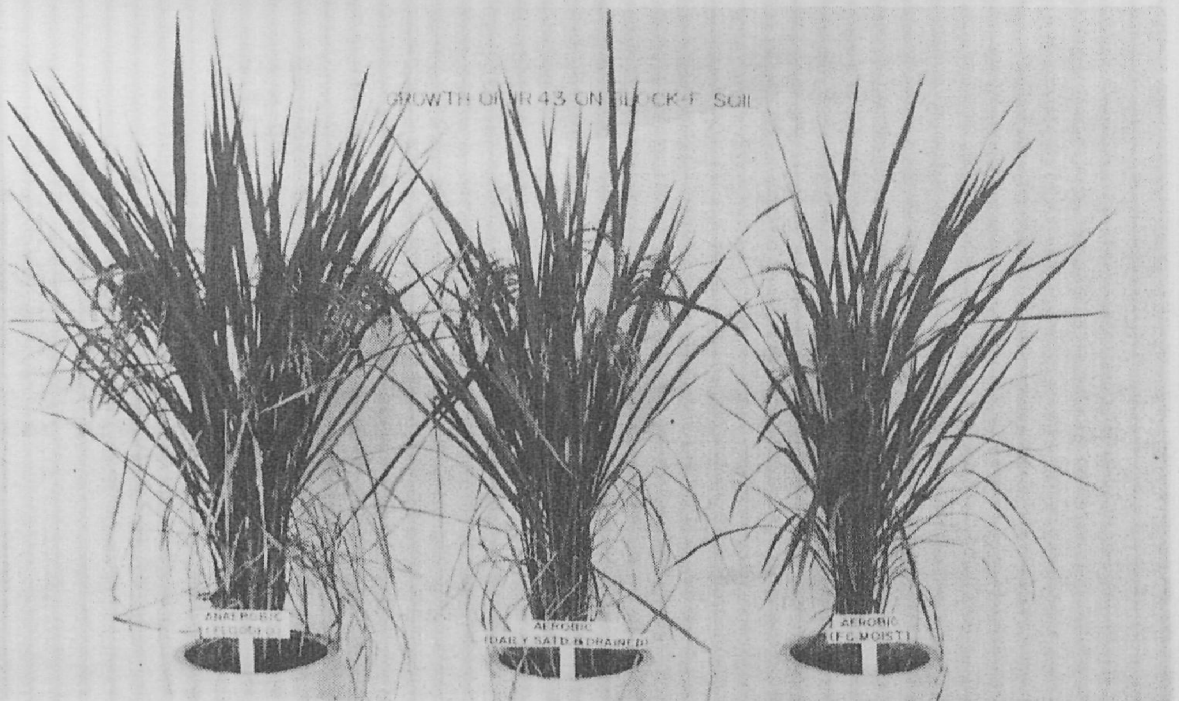


Plate 10. Growth of IR43 in the near-neutral Maahas B soil under (a) Flooded, (b) Wet, and (c) Moist condition.

Table 18. Growth and dry matter yield of 8 week old IR43^a in six soils under moist, wet and flooded conditions.

| Soil | Treatment | | Plant height (cm) | Tiller number per pot | Dry matter yield of shoot (g/pot) |
|----------|-----------------|--|-------------------|-----------------------|-----------------------------------|
| | Moisture regime | | | | |
| Luisiana | Moist | | 87.3 g | 18 de | 15.5 de |
| | Wet | | 95.1 f | 19 de | 16.6 de |
| | Flooded | | 104.3 e | 22 cd | 22.6 c |
| Maahas A | Moist | | 97.1 f | 16 ef | 12.7 ef |
| | Wet | | 115.9 bc | 20 de | 26.5 c |
| | Flooded | | 123.7 a | 22 cd | 34.7 b |
| Pila | Moist | | 81.3 h | 11 g | 9.8 f |
| | Wet | | 86.7 g | 12 fg | 12.6 ef |
| | Flooded | | 119.0 b | 17 e | 22.7 c |
| Burabod | Moist | | 96.3 f | 25 bc | 17.7 d |
| | Wet | | 109.4 d | 26 bc | 25.3 c |
| | Flooded | | 88.4 g | 17 e | 13.3 ef |
| Rotonda | Moist | | 103.4 e | 19 de | 18.7 d |
| | Wet | | 113.6 cd | 22 cd | 25.3 c |
| | Flooded | | 117.1 bc | 32 a | 46.2 a |
| Maahas B | Moist | | 93.0 f | 19 de | 15.0 de |
| | Wet | | 109.8 d | 20 de | 25.8 c |
| | Flooded | | 123.7 a | 28 ab | 49.1 a |

^aMean of 3 replications. In a column, means followed by a common letter are not significantly different by DMRT at the 5% level.

Grain yield

Table 19 shows that grain yields in the Maahas A, Pila, Rotonda and Maahas B soils were significantly higher under flooded than under non-flooded conditions. In the Luisiana soil, yields under flooded and non-flooded conditions did not differ significantly. In all these soils, wet regimes produced significantly more grains than did the moist regimes. Grain yield in the Burabod soil was highest under wet regime, followed by the flooded and moist regimes.

Compared to that obtained under flooded conditions, grain yields under wet regimes of the Maahas A, Pila, Rotonda and Maahas B soils were 83, 26, 81 and 43 per cent, respectively. Since comparable amounts of water were supplied under the wet (aerobic) and flooded (anaerobic) regimes, the observed yield reductions could apparently be attributed to the adverse chemical factors prevalent under aerobic conditions of the soils. The apparent contributions of aerobic conditions of soils to the yield reductions in rice were thus computed for Maahas A, Pila, Rotonda and Maahas B soils. Data from the previous (Experiment No. 3) and the present experiments are presented in Table 20.

Table 19. Grain and straw yield of IR43 in six soils under moist, wet and flooded conditions.^a

| Soil | Treatment | | Grain yield ----- | Straw yield g/pot ----- |
|----------|--------------------|--|-------------------------|-------------------------------|
| | Moisture regime | | | |
| Luisiana | Moist | | 23.1 hi | 53.7 gh |
| | Wet | | 40.2 efg | 60.8 fg |
| | Flooded | | 33.2 fgh | 119.7 a |
| Maahas A | Moist | | 29.0 h | 52.2 ghi |
| | Wet | | 54.2 d | 69.6 ef |
| | Flooded | | 65.5 c | 72.7 e |
| Pila | Moist | | 12.7 j | 37.9 j |
| | Wet | | 29.2 h | 35.9 j |
| | Flooded | | 112.4 a | 108.3 b |
| Burabod | Moist | | 18.7 ij | 67.6 ef |
| | Wet | | 66.7 c | 98.2 c |
| | Flooded | | 30.7 gh | 43.0 ij |
| Rotonda | Moist | | 41.3 ef | 64.7 ef |
| | Wet | | 75.1 c | 87.9 d |
| | Flooded | | 93.1 b | 85.8 d |
| Maahas B | Moist | | 25.6 hi | 48.7 hi |
| | Wet | | 45.8 de | 89.7 cd |
| | Flooded | | 106.8 a | 114.9 ab |

^aMean of 3 replications. In a column, means followed by a common letter are not significantly different by DMRT at the 5% level.

Straw yield

Straw yields in the Luisiana, Pila and Maahas B soils were significantly higher under flooded than under non-flooded conditions (Table 19). The flooded and wet regimes produced comparable straw yields in the Maahas A and Rotonda soils, and the yields under these two regimes were significantly higher than those under moist regimes. Burabod soil, however, produced significantly lower yield of straw under flooded than under non-flooded conditions.

Table 20. Apparent contributions of aerobic conditions of some soils to the grain yield reductions in rice. IRRI Greenhouse (1986).

| Soil ^a | | Grain yields (g/pot) under different moisture regimes | | | % Yield reduction due to | |
|-------------------|----|---|------|---------|--|-----------------------------------|
| | | Moist | Wet | Flooded | Inadequate moisture ^b and aerobic conditions of soils | Aerobic conditions of soils |
| | | | | | | |
| Maahas A | I | 22.9 | 74.8 | 111.5 | 80 | 33 |
| | II | 29.0 | 54.2 | 65.5 | 56 | 17 |
| Maahas B | | 25.6 | 45.8 | 106.8 | 76 | 57 |
| Pila | I | 0 | 0 | 97.5 | 100 | 100 |
| | II | 12.7 | 29.2 | 112.4 | 89 | 74 |
| Rotonda | | 41.3 | 75.1 | 93.1 | 56 | 19 |

^aI - Experiment No. 3, 1986 Dry Season.
II - Experiment No. 4, 1986 Wet Season

^bAt constant field capacity moisture regime.

Experiment 5

Growth and Mineral Nutrition
of Two Rices in a Near-Neutral Soil
Under Non-flooded and Flooded Field Conditions

Growth and mineral nutrition of rice in several soils under non-flooded and flooded conditions were studied in detail in greenhouse. To examine the extent to which those findings are valid under field conditions, an experiment was conducted in Block UK1 of IRRI farm wherefrom the Maahas A soil had been sampled for the greenhouse studies. This experiment compared the growth and nutritional status of two rices under flooded and non-flooded conditions of the field. Effects of some amendments on the performance of these rices under two different water regimes were also tested.

MATERIALS AND METHODS

The experiment was conducted in Block UK1 of IRRI farm wherefrom the Maahas A soil had been collected for the greenhouse experiments. Although it was originally scheduled in 1985 Wet Season, but had to be postponed because of non-availability of the field. It was carried out in the following season, i.e., 1986 Dry Season. For the sake of putting it in order, this experiment is being reported before the other field experiment.

Experimental factors and levels

It was a 2 x 2 x 3 factorial experiment laid in a split plot design with 4 replications.

Mainplot treatments. Two moisture regimes were taken:

M1 - Non-flooded (Moisture level around Field Capacity)

M2 - Flooded (Submerged with 5cm level of standing water)

Subplot treatments. The following factorial combinations of 2 cultivars (V1 and V2) and 3 amendments (A1, A2 and A3) were allotted to the subplots:

A1V1

A1V2

A2V1

A2V2

A3V1

A3V2

The cultivars and amendments used are shown below:

Cultivars: V1 - IR64 (a lowland variety)

V2 - IR5931-110-1-3 (a promising upland line), which will be referred to as IR5931 when results are discussed.

Amendments: A1 - NK

A2 - NPK

A3 - NPK + chicken manure

Sources and rates of amendment application

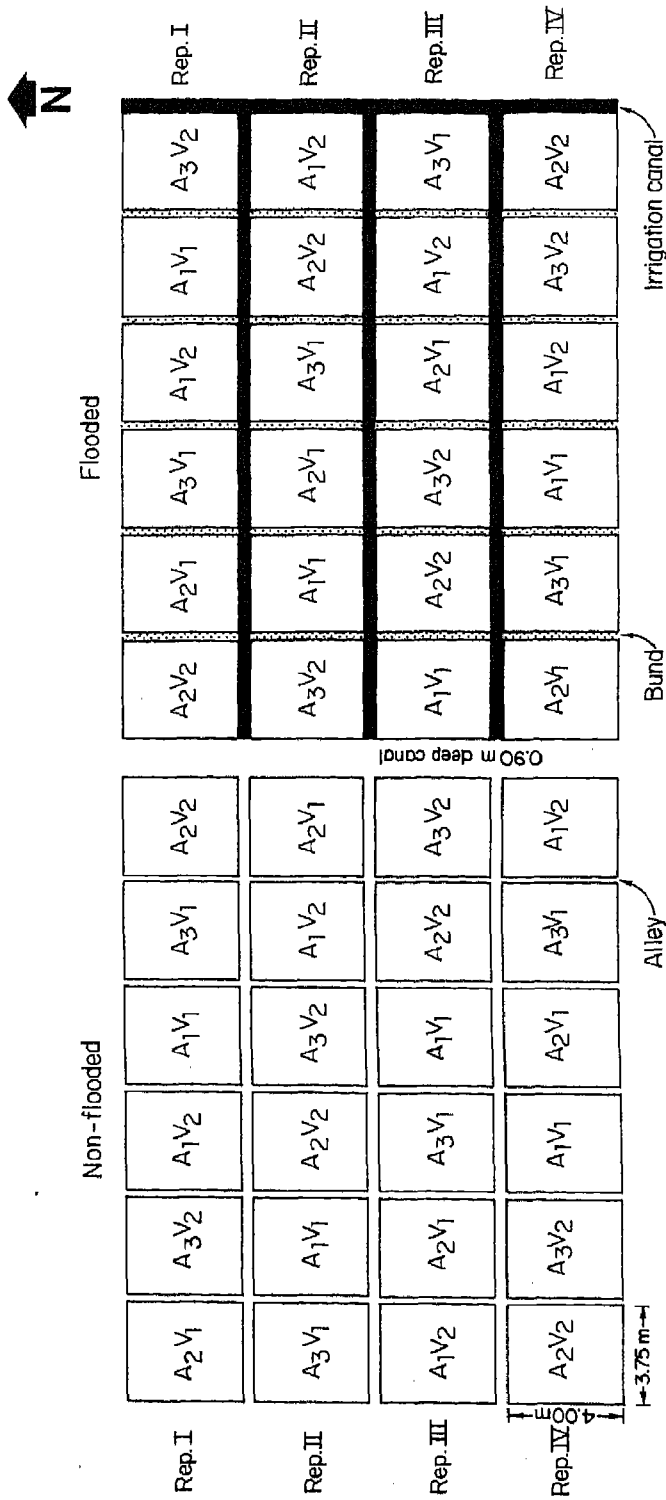
Nitrogen was applied as ammonium sulfate at the rate of 50 kg N/ha. P at the rate of 25 kg/ha was supplied in the form of triple superphosphate. Muriate of potash was used to apply K at the rate of 25 kg/ha. Air-dried chicken manure collected from a nearby poultry farm was applied at the rate of 5t/ha. Analyses of the chicken manure are shown in Table 21.

Land preparation

The entire field (57m x 19m) was plowed once and rotovated twice by tractor. After levelling, the rectangular field was divided into two equal plots by digging a 60 cm wide and 90 cm deep canal across the width of the field. Each plot was then divided into 24 subplots each of 4m x 3.75m size. While the plot meant for receiving the non-flooded treatment was maintained level, subplots in the other plot were bunded by levees and surrounded by irrigation canals. The lay-out of the field is shown in Fig. 56.

Application of amendments

Full dose of chicken manure (7.5 kg per plot) was applied to the respective plots two weeks before seeding and incorporated thoroughly into soil by rotovation. Full doses of P and K were applied to the respective plots and mixed thoroughly with soil at final land preparation, that is, two



Amendments: A₁ - NK, A₂ - NPK, A₃ - NPK + Chicken manure.
 Cultivars: V₁ - IR64, V₂ - IR5931 - IIO - 1 - 3

Fig. 56. Lay-out of the experimental plots in the field. Block UK1, IRRI Farm.

days before seeding in the non-flooded and one day before transplanting in flooded plots. Nitrogen was applied in two splits (33 + 17 kg N/ha). The first application to the flooded plots was made 1 day before transplanting and was incorporated in the soil during the final harrowing. The first application was broadcast on the non-flooded plots 3 weeks after the emergence of seedlings. The second applications of N were broadcast in both flooded and non-flooded plots at the panicle initiation stage of the crop.

Planting

Overnight soaked seeds were dibbled at 2-3 cm depth and 20cm x 20cm spacing. Each hill received 5 to 6 seeds. Immediately after seeding, one irrigation (by sprinkler) was given to help germination of the seeds. For raising seedlings for the flooded plots, wet seedbeds (2 beds for 2 cultivars) were established at the same time in an adjacent block.

After emergence and stand establishment, each hill in non-flooded plots was thinned to keep 3 seedlings for growing upto maturity. The 3 week old seedlings raised in seedbeds were transplanted to the flooded and puddled plots at 3 seedlings per hill with 20cm x 20cm spacing. Three days after transplanting, the poor, dead and floating seedlings were replaced.

Irrigation

Moisture levels in the non-flooded plots were maintained near field capacity by twice weekly irrigation using sprinkler. Adjustment was made for rainfall received. Crop was never allowed to suffer from any visible moisture stress symptoms. The flooded plots were irrigated daily as necessary to maintain 5cm level of standing water.

Weeding

All the plots were kept free of weeds by regular hand weeding as necessary.

Pesticide application

'Furadan' (a granular broad-spectrum insecticide) at the rate of 60 kg/ha was incorporated in all the plots during land preparation. As preventive measures against insect pest damage, the crop was sprayed 2 times with 'Azodrin' at recommended dose.

Measurement of soil redox potential

Sixteen bright platinum electrodes were installed at 15 cm depth at randomly selected points on both flooded and non-flooded plots. Soil redox potentials were recorded at 7, 9, 12 and 15 weeks after transplanting by using saturated calomel electrode and a portable potentiometer (Model: CORNING pH/Temp Meter 4).

Collection and preparation of plant samples for analysis

Flag leaves. At 15 weeks after seeding, about 15 flag leaves were collected at random from each plot, brought to the laboratory, washed with tap water followed by 0.1(N)HCl and demineralized water. The washed fresh leaves were then chopped into uniformly small pieces using stainless steel scissors and analyzed for active (ortho-phenanthroline extractable) Fe.

Straw. At harvest time, six hills from each plot were harvested at random above ground surface and brought to the greenhouse for yield component estimation. After measuring height, counting and separating panicles, the six sub-samples were combined together to get the composite straw sample for each plot. The basal 5-6 cm portion, and the dead and dirty leaves were discarded from the samples before washing and processing. The washing and processing were done in same way as described earlier (Experiment 2).

Harvesting

For estimating grain yield, plants were harvested from an area of 5 m² of each plot. Total 125 hills of the harvesting area were collected in two separate bundles, one of 25 hills and the other of 100 hills. After threshing, the grains were combined together to get total grain yield from 5 m² area of each plot. The small bundle of 25 hills from each plot was saved after threshing, to estimate straw yield from 1 m² area.

The threshed grain and straw samples were dried on an open drier for about one week and then weighed. Grain yields were corrected to 14% moisture content and expressed in t/ha.

Analysis of plant samples

Fresh flag leaves were analyzed for ortho-phenanthroline extractable Fe content following the method described by Katyal and Sharma (1980). Straw samples were analyzed for total N, P, K, Ca, Mg, Fe, Mn, Zn, Cu, Na and crude SiO_2 following the same methods as used in the previous experiments.

RESULTS AND DISCUSSION

Redox conditions of the field under non-flooded and flooded conditions

Recorded redox potential values (Table 22) indicated oxidized and reduced status of the non-flooded and flooded plots, respectively.

Nutritional status of two rices under non-flooded and flooded field conditions

Fe²⁺ concentration in the flag leaves. Table 24 shows that active iron (Fe²⁺) concentrations in flag leaves of both the cultivars were significantly lower under non-flooded than that under the flooded regime. Under non-flooded condition, Fe²⁺ concentrations in both the rices were lower

Table 21. Analysis of the chicken manure^a
(oven-dry weight basis).

| | |
|------------------|-----------|
| Organic C | 19.1 % |
| N | 2.32 % |
| P | 1.21 % |
| K | 2.30% |
| Ca | 0.27% |
| Mg | 1.30% |
| Na | 0.77 % |
| Fe | 0.73 % |
| Mn | 0.13 % |
| Zn | 652 mg/kg |
| Cu | 106 mg/kg |
| SiO ₂ | 35.0% |

^aOrg. C by the Walkley and Black wet-digestion method and other elements by the methods used for plant analysis.

Table 22. In situ redox potentials of rice field under two different moisture regimes. Block UK1, IRR1 Farm. 1986 dry season.

| Moisture regime | Redox potential (mV) | | | |
|-----------------|---------------------------|-----|------|------|
| | Weeks after transplanting | | | |
| | 7 | 9 | 12 | 15 |
| Non-flooded | 541 | 537 | 575 | 564 |
| Flooded | -58 | -65 | -128 | -145 |

than the proposed critical limit of 40-45 ppm (Katyal and Sharma 1984, Singh and Singh 1984), however, it is only IR64 that showed clear Fe chlorosis symptoms. Under both the moisture regimes, Fe^{2+} concentrations in IR5931 were remarkably higher than that in IR64. Application of P and organic manure had no measurable influence on the tissue Fe^{2+} content.

Nutrient concentrations in straw. Concentrations of various mineral nutrients in straw are presented in Tables 23 and 24, and described under the following heads:

- a. Nitrogen - N concentration in straw was higher under non-flooded than under the flooded regime and this difference was significant only in IR64. Since total dry matter production of this cultivar was much higher under flooded regime, the observed lower N concentration could be attributed to its dilution in tissue. Neither P nor the chicken manure showed any marked effect on the tissue N content.
- b. Phosphorus - P concentration in straw was significantly lower under flooded than under non-flooded regime. The greenhouse experiment (Experiment 3, 1986 dry season) produced the same results for this particular soil and moisture regimes. It has been shown that the remarkably lower P content in straw under the flooded regime may be attributed partly to the dilution in plants and partly to higher

translocation of P from straw to grains. The cultivars did not show any marked variation in their tissue P content. Application of P and chicken manure also had no effect on P concentration in tissue. Probably, the rate of P application was insufficient to produce any appreciable effect.

- c. Potassium - The moisture regimes did not have any remarkable effect on K concentration in straw. In both the moisture regimes, IR5931 had markedly higher K content than did IR64. Application of chicken manure under flooded condition increased the K concentration significantly only in IR64; no other treatments showed any appreciable effect on tissue K content.
- d. Calcium - Ca concentrations in straw of both the cultivars were significantly higher under flooded than under non-flooded conditions. Under non-flooded regime, Ca content in tissue did not vary with the cultivars and the amendments applied. Application of P and chicken manure under flooded condition, however, increased Ca concentration in IR5931.
- e. Magnesium - Both the rices had significantly higher Mg concentrations in straw under flooded than under non-flooded regime. In the non-flooded regime, IR5931 had markedly higher Mg content than did IR64. Under

flooded condition, no appreciable difference was noted between the two cultivars and application of the chicken manure markedly reduced Mg concentration in tissues.

- f. Sodium - Na concentrations in straw of both the rices were significantly higher under flooded than under non-flooded conditions. Under both the moisture regimes, IR5931 had remarkably higher Na content than did IR64. Applied P and chicken manure did not show any consistent effect on tissue Na content.
- g. Iron - Total Fe concentrations in straw did not vary significantly with the moisture regimes, cultivars and the applied amendments. IR64 plants that showed chlorotic symptoms typical of Fe deficiency under non-flooded condition, had even higher total Fe content in tissue. These findings indicate that chlorosis in rice is not always associated with the total Fe content in tissue. The ortho-phenanthroline extractable ferrous iron was found to be the active fraction in this respect (see analysis of Fe^{2+} concentration in flag leaves).
- h. Manganese - In both the rices, Mn concentrations in straw were significantly higher under flooded than under non-flooded regimes. Under non-flooded regime, tissue Mn concentration was very low and

Table 24. Concentration of mineral nutrients (Fe, Mn, Zn, Cu and Na) in straw and active Fe in flag leaves of two rices grown under non-flooded and flooded conditions of Block UK1, IRRI Farm,^a 1986 Dry Season.

| Treatment | Active Fe (mg/kg) | | Total Fe (mg/kg) | | Mn (mg/kg) | |
|-------------------------------|-------------------|------------|-------------------|-----------|-------------------|-----------|
| | Non-flooded | Flooded | Non-flooded | Flooded | Non-flooded | Flooded |
| A ₁ V ₁ | 32.3 AB(b) | 48.4 AB(a) | 76 A(a) | 61 A(a) | 21 A(b) | 456 A (a) |
| A ₁ V ₂ | 35.4 A (b) | 51.2 A (a) | 78 A(a) | 59 A(a) | 18 A(b) | 434 AB(a) |
| A ₂ V ₁ | 29.8 B(b) | 45.2 B(a) | 85 A(a) | 61 A(a) | 25 A(b) | 476 A (a) |
| A ₂ V ₂ | 34.8 AB(b) | 50.4 A (a) | 71 A(a) | 56 A(a) | 16 A(b) | 441 AB(a) |
| A ₃ V ₁ | 31.7 AB(b) | 45.1 B(a) | 85 A(a) | 61 A(a) | 20 A(b) | 385 C(a) |
| A ₃ V ₂ | 34.2 AB(b) | 49.9 AB(a) | 78 A(a) | 58 A(a) | 16 A(b) | 398 BC(a) |
| | <u>Zn (mg/kg)</u> | | <u>Cu (mg/kg)</u> | | <u>Na (mg/kg)</u> | |
| A ₁ V ₁ | 15.0 B(b) | 37.1 C(a) | 4.0 B(b) | 4.9 A(a) | 163 C(b) | 225 D(a) |
| A ₁ V ₂ | 27.0 A(b) | 48.3 A(a) | 5.0 A(a) | 3.8 C(b) | 213 ABC(b) | 463 A(a) |
| A ₂ V ₁ | 13.6 B(b) | 36.3 C(a) | 3.9 B(a) | 4.4 AB(a) | 183 BC (b) | 300 C(a) |
| A ₂ V ₂ | 25.6 A(b) | 50.9 A(a) | 4.9 A(a) | 3.9 BC(b) | 225 AB (b) | 463 A(a) |
| A ₃ V ₁ | 15.8 B(b) | 37.1 C(a) | 4.2 B(a) | 4.8 A (a) | 183 BC (b) | 300 C(a) |
| A ₃ V ₂ | 24.8 A(b) | 43.0 B(a) | 5.3 A(a) | 4.0 BC(b) | 250 A (b) | 400 B(a) |

A = Amendments. A₁ - NK, A₂ - NPK, A₃ - NPK + chicken manure.
V = Cultivars. V₁ - IR64. V₂ - IR5931-110-1-3.

^a Means of 4 replications. In a column, means followed by a common capital letter and in a row, means followed by a common small letter (within parentheses) are not significantly different by DMRT at 5% level.

suspected to be in the deficient range. Regardless of the moisture regimes, there was no remarkable effect of the cultivars and the applied amendments on Mn concentration in tissues.

- i. Zinc - Flooding significantly increased Zn concentrations in straw of both the cultivars. Under both the moisture regimes, IR5931 had significantly higher Zn content than did IR64. Application of P and organic manure generally had no effect on tissue Zn concentration.
- j. Copper - Flooding significantly decreased Cu concentration in IR5931 straw and slightly increased it in IR64. Under non-flooded regime, IR5931 had significantly higher Cu content than that of IR64. Contrastingly, under flooded condition it was remarkably higher in IR64 than in IR5931. None of the applied amendments showed any influence on the tissue Cu content.
- k. Silica - Flooding increased crude SiO_2 content in straw significantly in both the rices. Under non-flooded regime, IR5931 had significantly higher SiO_2 content in straw than that in IR64; contrastingly, under flooded condition, IR64 had higher SiO_2 content than that in IR5931. Only under flooded regime, application of chicken manure increased the SiO_2 content in IR5931.

Growth, some yield components and yields of two rices under non-flooded and flooded field conditions

Visual symptoms. Under non-flooded conditions, IR64 showed very poor growth with chlorotic symptoms, whereas IR5931 grew quite normally without any symptom of chlorosis. Under flooded conditions, IR64 grew more vigorously than IR5931, and none of the cultivars showed any chlorotic symptoms. Tillering of IR5931 was markedly poor than that of IR64 under the flooded regime. IR64 matured about 10 days earlier than did IR5931.

Plant height. Height of the plants at maturity are presented in Table 25. It shows that height of both the cultivars were significantly higher under flooded than under non-flooded conditions. IR5931 grew significantly taller than IR64 under both the water regimes. Application of P and chicken manure did not produce any effect on plant height.

Panicle number. Table 25 shows that panicle number per hill of IR64 was significantly higher under flooded than under non-flooded conditions. Contrastingly, IR5931 produced more panicles under non-flooded condition. With respect to panicle production, IR64 proved significantly superior to IR5931 under flooded but significantly inferior to the same cultivar under non-flooded regime. Application of P and chicken manure did not show any consistent effects on panicle formation, regardless of cultivars and moisture regimes.

Unfilled spikelet percentage. In both the cultivars, spikelet sterility was significantly higher under non-flooded than under flooded conditions (Table 25). Under non-flooded regime, IR64 had significantly higher percentage of unfilled spikelets than did IR5931; whereas under flooded condition, IR5931 showed higher sterility. Application of P and chicken manure showed no remarkable influence on the sterility percentage.

100 grain weight. Table 25 shows that 100 grain weights of both the cultivars were significantly higher under flooded than under non-flooded conditions. Under the non-flooded regime, 100 grain weight of IR5931 was significantly higher than that of IR64. Contrastingly, IR64 produced significantly heavier grains than did IR5931 under the flooded regime. In general, application of P and chicken manure did not have any remarkable effect on this trait.

Grain yield. Table 26 shows that grain yield of IR64 was very poor and significantly lower than that of IR5931 under the non-flooded condition. Contrastingly, IR64 yielded significantly higher than IR5931 under the flooded regime. Flooding increased grain yield in both the cultivars. The increase due to flooding was highly significant in IR64 and generally

Table 25. Plant height (at harvest), panicle number, unfilled spikelet percentage and 100 grain weight of two rices grown under non-flooded and flooded conditions of Block UKI, IRRI Farm.^a 1986 Dry Season.

| Treatment | Plant height (cm) | | Panicle No./hill | | Unfilled spikelet % | | 100 grain weight (gm) | |
|-------------------------------|-------------------|-----------|------------------|-------------|---------------------|------------|-----------------------|-----------|
| | Non-flooded | Flooded | Non-flooded | Flooded | Non-flooded | Flooded | Non-flooded | Flooded |
| A ₁ V ₁ | 58.7 B(b) | 85.8 B(a) | 8.5 B(b) | 11.9 BC(a) | 53.1 B(a) | 23.1 AB(b) | 1.65 C(b) | 2.52 A(a) |
| A ₁ V ₂ | 81.7 A(b) | 97.8 A(a) | 13.2 A(a) | 9.8 D(b) | 40.3 C(a) | 28.3 A(b) | 2.11 A(a) | 2.19 B(a) |
| A ₂ V ₁ | 59.4 B(b) | 87.8 B(a) | 8.6 B(b) | 13.3 AB(a) | 54.3 B(a) | 19.1 B(b) | 1.64 C(b) | 2.51 A(a) |
| A ₂ V ₂ | 80.7 A(b) | 97.6 A(a) | 13.0 A(a) | 9.4 D(b) | 40.8 C(a) | 25.5 AB(b) | 2.09 A(b) | 2.22 B(a) |
| A ₃ V ₁ | 55.5 B(b) | 90.2 B(a) | 8.7 B(b) | 13.8 A(a) | 62.2 A(a) | 17.9 B(b) | 1.69 C(b) | 2.56 A(a) |
| A ₃ V ₂ | 85.4 A(b) | 97.2 A(a) | 12.3 A(a) | 10.9 CD (a) | 35.2 C(a) | 24.9 AB(b) | 1.96 B(b) | 2.15 B(a) |

A = Amendments. A₁ - NK, A₂ - NPK, A₃ - NPK + chicken manure.
V = Cultivars. V₁ - IR64. V₂ - IR5931-110-1-3.

^aMeans of 4 replications. In a column, means followed by a common capital letter and in a row, means followed by a common small letter (within parentheses) are not significantly different by DMRT at 5% level.

Table 26. Grain and straw yield of two rices grown under non-flooded and flooded conditions of Block UK1, IRRI farm.^a 1986 Dry Season.

| Treatment | Grain Yield (t/ha) | | Straw Yield (t/ha) | |
|-------------------------------|--------------------|------------|--------------------|------------|
| | Non-flooded | Flooded | Non-flooded | Flooded |
| A ₁ V ₁ | 0.64 BC(b) | 3.18 B(a) | 2.96 D(b) | 4.28 BC(a) |
| A ₁ V ₂ | 1.92 A(a) | 2.26 D(a) | 4.52 C(a) | 4.70 B(a) |
| A ₂ V ₁ | 0.81 B (b) | 3.28 AB(a) | 2.91 D(b) | 4.15 C(a) |
| A ₂ V ₂ | 2.17 A (a) | 2.23 D (a) | 5.26 B(a) | 4.32 BC(b) |
| A ₃ V ₁ | 0.44 C (b) | 3.58 A (a) | 2.44 E (b) | 4.66 B (a) |
| A ₃ V ₂ | 2.12 A (b) | 2.72 C (a) | 5.72 A (a) | 5.38 A (a) |

A = Amendments. A₁ - NK, A₂ - NPK, A₃ - NPK + chicken manure.
 V = Cultivars. V₁¹ - IR64. V₂² - IR5931-110-1-3.

^aMeans of 4 replications. In a column, means followed by a common capital letter and in a row, means followed by a common small letter (within parentheses) are not significantly different by DMRT at 5% level.

non-significant in IR5931 (in presence of applied chicken manure, however, flooding gave significant increase in grain yield of IR5931). Although under non-flooded conditions, there was no remarkable response of the cultivars to any of two amendments; under flooded condition, chicken manure application showed some increase in grain yields.

Straw yield. IR64 gave significantly higher straw yield under flooded than under the non-flooded condition (Table 26). Contrastingly, average straw yield of IR5931 was slightly higher under non-flooded than under the flooded condition. Application of P and chicken manure to the non-flooded and chicken manure to the flooded plots increased straw yield of IR5931 appreciably.

The important findings of this field experiment may now be summarized:

1. Flooding increased grain yields of both IR64 (a lowland variety) and IR5931 (a promising upland line).
2. Remarkable difference was noted between the two cultivars regarding their adaptability under non-flooded soil conditions. Grain yields of IR64 and IR5931 under non-flooded regimes were 19 and 86 per cent, respectively of their yields under the flooded conditions.

3. Under non-flooded regime, application of P@ 25 kg/ha and chicken manure @ 5t/ha did not show any favorable effects on grain yields, but significantly increased straw yield of IR5931.
4. Regardless of cultivars and amendment applications, concentrations of SiO₂, Mn, Ca, Mg, Na, Zn and active Fe were significantly lower in plants grown under non-flooded than those under the flooded regime.
5. Concentration of Ortho-phenanthroline extractable (active) Fe²⁺ rather than total Fe concentration in tissue was found to be associated with Fe chlorosis in plants.

The differences in growth and mineral nutrition of rice under flooded and non-flooded regimes of a near-neutral soil were thus similar under both greenhouse and field conditions.

Experiment 6

Growth and Mineral Nutrition of Two Rices in an Acid Upland and the Influence of Some Amendments on Them

Chemical kinetics study in the greenhouse (Experiment 2) indicated that among the adverse factors prevalent in the acidic Luisiana soil under aerobic conditions: deficiencies of P, Fe and Ca, and toxicities of Mn and Al could be important. The present experiment was conducted to study the growth and nutrition of two rices in the Luisiana upland under farmer's field condition and to examine the effects of some applied amendments on them.

MATERIALS AND METHODS

This experiment was conducted in 1985 wet season in a farmer's field in San Pedro, Luisiana, Laguna wherefrom samples were collected for the greenhouse experiments.

Experimental factors and levels

a. Amendments

The following six amendments were included:

- A1 - NK
- A2 - NPK
- A3 - NPK + Fe soil application

- A4 - NPK + Fe foliar application
- A5 - NPK + Lime
- A6 - NPK + Ca

b. Cultivars

The following two cultivars were used for this trial:

- V1 - IR43
- V2 - IR5931-110-1-3, which will be referred to as IR5931 when results are discussed.

Experimental design

The plots for this 6 x 2 factorial experiment were arranged in a Randomized Complete Block Design with 4 replications.

Sources and rates of amendment application

Nitrogen was applied at the rate of 50 kg N/ha in the form of ammonium sulfate. Phosphorus was applied in the form of triple superphosphate at the rate of 25 kg P/ha. Muriate of potash was used to supply potassium at the rate of 25 kg K/ha. For soil application, Fe was applied as 50 kg $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ /ha and for foliar spray, 0.5% $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ solution (pH 3.5) was used. Lime was applied in the form of commercial grade lime (containing 50% Ca) at the rate of 3000 kg/ha and Ca in the form of technical grade CaCl_2 (containing 30% Ca) at the rate of 5000 kg/ha.

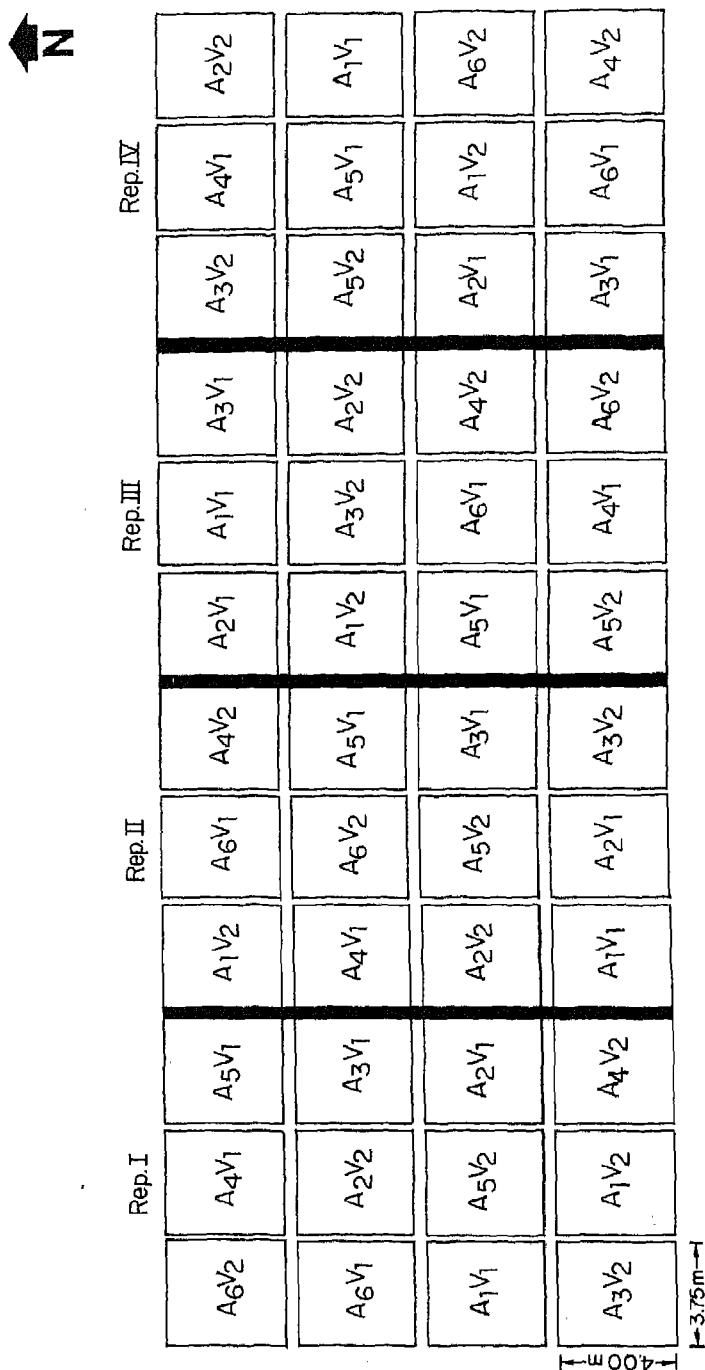
Land preparation and lay-out

A rectangular area of about 1000 sq.m. (55m x 18m) was plowed twice by country-plow and then by a power tiller. After rotovation and levelling of the field, the entire area was laid out for the 48 experimental plots each of 4m x 3.75m size. The arrangement of the plots is shown in Fig. 57.

Application of amendments

The full dose of lime (4.5 kg/plot) was incorporated thoroughly into top 15 cm soil layer of the respective plots by rotovator at 3 weeks before seeding. Half of the required CaCl_2 (3.75 kg/plot) was similarly incorporated in the respective plots at one week before seeding. To mix the applied lime and CaCl_2 with soil more thoroughly, these plots were rotovated several times (twice weekly) before seeding. P, K and Fe (soil application) in full doses were applied to the respective plots at 3 days before seeding and mixed well into the surface layer of soil.

Two-third (33 kg N/ha) of required nitrogen was applied by broadcasting at one month after seeding and one supplemental irrigation (by sprinkler) was given to help applied fertilizer entering the soil. The second split (17 kg N/ha) of N was broadcast at panicle initiation stage. The rest half (3.75 kg/plot) of CaCl_2 was broadcast onto the respective plots at



Amendments: A₁-NK, A₂-NPK, A₃-NPK Fe soil, A₄-NPK Fe foliar, A₅-NPK Lime, A₆-NPK Ca.

Cultivars: V₁-IR43, V₂-IR593T-110-1-3.

Fig. 57. Lay-out of the experimental plots in Louisiana upland. San Pedro, Louisiana.

9 weeks after seeding. Foliar sprayings of Fe were made at weekly intervals starting from 6 weeks after seeding and continued upto the grain filling stage.

Seeding

Overnight soaked seeds were dibbled at 2-3 cm depth and 20cm x 20cm spacing. Each hill received 5 to 6 seeds. Immediately after seeding, one irrigation (by sprinkler) was given to help germination of the seeds. Ten days after seeding, each hill was thinned to keep 3 seedlings for growing to maturity.

Weeding

Three hand weedings were done to keep the plots free of weed infestation.

Pesticide application

Six kg 'Furadan' (a granular insecticide) was broadcast on the entire field (1000 sq.m.) and incorporated into soil during land preparation. Since white-grubs were identified in root zones of the experimental plots, 'Basudin' (a granular insecticide) was applied at 4 and 6 weeks after seeding, each time 4 kg Basudin broadcast over the entire field. As leaf folder infestation broke out in the field at post-flowering stage, 3 to 4 foliar sprayings of 'Azodrin' at recommended dose were made to protect the crop from damage.

Monitoring of rainfall, soil moisture
tension and redox potential of soil

One rain gauge (TruChek^R) was installed in the field to record daily rainfall. Tensiometers were installed at 32 randomly selected points in the experimental area to monitor daily soil moisture tension at 15 cm depth. Average of these 32 readings was used to report the soil moisture status of the field. Thirty-two bright platinum electrodes were installed at 15 cm depth at randomly selected points to measure redox potential of soil. The average reading was used to report redox condition of the field.

Collection and preparation of plant
samples for analysis

Eight week old shoots. Plant samples from all the plots were collected by taking one whole plant (above ground part) per hill from 4 random hills outside the harvesting area and excluding two border rows. These four plants were combined together to get the composite sample of each plot. The samples were brought to the greenhouse and 5-8 cm of basal part was discarded (by cutting) to avoid visible contamination with soil particles. Then the samples were thoroughly washed with mild detergent solution and subsequently several times with demineralized water. After drying at 60°C temperature in an

oven for 3 days, the samples were chopped by using a stainless steel scissors, ground by using a UD cyclone mill and stored in envelopes for analyses.

Flagleaves. Starting from panicle initiation stage, the IR43 plants showed chlorotic symptoms, whereas the IR5931 plants looked normal green. The symptoms appeared most clearly on the flag leaves. At 12 weeks after seeding about 20 flag leaves were collected at random from each plot, brought to the laboratory, washed with tap water followed by 0.1(N) HCl and demineralized water. The washed fresh leaves were then chopped into uniformly small pieces using stainless steel scissors. A portion of these chopped fresh leaves was used for analyzing active iron content and the rest part was dried at 60°C temperature in an oven for 3 days before grinding with a UD cyclone mill and analyzed for total Fe and crude silica content.

Straw. At harvest, six hills from each plot were collected for yield component determination. From those plants straw samples were prepared for analyses in same way as described for the previous experiment.

Harvesting

The same procedure as detailed for the previous experiment was followed to harvest mature crop for estimation of grain and straw yields.

Plant analyses

The 8 week old shoot and straw samples were analyzed for N, P, K, Ca, Mg, Fe, Mn, Zn, Cu, Na and SiO_2 following same procedures as described earlier.

The fresh flag leaves were analyzed for ortho-phenanthroline extractable Fe following the procedure described by Katyal and Sharma (1980). Total Fe and crude SiO_2 contents of the dried and ground flag leaves were determined by the methods for described earlier.

RESULTS AND DISCUSSION

Soil moisture status

Figure 58 shows the weekly rainfall distribution and daily soil moisture tension (at 15 cm depth) in the field starting from 3 weeks after seeding to the harvesting of the crop. More than 1900 mm of rainfall was received during the growing season, and the soil moisture tension during the greater part of the season was less than 4 kPa indicating much higher soil moisture content than the field capacity moisture. However, because of a dry spell of continuous six days, soil moisture level went below field capacity for a period of 2 days during the pre-flowering stage.

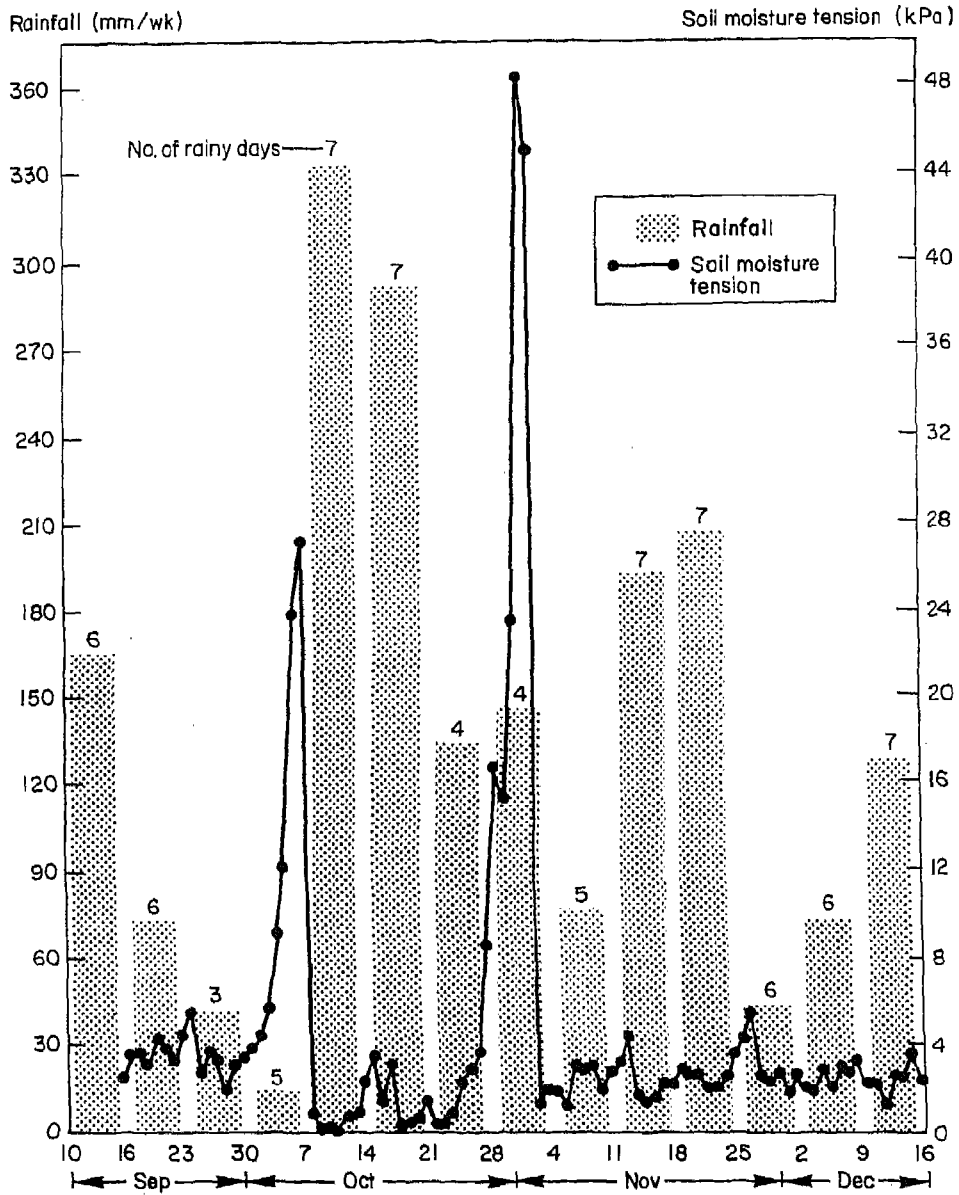


Fig. 58. Weekly rainfall distribution and daily soil moisture tension in Louisiana upland, recorded during the experimental season, 1985. San Pedro, Louisiana.

Soil redox status

Figure 59 shows changes in soil redox potential during the major part of the growing season. The observed Eh values (higher than 400 mV) indicated oxidized condition of the field throughout the season. Coinciding with the occurrence of a dry spell, soil Eh values went higher in the last week of October.

Mineral Nutrient Status of IR43 and IR5931 in Luisiana Upland

I. Concentrations of N, P, K, SiO₂, Ca, Mg, Fe, Mn, Zn, Cu and Na in 8 week old shoots and mature straw of the two rices, and influence of the applied amendments on them are presented in Tables 27 and 28, and are discussed below.

Nitrogen and Phosphorus

Both the week old shoot and mature straw of IR43 had significantly higher concentrations of N and P than those of IR5931. While liming increased the N concentrations, application of P increased the P concentrations in shoots of both the rices. Other amendments did not show any remarkable influence on the N and P concentrations.

Potassium

Concentration of K in 8 week old shoot was higher in IR5931 than in IR43. The observed lower K concentration in IR5931 at maturity could be attributed to its dilution in the tissue,

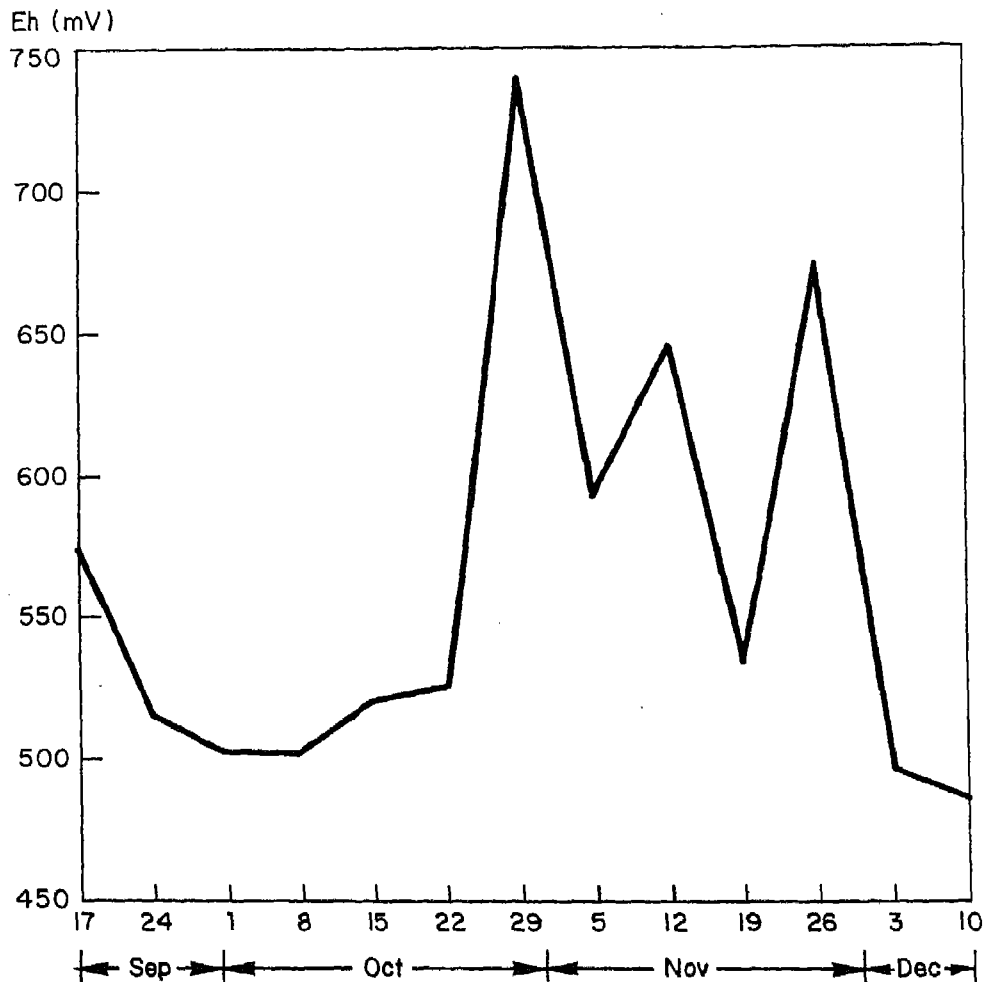


Fig. 59. Changes in soil redox potentials in Luisiana upland, recorded during the experimental season. 1985. San Pedro, Luisiana.

Table 27. Concentration of mineral nutrients in 8 week old shoots of two rices grown in Louisiana upland. ^a 1985 wet season.

| Treatment | N | P | K | % | SiO ₂ | Ca | Mg | Fe | Mn | Zn | Cu | Na |
|-------------------------------|-----------|----------|----------|---------|------------------|----------|---------|--------|------|-------|-------|----|
| A ₁ V ₁ | 2.17 de | .150 cd | 2.42 d | 10.0 ab | .110 e | .237 d | 195 abc | 499 cd | 34 a | 16 c | 90 b | |
| A ₁ V ₂ | 2.15 de | .126 e | 2.60 cd | 8.5 c | .114 e | .266 bcd | 197 abc | 425 d | 32 a | 17 bc | 95 b | |
| A ₂ V ₁ | 2.54 abcd | .174 a | 2.77 bc | 9.8 ab | .118 de | .241 cd | 207 ab | 530 bc | 33 a | 17 bc | 101 b | |
| A ₂ V ₂ | 2.03 e | .164 abc | 2.75 bc | 10.1 ab | .119 cde | .255 bcd | 153 d | 596 ab | 34 a | 18 ab | 140 a | |
| A ₃ V ₁ | 2.47 bcd | .168 ab | 2.75 bc | 10.7 a | .118 de | .275 bcd | 168 cd | 615 a | 34 a | 17 bc | 108 b | |
| A ₃ V ₂ | 2.30 cde | .155 bcd | 3.25 a | 9.6 ab | .112 e | .259 bcd | 155 d | 533 bc | 34 a | 18 ab | 114 b | |
| A ₄ V ₁ | 2.31 cde | .164 abc | 2.72 bcd | 10.4 ab | .119 cde | .253 bcd | 209 ab | 603 ab | 31 a | 17 bc | 86 b | |
| A ₄ V ₂ | 2.26 cde | .155 bcd | 2.70 bcd | 9.9 ab | .121 cde | .292 ab | 215 ab | 480 cd | 34 a | 18 ab | 97 b | |
| A ₅ V ₁ | 2.72 ab | .165 abc | 2.57 cd | 9.6 ab | .143 b | .280 bc | 215 ab | 306 e | 30 a | 16 c | 105 b | |
| A ₅ V ₂ | 2.83 ab | .159 acd | 2.92 b | 9.3 bc | .157 a | .321 a | 176 bcd | 335 e | 30 a | 18 ab | 144 a | |
| A ₆ V ₁ | 2.87 a | .161 abc | 2.65 bcd | 10.4 ab | .132 bc | .256 bcd | 220 a | 620 a | 33 a | 19 a | 113 b | |
| A ₆ V ₂ | 2.59 abc | .145 d | 2.82 bc | 10.1 ab | .130 cd | .256 bcd | 208 ab | 621 a | 34 a | 19 a | 91 b | |

A = Amendments. A₁ - NK, A₂ - NPK, A₃ - NPK Fe_{soil}, A₄ - NPK Fe_{foliar}, A₅ - NPK Ca.

V = Cultivars. V₁ - IR43, V₂ - IR5931-110-1-3.

^aMeans of 4 replications. In a column, treatment means having a common letter are not significantly different by DMRT at 5% level.

as the total dry matter yield was much higher in IR5931 than in IR43. None of the amendments applied showed any consistent influence on K concentration in tissue.

Silica

In the vegetative growth stage, average silica concentration was higher in IR43 than in IR5931. At maturity, however, SiO_2 concentrations did not show any appreciable difference between the two cultivars. SiO_2 concentrations in tissue were not markedly influenced by the amendments tried.

Calcium

Average Ca concentrations in 8 week old shoots of IR43 and IR5931 did not differ significantly. The observed lower concentration of Ca in mature straw of IR5931 could be due its dilution in tissue. Liming significantly increased the Ca concentration in both the cultivars.

Magnesium

In both shoots as well as straw, Mg concentrations were higher in IR5931 than in IR43 and liming significantly increased it in both the cultivars.

Table 28. Concentration of mineral nutrients in straw of two rices grown in Luisiana upland.^a 1985 Wet Season.

| Treatment | N | P | K | SiO ₂ | Ca | Mg | Fe | Mn | Zn | Cu | Na |
|-------------------------------|----------|-----------|---------|------------------|----------|----------|--------|----------|-------|-------|---------|
| | | | | | | | | | | | |
| A ₁ V ₁ | 0.93 bcd | .065 bcd | 2.8 abc | 10.6 a | .066 cd | .217 de | 98 bc | 1138 bc | 88 ab | 19 cd | 350 bcd |
| A ₁ V ₂ | 0.90 cd | .057 d | 2.6 cd | 9.5 ab | .061 d | .223 de | 115 b | 1063 bc | 80 bc | 25 a | 388 abc |
| A ₂ V ₁ | 0.99 bc | .074 ab | 2.9 ab | 8.9 b | .069 bcd | .237 cd | 89 bc | 1175 abc | 91 a | 17 de | 313 d |
| A ₂ V ₂ | 0.87 cd | .062 cd | 2.3 e | 9.5 ab | .066 cd | .258 bc | 91 bc | 1088 bc | 85 ab | 17 de | 413 a |
| A ₃ V ₁ | 0.99 bc | .075 ab | 3.0 a | 10.1 ab | .077 ab | .213 de | 100 bc | 1238 ab | 80 bc | 21 bc | 325 d |
| A ₃ V ₂ | 0.83 d | .062 cd | 2.7 bc | 9.8 ab | .062 d | .230 cde | 89 bc | 1075 bc | 86 ab | 19 cd | 413 a |
| A ₄ V ₁ | 0.98 bc | .068 abcd | 3.0 a | 9.8 ab | .062 d | .234 cde | 228 a | 1250 ab | 81 bc | 17 de | 325 d |
| A ₄ V ₂ | 0.97 bc | .060 d | 2.4 de | 9.9 ab | .063 d | .236 cd | 218 a | 988 c | 75 cd | 19 cd | 400 ab |
| A ₅ V ₁ | 1.17 a | .073 abc | 3.0 a | 9.6 ab | .080 a | .289 ab | 64 c | 650 d | 69 d | 14 e | 333 cd |
| A ₅ V ₂ | 1.04 b | .058 d | 2.7 bc | 10.3 ab | .075 abc | .300 a | 92 bc | 638 d | 75 cd | 19 cd | 413 a |
| A ₆ V ₁ | 0.97 bc | .077 a | 2.8 abc | 10.3 ab | .066 cd | .180 f | 84 bc | 1363 a | 69 d | 17 de | 313 d |
| A ₆ V ₂ | 0.84 d | .058 d | 2.6 cd | 9.6 ab | .058 d | .200 ef | 109 b | 1100 bc | 86 ab | 24 ab | 425 a |

A = Amendments. A₁ - NK, A₂ - NPK, A₃ - NPK Fe_{soil}, A₄ - NPK Fe_{foliar}, A₅ - NPK Ca.

V = Cultivars. V₁ - IR43, V₂ - IR5931-110-1-3.

^a Means of 4 replications. In a column, treatment means having a common letter are not significantly different by DMRT at 5% level.

Iron

In the vegetative growth stage, IR43 had significantly higher average concentration of Fe than did IR5931. In mature straw, however, Fe concentrations did not vary with the cultivars. Foliar spraying of Fe increased the tissue Fe content significantly in both the rices and the other amendments did not show any remarkable effect.

Manganese

Average Mn concentrations were higher in IR43 than in IR5931 at both the growth stages. Liming significantly reduced Mn concentrations in both the cultivars.

Zinc

Zinc concentrations in tissue did not vary significantly with the cultivars and the amendments tried.

Copper and sodium

Average Cu as well as Na concentrations were higher in IR5931 than in IR43 at both the growth stages. None of the applied amendments showed any significant effect on Cu and Na concentrations in the tissues.

II. Concentrations of total Fe, active (Ortho-phenanthroline extractable) Fe and crude silica in flag leaves of the two cultivars and influence of the applied amendments on them are presented in Table 29 described below:

Regardless of amendment application, the active Fe concentration in IR43 was significantly lower (lower than the proposed critical limit of 40-45 ppm) than that in IR5931. Concentrations of Total Fe in tissue did not show any consistent difference between the two cultivars. Foliar spraying of Fe significantly increased both total and active Fe concentrations in flag leaves, while other amendments showed no effects.

Crude SiO₂ concentration in flag leaves of IR5931 was significantly higher than that in IR43 under all the treatments. None of the amendments showed any measurable effect on the SiO₂ content in tissue.

Growth, Some Yield Components and Yields
of IR43 and IR5931 in Luisiana Upland

Visual symptoms

In the early growth stage both IR43 and IR5931 plants were equally vigorous, but with time IR5931 grew faster and taller than IR43. Tillering in IR43, however, was more profuse than in IR5931. Starting from 6 weeks after seeding, IR43 started showing mild chlorotic symptoms whereas IR5931 had normal green

Table 29. Concentration of total Fe, active Fe and crude SiO₂ in flag leaves of two rices grown in Luisiana upland.^a 1985 wet season.

| Treatment | Total Fe (mg/kg) | Active Fe (mg/kg) | SiO ₂ (%) |
|-------------------------------|---------------------|----------------------|-------------------------|
| A ₁ V ₁ | 179 bc | 37.2 c | 8.2 cd |
| A ₁ V ₂ | 216 b | 50.6 b | 12.3 a |
| A ₂ V ₁ | 149 c | 38.0 c | 8.5 cd |
| A ₂ V ₂ | 213 b | 49.2 b | 12.7 a |
| A ₃ V ₁ | 191 b | 35.7 c | 8.1 d |
| A ₃ V ₂ | 205 b | 46.7 b | 12.2 a |
| A ₄ V ₁ | 265 a | 58.3 a | 8.8 cd |
| A ₄ V ₂ | 284 a | 61.0 a | 11.0 b |
| A ₅ V ₁ | 194 b | 35.7 c | 7.9 d |
| A ₅ V ₂ | 190 b | 48.2 b | 12.2 a |
| A ₆ V ₁ | 206 b | 35.7 c | 9.4 c |
| A ₆ V ₂ | 216 b | 46.8 b | 12.9 a |

A = Amendments. A₁ - NK, A₂ - NPK, A₃ - NPK Fe_{soil},

A₄ - NPK Fe_{foliar}, A₅ - NPK Lime, A₆ - NPK Ca.

V = Cultivars. V₁ - IR43, V₂ - IR5931-110-1-3.

^aMeans of 4 replications. In a column, treatments means having a common letter are not significantly different by DMRT at 5% level.

foliage. The mild chlorotic symptoms was least marked under the soil applied Fe treatment. From pre-flowering stage onwards, chlorotic symptoms in IR43 (comparative to the normal green plants of IR5931) became more clear under all the treatments except foliar spray of Fe.

Plant height

Height of the plants recorded at panicle initiation stage (Table 30) shows that IR5931 plants were significantly taller than IR43 under all the treatments. While none of the amendments affected the height of IR43, application of P increased the height of IR5931 significantly.

Tiller number

Tiller number per hill counted at panicle initiation stage (Table 30) indicates that IR43 produced more tillers than did IR5931. However, this difference was not statistically significant in presence of applied Ca, lime and foliar Fe. None of the amendments affected tiller production significantly.

Panicle number

Panicle number per hill at harvest (Table 31) were not significantly different between IR43 and IR5931. Also, panicle production was not significantly influenced by any of the amendments applied.

Table 30. Plant height and tiller number of two rices (at panicle initiation stage) grown in Luisiana upland.^a
1985 Wet Season.

| Treatment | Plant height (cm) | Tiller number per hill |
|-------------------------------|----------------------|---------------------------|
| A ₁ V ₁ | 70 d | 24.1 a |
| A ₁ V ₂ | 82 c | 17.8 d |
| A ₂ V ₁ | 73 d | 23.8 ab |
| A ₂ V ₂ | 99 a | 20.2 bcd |
| A ₃ V ₁ | 75 d | 23.6 ab |
| A ₃ V ₂ | 91 b | 19.4 cd |
| A ₄ V ₁ | 74 d | 22.0 abc |
| A ₄ V ₂ | 90 b | 19.2 cd |
| A ₅ V ₁ | 74 d | 21.7 abc |
| A ₅ V ₂ | 93 ab | 19.0 cd |
| A ₆ V ₁ | 71 d | 23.3 ab |
| A ₆ V ₂ | 92 b | 20.5 abcd |

A = Amendments. A₁ - NK, A₂ - NPK, A₃ - NPK

Fe_{soil}, A₄ - NPK Fe_{foliar}, A₅ - NPK Ca.

V = Cultivars. V₁ - IR43, V₂ - IR5931-110-1-3.

^aMeans of 4 replications. In a column, treatment means having a common letter are not significantly different by DMRT at 5% level.

Table 31. Panicle number, unfilled spikelet percentage and 100 grain weight of two rices grown in Luisiana upland.^a 1985 Wet Season.

| Treatment | Panicle number per hill at harvest | Unfilled spikelet % | 100 grain weight (gm) |
|-------------------------------|--|---------------------------|-----------------------------|
| A ₁ V ₁ | 14.7 a | 46.5 abc | 2.17 ab |
| A ₁ V ₂ | 12.0 b | 48.1 abc | 2.26 ab |
| A ₂ V ₁ | 15.6 a | 49.8 ab | 2.12 b |
| A ₂ V ₂ | 15.1 a | 43.4 bcd | 2.24 ab |
| A ₃ V ₁ | 16.0 a | 47.5 abc | 2.20 ab |
| A ₃ V ₂ | 15.2 a | 41.4 cd | 2.30 a |
| A ₄ V ₁ | 16.5 a | 43.9 bcd | 2.20 ab |
| A ₄ V ₂ | 14.8 a | 42.3 cd | 2.24 ab |
| A ₅ V ₁ | 15.0 a | 45.7 abc | 2.24 ab |
| A ₅ V ₂ | 15.1 a | 38.7 d | 2.28 a |
| A ₆ V ₁ | 14.6 ab | 52.2 a | 2.21 ab |
| A ₆ V ₂ | 14.5 ab | 43.2 bcd | 2.29 a |

A = Amendments. A₁ - NK, A₂ - NPK, A₃ - NPK Fe_{soil},

A₄ - NPK Fe_{foliar}, A₅ - NPK Ca.

V = Cultivars. V₁ - IR43, V₂ - IR5931-110-1-3.

^aMeans of 4 replications. In a column, treatment means having a common letter are not significantly different by DMRT at 5% level.

Unfilled spikelet percentage

Average sterility percentage was higher in IR43 than in IR5931 spikelets (Table 31). None of the amendments had any significant effect on spikelet sterility in IR43, whereas combined application of P and lime significantly reduced the sterility in IR5931.

100 grain weight

Average 100 grain weight of IR5931 was higher than that of IR43. None of the applied amendments affected the 100 grain weights significantly (Table 31).

Grain yield

In presence of applied P, grain yield of IR5931 was significantly higher than that of IR43 under all the treatments (Table 32). While IR43 did not respond to any of the amendments applied, application of P, Fe and lime significantly increased grain yield of IR5931. The highest yield of this cultivar was obtained by combined application of P and lime, while application of P and Fe (to soil) together proved to be the second best amendments. The observed non-significant increase in yield with the foliar application of Fe could be attributed to non-uniform and inefficient translocation and distribution of applied Fe from leaves into the tissues. In fact, discrete dark green spots on foliage were noted under this treatment. The

Table 32. Grain and straw yield of two rices grown in Luisiana upland.^a 1985 WS.

| Treatment | Grain Yield ----- t/ha ----- | Straw Yield ----- |
|-------------------------------|---------------------------------|----------------------|
| A ₁ V ₁ | 2.52 d | 4.34 abc |
| A ₁ V ₂ | 2.70 d | 4.41 abc |
| A ₂ V ₁ | 2.54 d | 4.23 bc |
| A ₂ V ₂ | 3.05 c | 4.24 bc |
| A ₃ V ₁ | 2.64 d | 4.18 bc |
| A ₃ V ₂ | 3.40 b | 4.85 a |
| A ₄ V ₁ | 2.69 d | 4.11 c |
| A ₄ V ₂ | 3.11 bc | 4.72 ab |
| A ₅ V ₁ | 2.34 d | 4.05 c |
| A ₅ V ₂ | 3.77 a | 4.76 ab |
| A ₆ V ₁ | 2.46 d | 4.27 abc |
| A ₆ V ₂ | 3.06 c | 4.38 abc |

A = Amendments. A₁ - NK, A₂ - NPK, A₃ - NPK

Fe_{soil}, A₄ - NPK Fe_{foliar}, A₅ - NPK Ca.

V = Cultivars. V₁ - IR43, V₂ - IR5931-110-1-3.

^aMeans of 4 replications. In a column, treatment means having a common letter are not significantly different by DMRT at 5% level.

yield increase in IR5931 obtained by liming could be attributed to the alleviation of Mn (and perhaps Al) toxicity and increased availability of P and Ca. Since liming at the applied rate did not raise the soil pH above 5.4 during the grand growth phase of the crop (following liming, soil pH were found to be 5.0 and 5.7 at the seeding- and harvesting time, respectively), Fe availability in the soil might not have been affected adversely. Plant analysis data supported this contention.

Straw yield

Average straw yield of IR5931 was higher than that of IR43. The straw production was not significantly influenced by any of the applied amendments (Table 32).

The results of this field experiment may be summarized as follows:

1. Remarkable difference was found between the cultivars regarding their adaptability in the acid upland. The IR5931 proved significantly superior to IR43 in all aspects of growth and performance. While IR43 suffered from moderate Fe chlorosis and did not respond to the applied amendments, IR5931 grew quite normally and were ameliorant- responsive.

2. Concentration of total Fe in tissue was not associated with Fe chlorosis in IR43. Ortho-phenanthroline extractable (active) Fe was a sensitive analysis in this regard.
3. Analysis of flag leaves rather than whole plant appeared to give better index of SiO_2 availability to plants.
4. Application of P @25 kg/ha significantly increased P concentrations in tissue and grain yield of the efficient cultivar, IR5931.

Lime application @ 3t/ha significantly increased concentrations of Ca and Mg, decreased that of Mn in tissues, and significantly increased grain yield of IR5931.

The tissue analyses and the observed effects of ameliorants on them indicate that: lower solubility of Mn were the important growth retarding factors in this soil.

SUMMARY AND CONCLUSIONS

Rice generally yields less in well-drained or aerobic soils than in the same soils rendered anaerobic by flooding. This poor yield is most commonly attributed to moisture stress. Under aerobic or oxidized conditions, however, solubility and availability of several mineral nutrients may be low. This may also contribute to the poor performance of upland rice. In a preliminary experiment (Experiment 1) conducted to examine the growth of rice under controlled aerobic and anaerobic conditions of two soils, it was found that at the same level (field capacity) of moisture supply, rice growth was much poorer under aerobic soil conditions.

In order to identify the unfavorable chemical factors in aerobic regimes, the chemical kinetics of four soils (a Sulfaquept of pH 3.9, a Tropudult of pH 4.5, a Tropudalf of pH 6.6 and a calcareous Tropaquept of pH 7.6) were compared under field capacity moist (aerobic) and flooded (anaerobic) conditions (Experiment 2). Results of the chemical kinetics study and plant analyses suggested that lower availability of Fe and Si in all soils, lower availability of P in most soils, lower availability of Mn in near-neutral and calcareous soils, lower availability of Ca in strongly acidic soils, and excessive concentrations of Al and Mn in strongly acidic soils may contribute to poor growth of rice under field capacity

moisture (aerobic) regimes. Grain yields of rice in the field capacity (FC) moist soils did not exceed 38% of that under the flooded regimes. The more than 62% reduction in grain yields, however, could not be attributed solely to these unfavorable soil chemical factors identified in aerobic regimes. Under FC moisture regimes, the complete water requirement of rice crop may not be met, and thus grain yield could also have been affected by the inadequate supply of water.

In Experiments 3 and 4, an additional treatment (wet regime) was included to maintain aerobic conditions of soils at abundant supply (comparable to that under the flooded regime) of water in attempt to separate the effects of unfavorable chemical factors from that of inadequate water supply. Also, two more soils (an Eutropept of pH 6.1 and a Trophaept of pH 6.6) were added. The chemical kinetics studies of the soils and plant analyses revealed that compared to those under the flooded (anaerobic) conditions, in both moist and wet regimes availability of P, Fe and Na were lower in all soils, availability of Mn was very low in soils of pH >6, solubility of Al and Mn were very high (toxic concentrations of Mn in tissue) in the strongly acidic soils; and there was no appreciable difference between the moist and wet regimes in these regards. Thus, the soil chemical environments remained equally unfavorable under both FC moist and wet aerobic regimes.

Results of these studies also indicated that concentration of total Fe in tissue did not reflect the status of metabolically-active Fe in plants, especially in near-neutral and high pH soils. No appreciable difference was found in the tissue concentrations of total Fe in chlorotic and normal green plants.

Grain yields were highest under flooded regime, followed by the wet and moist regimes, of all soils except the two strongly acidic soils where flooding produced Fe toxicity problems resulting in poor growth and yield of rice.

Since comparable amounts of water were supplied under the wet (aerobic) and flooded (anaerobic) regimes, the yield reductions observed in the wet regimes could apparently be attributed to the unfavorable chemical factors prevalent under aerobic soil conditions. The apparent contributions of aerobic conditions of soils were 19% in a moderately acidic soil, 17 to 57% (mean 36%) in near-neutral soils, and 74 to 100% in a calcareous soil.

To substantiate the findings of the greenhouse experiments, one field experiment (Experiment 5) was conducted in a near-neutral soil to compare the growth and mineral nutrition of two rice cultivars (IR64 and IR5931-110-1-3) under non-flooded (moisture level around FC) and flooded regimes. It was found that both the rices yielded less under non-flooded regime, although remarkable differences in the performance of the

cultivars were observed. Grain yields of IR64 and IR5931 under non-flooded conditions were 19 and 86 percent respectively of their yields under the flooded regime. Both the cultivars contained significantly lower Ca, Mg, Na, Mn, Zn, Si and active Fe in tissue under non-flooded (aerobic) than under flooded (anaerobic) conditions. IR64 showed Fe chlorosis under the non-flooded regime. While no significant difference in the concentrations of total Fe was found between normal green and chlorotic plants, the ortho-phenanthroline extractable (active) Fe in tissue was significantly lower in the chlorotic plants.

Another experiment (Experiment 6) was conducted in a farmer's field to study growth and mineral nutrition of two rice cultivars (IR43 and IR5931-110-1-3) in a typical acid upland. Marked difference in the performance of the two cultivars was noticed. IR5931 proved significantly superior to IR43 in all respects. IR43 suffered from moderate Fe chlorosis and did not respond to the amendments applied. On the other hand, IR5931 grew with normal vigour and responded significantly to applied P and lime. While total Fe concentrations were not significantly different between chlorotic IR43 and normal green IR5931 plants, ortho-phenanthroline extractable Fe concentration was significantly lower in IR43. The nutrient analyses of tissue and the plant responses to the amendments applied indicated that lower availability of P, Ca, Mg, Si and active

Fe, and excessive concentration of Mn were the unfavorable chemical factors limiting rice growth in this aerobic acid soil. This result confirmed the findings of the greenhouse experiments.

Conclusions

1. At all levels of moisture supply, growth and yield of rice are retarded by the unfavorable chemical regime prevalent under the aerobic conditions of most soils.
2. Apparent contribution of the unfavorable chemical regime in aerobic soils to yield reduction in upland rice (variety IR43) was found to be 19% in a moderately acid soil, 36% in near-neutral soils, and 74-100% in a calcareous soil.
3. The adverse chemical factors prevalent under aerobic conditions are soil specific. The specific chemical factors associated with poor growth and yield of rice in aerobic soils with abundant supply of water were found to be:
 - o lower availability of P, Fe and Na in all soils
 - o lower availability of Ca in strongly acidic soils
 - o lower availability of Mn in near-neutral and high pH soils

- o toxic concentration of Mn in strongly acidic soils with high active Mn content
- o toxic concentration of Al in strongly acidic soils with high percent Al saturation

When moisture supply is not abundant and is around FC or less, lower availability of Si would be an additional limiting factor in all soils.

4. Solubility of Si in most soils appears to be strongly controlled by pH, regardless of the redox conditions of the soils. Acidic soils would have higher Si solubility in aerobic than in anaerobic conditions, since pH is lower under aerobic conditions. Decreased availability of Si to upland rice, as is reported frequently, could not be due to lower solubility of Si in most soils, but to inadequate moisture supply. Apparently, Si is taken up by rice in the transpiration stream; when more water is transpired, more Si is accumulated in the tissue.
5. Concentration of total Fe in tissue is not always a satisfactory index of metabolically-active Fe status in plants, especially in near-neutral and high pH soils. Ortho-phenanthroline extractable Fe is a more sensitive index in this regard under all conditions.

6. Remarkable differences exist in the adaptability of rice cultivars under aerobic soil conditions. IR43 and IR64 were found to be inefficient in aerobic acid and near-neutral soils, respectively. IR5931 was found to adapt well under aerobic conditions of both acidic and near-neutral soils.
7. Adverse chemical environments of aerobic acid soils could be improved by application of amendments like P and lime. Application of P @ 25 kg/ha and lime @ 3 t/ha to an acidic Tropudult (pH 4.5) significantly increased availability of P, Ca and Mg to rice and decreased the tissue concentration of Mn. Both the amendments significantly increased yield of IR5931. A similar attempt to improve the chemical environment of an aerobic soil of near-neutral reaction by applying some amendments (P and Organic manure) proved unsuccessful.

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APPENDIX

Appendix Table 1. Kinetics of Eh in 4 soils under moist and flooded conditions.

| Soil | Treatment | Moisture regime | Weeks | | | | | | | | | | | | |
|-----------|-----------|-----------------|--------|-----|-----|------|------|------|------|------|------|------|------|------|------|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| | | | Eh(mV) | | | | | | | | | | | | |
| Louisiana | Moist | | 408 | 482 | 512 | 658 | 629 | 647 | 667 | 729 | 661 | 737 | 747 | 719 | 762 |
| | Flooded | | 191 | 13 | -26 | -224 | -248 | -270 | -265 | -275 | -273 | -276 | -263 | -280 | -273 |
| Maahas A | Moist | | 357 | 510 | 485 | 579 | 568 | 628 | 605 | 693 | 612 | 695 | 715 | 715 | 703 |
| | Flooded | | 40 | 46 | 29 | -158 | -186 | -175 | -204 | -251 | -262 | -267 | -263 | -295 | -282 |
| Pila | Moist | | 304 | 455 | 475 | 601 | 590 | 605 | 593 | 633 | 609 | 644 | 646 | 653 | 631 |
| | Flooded | | 25 | -67 | -68 | -213 | -213 | -228 | -252 | -273 | -293 | -307 | -307 | -311 | -297 |
| Burabod | Moist | | 448 | 652 | 619 | 735 | 714 | 731 | 729 | 791 | 758 | 782 | 799 | 772 | 800 |
| | Flooded | | 114 | -23 | -29 | -155 | -159 | -202 | -193 | -196 | -202 | -197 | -175 | -217 | -176 |

Appendix Table 2. Kinetics of solution Eh in 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | | | |
|-----------|-----------------|---------|-----|-----|-----|-----|-----|-----|-----|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | | Eh (mV) | | | | | | | |
| Luisiana | Moist | 424 | 313 | 350 | 363 | 350 | 294 | 358 | 311 |
| | Flooded | 413 | 109 | -33 | -63 | -61 | -48 | -23 | -36 |
| Maahas A | Moist | 302 | 222 | 192 | 150 | 284 | 235 | 330 | 295 |
| | Flooded | 326 | 56 | 31 | -35 | -40 | -59 | -32 | -59 |
| Pila | Moist | 240 | 285 | 115 | 117 | 265 | 203 | 310 | 276 |
| | Flooded | 250 | 291 | 53 | -10 | -23 | -25 | 3 | -5 |
| Burabod | Moist | 497 | 514 | 378 | 393 | 483 | 406 | 504 | 462 |
| | Flooded | 471 | 124 | 131 | 127 | 115 | 143 | 176 | 148 |

Appendix Table 3. Kinetics of solution pH in 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | | | |
|-----------|-----------------|-------|------|------|------|------|------|------|------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | | pH | | | | | | | |
| Luisiana | Moist | 4.60 | 4.90 | 4.30 | 4.20 | 4.30 | 4.50 | 4.70 | 4.90 |
| | Flooded | 4.60 | 6.00 | 6.50 | 6.70 | 6.80 | 6.80 | 6.70 | 6.70 |
| Maahas A | Moist | 6.60 | 6.40 | 6.35 | 6.50 | 6.60 | 6.46 | 6.40 | 6.50 |
| | Flooded | 6.50 | 7.00 | 6.80 | 7.00 | 7.00 | 7.00 | 6.90 | 7.10 |
| Pila | Moist | 7.40 | 7.16 | 7.25 | 7.40 | 7.33 | 7.25 | 7.12 | 7.41 |
| | Flooded | 7.40 | 7.15 | 6.98 | 7.00 | 7.00 | 7.09 | 7.02 | 7.13 |
| Burabod | Moist | 3.82 | 3.94 | 3.83 | 3.74 | 3.65 | 3.56 | 3.37 | 3.53 |
| | Flooded | 3.85 | 5.42 | 5.33 | 5.59 | 5.76 | 5.50 | 5.23 | 5.58 |

Table 4. Kinetics of solution EC in 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | | | |
|-----------|-----------------|--------------------------|------|------|------|------|------|------|------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | | EC (dS m ⁻¹) | | | | | | | |
| Luisiana | Moist | 1.24 | 1.14 | 1.60 | 1.73 | 1.28 | 1.03 | 0.74 | 0.38 |
| | Flooded | 1.24 | 1.88 | 2.89 | 1.86 | 1.37 | 1.15 | 0.94 | 0.86 |
| Maahas A | Moist | 0.73 | 1.46 | 1.39 | 0.91 | 0.81 | 0.81 | 0.69 | 0.72 |
| | Flooded | 0.97 | 1.70 | 1.80 | 1.94 | 2.06 | 1.91 | 1.59 | 1.81 |
| Pila | Moist | 1.64 | 2.01 | 1.70 | 1.12 | 1.09 | 1.09 | 1.08 | 1.10 |
| | Flooded | 1.90 | 2.55 | 2.69 | 2.35 | 2.40 | 2.38 | 2.42 | 2.57 |
| Burabod | Moist | 1.72 | 2.50 | 2.22 | 2.02 | 2.37 | 2.72 | 2.14 | 2.23 |
| | Flooded | 1.60 | 2.40 | 1.45 | 0.57 | 0.32 | 0.16 | 0.12 | 0.12 |

Appendix Table 5. Kinetics of water soluble oxidizable matter in 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | | | |
|-----------|-----------------|--------------------------|------|------|------|------|------|------|------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | | OxM(me L ⁻¹) | | | | | | | |
| Luisiana | Moist | 8.7 | 4.5 | 1.6 | 3.3 | 1.3 | 0.6 | 1.5 | 1.1 |
| | Flooded | 7.7 | 19.1 | 18.5 | 15.3 | 15.0 | 14.4 | 12.7 | 12.8 |
| Maahas A | Moist | 3.4 | 1.2 | 1.6 | 3.0 | 1.5 | 1.1 | 0.8 | 0.7 |
| | Flooded | 3.2 | 3.4 | 3.7 | 4.4 | 3.3 | 2.7 | 2.2 | 2.1 |
| Pila | Moist | 5.9 | 3.5 | 2.6 | 3.3 | 2.0 | 1.7 | 1.6 | 1.8 |
| | Flooded | 6.6 | 4.3 | 4.1 | 5.0 | 5.3 | 5.8 | 7.9 | 6.8 |
| Burabod | Moist | 6.7 | 3.4 | 1.5 | 3.2 | 1.8 | 2.2 | 1.3 | 1.6 |
| | Flooded | 6.6 | 16.0 | 9.7 | 8.1 | 7.7 | 5.6 | 5.4 | 4.6 |

Appendix Table 6. Kinetics of P_{CO_2} in 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | | | |
|-----------|-----------------|------------------|------|------|------|------|------|------|------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | | P_{CO_2} (kPa) | | | | | | | |
| Luisiana | Moist | 31.3 | 11.0 | 7.2 | 27.9 | 13.9 | 11.7 | 14.2 | 4.7 |
| | Flooded | 31.5 | 32.9 | 52.6 | 21.0 | 14.5 | 14.0 | 13.6 | 12.0 |
| Maahas A | Moist | 1.8 | 0.7 | 1.0 | 1.3 | 1.4 | 1.9 | 2.5 | 0.8 |
| | Flooded | 1.6 | 7.0 | 15.2 | 13.9 | 13.6 | 14.2 | 12.8 | 11.5 |
| Pila | Moist | 1.2 | 0.9 | 0.6 | 0.7 | 1.0 | 1.3 | 1.9 | 0.7 |
| | Flooded | 1.3 | 9.8 | 16.6 | 15.6 | 15.0 | 15.3 | 15.5 | 13.8 |
| Burabod | Moist | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| | Flooded | n.d. | 16.4 | 37.5 | 43.4 | 20.8 | 22.1 | 20.8 | 10.9 |

n.d. - not determined

Appendix Table 7. Kinetics of water soluble NH_4^+-N in 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | | | |
|-----------|-----------------|----------------------------|------|------|------|------|-----|-----|-----|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | | NH_4^+-N ($mg L^{-1}$) | | | | | | | |
| Luisiana | Moist | 13.0 | 20.2 | 14.8 | 2.4 | 0.3 | 0.1 | 0.1 | 0.1 |
| | Flooded | 12.0 | 28.2 | 43.6 | 38.9 | 16.4 | 5.8 | 0.7 | 0.7 |
| Maahas A | Moist | 2.0 | 0.1 | 0.1 | 0.3 | 0.2 | 0.1 | 0.1 | 0.1 |
| | Flooded | 3.0 | 10.5 | 9.0 | 0.3 | 0.4 | 0.1 | 0.1 | 0.1 |
| Pila | Moist | 6.1 | 0.3 | 0.3 | 0.3 | 0.1 | 0.3 | 0.2 | 0.2 |
| | Flooded | 6.7 | 16.0 | 17.8 | 5.5 | 0.2 | 0.3 | 0.3 | 0.3 |
| Burabod | Moist | 23.6 | 46.5 | 37.5 | 21.3 | 2.6 | 0.9 | 0.2 | 0.2 |
| | Flooded | 22.1 | 31.3 | 26.0 | 17.8 | 12.7 | 3.0 | 0.3 | 0.3 |

Appendix Table 8. Kinetics of solution NO_3^- -N in the solutions of 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | | | |
|-----------|-----------------|---|-------|--------|--------|--------|--------|-------|----|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | | NO_3^- -N (mg L^{-1}) | | | | | | | |
| Luisiana | Moist | 57.50 | 64.90 | 134.40 | 228.70 | 185.00 | 168.30 | 58.50 | |
| | Flooded | 59.40 | 0.55 | n.d. | n.d. | n.d. | n.d. | n.d. | |
| Maahas A | Moist | 0.13 | 90.60 | 87.10 | 21.90 | 2.40 | 0.60 | 0.70 | |
| | Flooded | 0.24 | 0.03 | n.d. | n.d. | n.d. | n.d. | n.d. | |
| Pila | Moist | 0.25 | 91.50 | 85.60 | 33.00 | 11.40 | 2.10 | 0.70 | |
| | Flooded | 0.50 | 0.10 | n.d. | n.d. | n.d. | n.d. | n.d. | |
| Burabod | Moist | 0.24 | 0.03 | 0.06 | 0.05 | n.d. | n.d. | n.d. | |
| | Flooded | 0.25 | 0.22 | n.d. | n.d. | n.d. | n.d. | n.d. | |

n.d. - non-detectable

Appendix Table 9. Kinetics of water soluble P in 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | |
|-----------|-----------------|---------------------------|-------|-------|-------|-------|-------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 |
| | | P (mg L^{-1})* | | | | | |
| Luisiana | Moist | 0.070 | 0.120 | 0.005 | 0.015 | 0.003 | n.d. |
| | Flooded | 0.150 | 0.210 | 0.013 | 0.015 | 0.026 | 0.023 |
| Maahas A | Moist | 0.580 | 0.210 | 0.100 | 0.120 | 0.226 | 0.063 |
| | Flooded | 0.560 | 0.370 | 0.210 | 0.160 | 0.145 | 0.076 |
| Pila | Moist | 2.770 | 1.350 | 1.280 | 1.350 | 1.050 | 0.340 |
| | Flooded | 2.480 | 1.380 | 3.230 | 3.420 | 1.200 | 0.660 |
| Burabod | Moist | 0.030 | 0.080 | 0.060 | 0.060 | 0.090 | 0.010 |
| | Flooded | 0.030 | 0.060 | 0.200 | 0.280 | 0.450 | 0.030 |

n.d. - non-detectable

Appendix Table 10. Kinetics of water soluble Fe in 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | | | |
|-----------|-----------------|--------------------------|--------|--------|--------|--------|--------|--------|--------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | | Fe (mg L ⁻¹) | | | | | | | |
| Luisiana | Moist | 0.30 | 0.30 | 0.41 | 1.28 | 0.26 | 0.32 | 0.16 | 0.39 |
| | Flooded | 0.33 | 131.66 | 380.00 | 195.83 | 156.66 | 134.25 | 120.16 | 110.16 |
| Maahas A | Moist | 0.55 | 0.32 | 0.82 | 0.56 | 2.36 | 2.07 | 2.41 | 3.28 |
| | Flooded | 0.55 | 6.95 | 10.70 | 22.00 | 27.93 | 40.86 | 42.87 | 40.33 |
| Pila | Moist | 0.10 | 0.10 | 0.35 | 0.22 | 0.11 | 0.34 | 0.21 | 0.10 |
| | Flooded | 0.10 | 0.58 | 2.02 | 2.38 | 3.00 | 3.10 | 5.15 | 4.13 |
| Burabod | Moist | 2.66 | 2.32 | 1.30 | 3.47 | 1.58 | 1.04 | 1.23 | 0.75 |
| | Flooded | 2.05 | 503.33 | 164.17 | 38.93 | 19.70 | 14.61 | 15.17 | 16.00 |

Appendix Table 11. Kinetics of water soluble Mn in 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | | | |
|-----------|-----------------|--------------------------|-------|-------|-------|-------|-------|-------|-------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | | Mn (mg L ⁻¹) | | | | | | | |
| Luisiana | Moist | 7.92 | 5.23 | 6.42 | 9.41 | 6.63 | 3.83 | 1.70 | 0.52 |
| | Flooded | 8.07 | 22.07 | 25.57 | 6.67 | 2.93 | 1.60 | 0.85 | 0.60 |
| Maahas A | Moist | 0.70 | 0.13 | 0.13 | 0.10 | 0.05 | 0.03 | 0.07 | 0.07 |
| | Flooded | 0.60 | 21.53 | 27.20 | 39.72 | 22.93 | 15.30 | 10.93 | 8.63 |
| Pila | Moist | 0.16 | 0.12 | 0.17 | 0.08 | 0.01 | 0.00 | 0.01 | 0.02 |
| | Flooded | 0.12 | 24.48 | 28.57 | 29.02 | 26.10 | 24.20 | 21.87 | 17.76 |
| Burabod | Moist | 2.76 | 4.12 | 3.50 | 3.43 | 4.00 | 4.93 | 3.53 | 3.38 |
| | Flooded | 2.58 | 2.52 | 1.15 | 0.30 | 0.17 | 0.09 | 0.11 | 0.14 |

Appendix Table 12. Kinetics of water soluble K in 4 soils under aerobic and submerged conditions.

| Treatments | | Weeks | | | | | | |
|------------|-----------------|-------------------------|------|------|------|------|------|------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | K (mg L ⁻¹) | | | | | | |
| Luisiana | Moist | 13.2 | 13.1 | 14.4 | 5.6 | 0.2 | 0.2 | 0.5 |
| | Flooded | 14.7 | 16.0 | 16.7 | 12.4 | 4.5 | 2.5 | 0.2 |
| Maahas A | Moist | 29.7 | 44.7 | 39.5 | 28.1 | 22.3 | 23.8 | 23.2 |
| | Flooded | 37.9 | 53.6 | 51.9 | 34.9 | 28.6 | 31.3 | 31.0 |
| Pila | Moist | 32.1 | 33.0 | 28.3 | 19.1 | 14.5 | 15.5 | 16.1 |
| | Flooded | 34.7 | 36.8 | 34.7 | 22.2 | 5.6 | 6.3 | 7.8 |
| Burabod | Moist | 25.2 | 33.7 | 27.1 | 10.8 | 1.1 | 0.9 | 0.8 |
| | Flooded | 23.0 | 20.4 | 15.1 | 7.6 | 4.2 | 1.4 | 0.2 |

Appendix Table 13. Kinetics of water soluble Ca in 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | | | |
|-----------|-----------------|--------------------------|-------|-------|-------|-------|-------|-------|-------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | | Ca (mg L ⁻¹) | | | | | | | |
| Luisiana | Moist | 127.2 | 106.6 | 153.3 | 195.9 | 135.8 | 97.3 | 59.7 | 27.6 |
| | Flooded | 124.5 | 196.6 | 275.8 | 167.2 | 117.8 | 108.3 | 95.0 | 80.0 |
| Maahas A | Moist | 57.5 | 115.8 | 98.3 | 69.6 | 60.0 | 58.2 | 49.3 | 46.2 |
| | Flooded | 77.9 | 150.8 | 157.5 | 211.6 | 175.3 | 165.6 | 141.3 | 131.2 |
| Pila | Moist | 275.6 | 324.1 | 229.1 | 177.5 | 147.1 | 159.6 | 174.8 | 145.8 |
| | Flooded | 316.8 | 470.0 | 455.0 | 434.3 | 420.0 | 442.7 | 464.7 | 450.8 |
| Burabod | Moist | 227.9 | 356.6 | 248.3 | 302.3 | 344.2 | 404.0 | 347.1 | 344.6 |
| | Flooded | 207.5 | 218.3 | 86.7 | 28.8 | 13.8 | 8.8 | 7.2 | 8.1 |

Appendix Table 14. Kinetics of water soluble Mg in 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | | | |
|-----------|-----------------|--------------------------|-------|-------|-------|-------|-------|-------|-------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | | Mg (mg L ⁻¹) | | | | | | | |
| Luisiana | Moist | 46.0 | 38.0 | 55.0 | 66.6 | 46.3 | 33.0 | 18.6 | 8.0 |
| | Flooded | 45.3 | 73.3 | 113.3 | 74.0 | 58.2 | 55.7 | 49.8 | 45.0 |
| Maahas | Moist | 35.6 | 83.6 | 74.6 | 47.6 | 39.8 | 41.1 | 35.8 | 32.9 |
| | Flooded | 55.6 | 113.6 | 126.3 | 158.3 | 163.5 | 164.3 | 146.0 | 150.3 |
| Pila | Moist | 82.7 | 93.7 | 67.7 | 49.3 | 43.1 | 46.0 | 47.7 | 41.8 |
| | Flooded | 97.3 | 144.0 | 147.0 | 144.7 | 156.0 | 164.9 | 166.3 | 160.3 |
| Burabod | Moist | 48.3 | 73.7 | 57.0 | 62.3 | 75.0 | 96.0 | 70.7 | 69.8 |
| | Flooded | 46.0 | 45.6 | 19.3 | 5.0 | 2.0 | 0.2 | 0.7 | 0.8 |

Appendix Table 15. Kinetics of water soluble SO₄⁼ in 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | | | |
|-----------|-----------------|--|------|------|------|------|------|------|--|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 | |
| | | SO ₄ ⁼ (mg L ⁻¹) | | | | | | | |
| Luisiana | Moist | 229 | 317 | 106 | 85 | 94 | 128 | 105 | |
| | Flooded | 228 | 723 | 218 | 52 | 32 | 31 | 25 | |
| Maahas A | Moist | 214 | 321 | 237 | 245 | 285 | 355 | 305 | |
| | Flooded | 308 | 353 | 206 | 82 | 36 | 11 | 9 | |
| Pila | Moist | 603 | 822 | 422 | 315 | 309 | 386 | 403 | |
| | Flooded | 660 | 657 | 350 | 157 | 33 | 23 | 19 | |
| Burabod | Moist | 1080 | 2015 | 1308 | 1292 | 1458 | 1778 | 1476 | |
| | Flooded | 1010 | 2100 | 745 | 242 | 37 | 33 | 27 | |

Appendix Table 16. Kinetics of water soluble Si in 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | | | |
|-----------|-----------------|---------------------------|------|------|------|------|------|------|------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | | Si (mg L^{-1}) | | | | | | | |
| Luisiana | Moist | 29.1 | 25.9 | 26.0 | 20.4 | 18.3 | 15.1 | 14.7 | 7.2 |
| | Flooded | 29.6 | 15.9 | 13.3 | 11.0 | 9.8 | 7.3 | 5.7 | 6.7 |
| Maahas A | Moist | 25.3 | 27.7 | 24.9 | 22.0 | 25.6 | 26.2 | 27.2 | 25.1 |
| | Flooded | 25.9 | 22.1 | 21.0 | 19.0 | 20.6 | 17.8 | 18.1 | 17.7 |
| Pila | Moist | 27.5 | 27.4 | 23.6 | 20.3 | 25.2 | 26.3 | 26.8 | 23.4 |
| | Flooded | 26.7 | 34.5 | 34.3 | 34.0 | 27.9 | 27.7 | 28.4 | 28.4 |
| Burabod | Moist | 36.2 | 53.1 | 36.1 | 34.6 | 41.8 | 43.5 | 46.1 | 27.0 |
| | Flooded | 35.0 | 33.6 | 25.6 | 21.5 | 24.5 | 20.3 | 16.1 | 7.9 |

Appendix Table 17. Kinetics of water soluble Zn in 4 soils under moist and flooded conditions.

| Treatment | | Weeks | | | | | | | |
|-----------|-----------------|---------------------------|------|------|------|------|------|------|------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | | Zn (mg L^{-1}) | | | | | | | |
| Luisiana | Moist | 0.27 | 0.36 | 0.41 | 0.55 | 0.38 | 0.34 | 0.20 | 0.09 |
| | Flooded | 0.26 | 0.19 | 0.12 | 0.23 | 0.16 | 0.09 | 0.10 | 0.06 |
| Maahas A | Moist | 0.17 | 0.13 | 0.12 | 0.13 | 0.07 | 0.13 | 0.08 | 0.07 |
| | Flooded | 0.12 | 0.08 | 0.05 | 0.05 | 0.05 | 0.02 | 0.04 | 0.03 |
| Pila | Moist | 0.06 | 0.08 | 0.06 | 0.06 | 0.06 | 0.05 | 0.03 | 0.03 |
| | Flooded | 0.06 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.03 | 0.03 |
| Burabod | Moist | 0.57 | 1.22 | 0.95 | 0.97 | 0.95 | 1.10 | 0.92 | 0.84 |
| | Flooded | 0.55 | 0.09 | 0.05 | 0.07 | 0.09 | 0.14 | 0.13 | 0.06 |

Appendix Table 18. Kinetics of water soluble Cu in Burabod soil under moist and flooded conditions.

| Treatment Moisture regime | Weeks | | | | | | | |
|---------------------------------|--------------------------|------|------|------|------|------|------|------|
| | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | Cu (mg L ⁻¹) | | | | | | | |
| Moist | 0.16 | 0.29 | 0.23 | 0.27 | 0.29 | 0.35 | 0.27 | 0.24 |
| Flooded | 0.17 | 0.00 | 0.02 | 0.01 | 0.02 | 0.02 | 0.01 | 0.00 |

Appendix Table 19. Kinetics of water soluble Al in Luisiana and Burabod soils under moist and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | | | |
|----------|---------------------------------|--------------------------|------|------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
| | | Al (mg L ⁻¹) | | | | | | | |
| Luisiana | Moist | 0.05 | 0.20 | 0.37 | 0.50 | 0.22 | 0.15 | n.d. | n.d. |
| | Flooded | 0.06 | 0.13 | 0.03 | 0.01 | 0.12 | 0.00 | n.d. | n.d. |
| Burabod | Moist | 15.1 | 37.6 | 30.9 | 35.1 | 47.8 | 63.1 | 72.0 | 63.4 |
| | Flooded | 14.1 | 1.8 | 1.4 | 0.4 | 0.4 | 0.4 | n.d. | n.d. |

n.d.- not determined.

Appendix Table 20. Analysis of variance for mineral nutrient concentration in 8 week old shoot of two rices grown in four soils under two moisture regimes.

| Source of variation | df | Mean Squares | | | | | | | | | |
|---------------------|----|--------------|------------|----------|-------------|------------|------------------|----------|-----------|-----------|----------|
| | | N | P | K | Ca | Mg | SiO ₂ | Fe | Mn | Zn | Cu |
| Replication | 2 | 0.006 ns | 0.00001 ns | 0.011 ns | <0.00001 ns | 0.0011 ns | 0.11 ns | 39 ns | 816 ns | 14.0 ns | 0.3 ns |
| Treatment | 15 | 1.956 ** | 0.00951 ** | 1.078 ** | 0.00471 ** | 0.0228 ** | 1.75 ** | 17747 ** | 353415 ** | 404.6 ** | 111.3 ** |
| Soil (S) | 3 | 6.424 ** | 0.01895 ** | 3.494 ** | 0.01507 ** | 0.0366 ** | 1.82 ** | 33625 ** | 665635 ** | 1317.7 ** | 141.2 ** |
| Cultivar (V) | 1 | 0.727 ** | 0.01083 ** | 0.001 ns | 0.00594 ** | 0.0420 ** | 0.09 ns | 13 ns | 125563 ** | 12.5 ns | 13.0 * |
| Moisture (M) | 1 | 3.701 ** | 0.03679 ** | 2.837 ** | 0.00100 ** | 0.1378 ** | 1.30 ** | 83750 ** | 125563 ** | 845.8 ** | 972.0 ** |
| S x V | 3 | 0.244 ** | 0.00142 ** | 0.124 ** | 0.00072 ** | 0.0063 ** | 1.05 ** | 1447 ** | 17051 ** | 11.2 ns | 5.2 ns |
| S x M | 3 | 1.512 ** | 0.01049 ** | 0.751 ** | 0.00392 ** | 0.0075 ** | 4.16 ** | 25057 ** | 973307 ** | 393.6 ** | 81.0 ** |
| V x M | 1 | 0.001 ns | 0.00137 ** | 0.006 ns | 0.00238 ** | <0.0001 ns | 0.67 * | 88 ns | 1813 ns | 5.6 ns | 1.7 ns |
| S x V x M | 3 | 0.124 ** | 0.00035 * | 0.072 ** | 0.00073 ** | 0.0038 ** | 1.04 ** | 656 ns | 26768 ** | 12.6 ns | 0.3 ns |
| Error | 30 | 0.022 | 0.00008 | 0.011 | 0.00007 | 0.0004 | 0.14 | 285 | 1061 | 8.3 | 3.0 |
| C. V. (%) | | 5.74 | 4.29 | 3.94 | 7.02 | 5.80 | 3.58 | 14.97 | 8.90 | 12.54 | 18.87 |

*** Significant at the 0.05 and 0.01 levels of probability, respectively.

ns non-significant at the 0.05 level of probability.

Appendix Table 21. Analysis of variance for mineral nutrient uptake by 8 week old shoot of two rices grown in four soils under two moisture regimes.

| Source of variation | df | Mean Squares | | | | | | | | | |
|---------------------|----|--------------|------------|------------|---------|----------|------------------|----------|-----------|-----------|----------|
| | | N | P | K | Ca | Mg | SiO ₂ | Fe | Mn | Zn | Cu |
| Replication | 2 | 5818 ns | 111.4 ns | 13084 ns | 19 ns | 222 ns | 0.2 ns | 0.3 ns | 4.0 ns | 23756 ns | 1489 ns |
| Treatment | 15 | 104342 ** | 4111.8 ** | 596538 ** | 663 ** | 3612 ** | 8.3 ** | 9.4 ** | 458.6 ** | 314617 ** | 24764 ** |
| Soil (S) | 3 | 259887 ** | 5087.5 ** | 1178700 ** | 1411 ** | 7387 ** | 11.7 ** | 2.3 ** | 606.0 ** | 874185 ** | 12465 ** |
| Cultivar (V) | 1 | 280 ns | 18.0 ns | 124339 ** | 13 ns | 507 * | 0.9 * | 0.6 ns | 51.4 ** | 19602 ns | <1 ns |
| Moisture (M) | 1 | 455910 ** | 27246.3 ** | 1888530 ** | 3608 ** | 10034 ** | 46.3 ** | 110.9 ** | 1340.9 ** | 292969 ** | 86021 ** |
| S x V | 3 | 47185 ** | 1543.4 ** | 187168 ** | 306 ** | 1997 ** | 2.7 ** | 4.6 ** | 83.4 ** | 67368 ** | 10888 * |
| S x M | 3 | 47919 ** | 4080.0 ** | 889934 ** | 207 ** | 4349 ** | 10.2 ** | 0.9 ns | 1068.0 ** | 490969 ** | 68344 ** |
| V x M | 1 | 13940 ns | <0.1 ns | 71071 ** | 282 ** | <1 ns | 0.9 * | 0.9 ns | 0.9 ns | 18802 ns | 7701 ns |
| S x V x M | 3 | 10005 ns | 760.2 ** | 32236 ** | 92 ** | 813 ** | 0.9 ** | 1.8 ** | 71.1 ** | 30102 * | 881 ns |
| Error | 30 | 5121 | 60.9 | 6648 | 18 | 98 | 0.1 | 0.3 | 2.3 | 9927 | 2479 |
| CV (%) | | 12.47 | 14.53 | 11.78 | 14.29 | 12.55 | 13.07 | 21.95 | 13.39 | 17.97 | 26.67 |

*,** Significant at the 0.05 and 0.01 levels of probability, respectively.

ns non-significant at the 0.05 level of probability.

Appendix Table 22. Analysis of variance for mineral nutrient concentration in mature straw of two rices grown in four soils under two moisture regimes.

| Source of variation | df | Mean Squares | | | | | | | | | |
|---------------------|----|--------------|------------|----------|-----------|----------|------------------|-----------|------------|---------|----------|
| | | N | P | K | Ca | Mg | SiO ₂ | Fe | Mn | Zn | Cu |
| Replication | 2 | 0.002 ns | 0.00016 ns | 0.004 ns | 0.0001 ns | 0.002 ns | 0.65 ns | 47 ns | 4366 ns | 27 ns | 0.1 ns |
| Treatment | 15 | 0.485 ** | 0.00519 ** | 1.204 ** | 0.0079 ** | 0.031 ** | 31.34 ** | 35385 ** | 609807 ** | 1745 ** | 35.3 ** |
| Soil (S) | 3 | 1.386 ** | 0.01524 ** | 5.180 ** | 0.0219 ** | 0.039 ** | 8.13 ** | 49407 ** | 1290940 ** | 5789 ** | 41.6 ** |
| Cultivar (V) | 1 | <0.001 ns | 0.00005 ns | 0.143 ** | 0.0002 ns | 0.078 ** | 11.90 ** | 30200 ** | 112811 ** | 159 ns | 20.5 ** |
| Moisture (M) | 1 | 0.703 ** | 0.00293 ** | 0.333 ** | 0.0207 ** | 0.126 ** | 407.75 ** | 158011 ** | 62857 ** | 1906 ** | 297.0 ** |
| S x V | 3 | 0.090 ** | 0.00102 * | 0.074 ** | 0.0045 ** | 0.001 ns | 0.94 ns | 8129 ** | 24051 ** | 212 * | 1.0 ns |
| S x M | 3 | 0.535 ** | 0.00638 ** | 0.430 ** | 0.0031 ** | 0.044 ** | 6.32 ** | 40134 ** | 1637190 ** | 1985 ** | 26.7 ** |
| V x M | 1 | 0.312 ** | 0.00094 ns | 0.195 ** | 0.0019 ** | 0.002 ns | 0.25 ns | 25484 ** | 7178 ns | <1 ns | 1.2 ns |
| S x V x M | 3 | 0.077 ** | 0.00198 ** | 0.114 ** | 0.0023 ** | 0.003 * | 1.34 ns | 8024 ** | 35906 ** | 51 ns | 0.8 ns |
| Error | 30 | 0.010 | 0.00028 | 0.011 | 0.0002 | 0.001 | 0.66 | 525 | 3004 | 59 | 0.7 |
| CV (%) | | 12.03 | 10.25 | 6.22 | 11.35 | 10.72 | 7.42 | 16.00 | 14.30 | 19.96 | 15.67 |

*,** Significant at the 0.05 and 0.01 levels of probability, respectively.

ns non-significant at the 0.05 level of probability.

Appendix Table 23. Analysis of variance for total nutrient uptake by plants at harvest (straw plus panicle) of two rice grown in four soils under two moisture regimes.

| Source of variation | df | Mean Squares | | | | | | | | | |
|---------------------|----|--------------|-----------|----------|----------|----------|------------------|---------|---------|---------|----------|
| | | N | P | K | Ca | Mg | SiO ₂ | Fe | Mn | Zn | Cu |
| Replication | 2 | 0.0076 ns | 49 ns | 0.001 ns | 79 ns | 1876 ns | <1 ns | 16 ns | 15 ns | 0.1 ns | 0.06 ns |
| Treatment | 15 | 0.6346 ** | 18536 ** | 0.715 ** | 6853 ** | 22158 ** | 53 ** | 278 ** | 3009 ** | 10.5 ** | 1.61 ** |
| Soil (S) | 3 | 2.0566 ** | 13336 ** | 1.537 ** | 16724 ** | 45553 ** | 23 ** | 303 ** | 7133 ** | 39.3 ** | 1.05 ** |
| Cultivar (V) | 1 | 0.0015 ns | 2054 * | 0.069 ns | 168 ns | 38025 ** | 20 ** | 110 ** | 307 ** | 0.4 ns | 0.40 ** |
| Moisture (M) | 1 | 2.5993 ** | 195075 ** | 3.461 ** | 40136 ** | 15372 ** | 627 ** | 2369 ** | 64 ns | 6.3 ** | 14.78 ** |
| S x V | 3 | 0.0251 ** | 504 ns | 0.031 ns | 1668 ** | 2664 ns | 1 ns | 39 ** | 57 ns | 0.5 ns | 0.05 ns |
| S x M | 3 | 0.2195 ** | 8147 ** | 0.763 ** | 747 * | 36875 ** | 18 ** | 89 ** | 7689 ** | 9.1 ** | 1.39 ** |
| V x M | 1 | 0.0042 ns | 7650 ** | 0.115 * | 8 ns | 13702 ** | 11 ** | 276 ** | < 1 ns | 1.9 ** | 1.39 ** |
| S x V x M | 3 | 0.0034 ns | 2432 ** | 0.029 ns | 1690 ** | 3332 * | 4 * | 40 ** | 41 ns | 0.9 * | 0.07 ns |
| Error | 30 | 0.0032 | 333 | 0.018 | 252 | 982 | 1 | 8 | 23 | 0.2 | 0.04 |
| CV (%) | | 6.47 | 10.05 | 11.93 | 17.15 | 13.60 | 11.10 | 16.37 | 17.17 | 14.63 | 14.11 |

*,** Significant at the 0.05 and 0.01 levels of probability, respectively.

ns non-significant at the 0.05 level of probability.

Appendix Table 24. Analysis of variance for yield of two rices in four soils under two moisture regimes.

| Source of variation | df | Mean Squares | | |
|---------------------|----|--------------|--------------------------------------|-------------|
| | | Grain yield | Dry Matter Yield of 8 week old shoot | Straw yield |
| Replication | 2 | 2 ns | 17 ns | 16 ns |
| Treatment | 15 | 1984 ** | 582 ** | 440 ** |
| Soil (S) | 3 | 480 ** | 786 ** | 811 ** |
| Cultivar (V) | 1 | 104 * | 102 ** | 7 ns |
| Moisture (M) | 1 | 24336 ** | 3467 ** | 2170 ** |
| S x V | 3 | 4 ns | 237 ** | 96 ns |
| S x M | 3 | 930 ** | 621 ** | 511 ** |
| V x M | 1 | 987 ** | 75 * | 18 ns |
| S x V x M | 3 | 30 ns | 51 ** | 53 ns |
| Error | 30 | 20 | 10 | 44 |
| CV (%) | | 15.05 | 12.89 | 11.52 |

*,** Significant at the 0.05 and 0.01 levels of probability, respectively.

^{ns} non-significant at the 0.05 level of probability.

Appendix Table 25. Kinetics of Eh in four soils under moist, wet and flooded conditions.

| Treatment | | Weeks | | | | | | | | | | | | | |
|-----------|-----------------|---------|-----|------|------|------|------|------|------|------|------|------|------|------|--|
| Soil | Moisture regime | 0.5 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 14 | 16 | |
| | | Eh (mV) | | | | | | | | | | | | | |
| Luisiana | Moist | 442 | 428 | 502 | 538 | 604 | 578 | 594 | 588 | 639 | 709 | 686 | 703 | 513 | |
| | Wet | 425 | 24 | 32 | 91 | 96 | 149 | 211 | 160 | 38 | 15 | 292 | 279 | 304 | |
| | Flooded | 477 | -10 | -126 | -168 | -173 | -172 | -181 | -203 | -190 | -195 | -201 | -191 | -248 | |
| Maahas A | Moist | 442 | 607 | 685 | 661 | 669 | 575 | 575 | 568 | 625 | 670 | 664 | 711 | 388 | |
| | Wet | 497 | 533 | 672 | 634 | 607 | 495 | 562 | 480 | 594 | 431 | 591 | 682 | 360 | |
| | Flooded | 177 | -43 | -65 | -101 | -89 | -126 | -182 | -156 | -191 | -173 | -233 | -221 | -286 | |
| Pila | Moist | 366 | 544 | 673 | 550 | 668 | 628 | 603 | 644 | 656 | 673 | 711 | 543 | 409 | |
| | Wet | 306 | 406 | 463 | 423 | 404 | 418 | 307 | 239 | 285 | 318 | 283 | 343 | 242 | |
| | Flooded | 312 | 263 | 52 | -46 | -84 | -104 | -128 | -173 | -172 | -143 | -164 | -171 | -261 | |
| Burabod | Moist | 621 | 667 | 748 | 623 | 739 | 657 | 703 | 707 | 792 | 835 | 827 | 826 | 697 | |
| | Wet | 444 | 227 | 307 | 267 | 326 | 270 | 228 | 532 | 646 | 488 | 559 | 464 | 308 | |
| | Flooded | 509 | 110 | -56 | -113 | -124 | -139 | -137 | -156 | -161 | -135 | -162 | -156 | -186 | |

Appendix Table 26. Kinetics of solution Eh in 4 soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | | |
|----------|---------------------------------|--------|-----|-----|-----|-----|-----|-----|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | Eh(mV) | | | | | | |
| Luisiana | Moist | 297 | 288 | 341 | 349 | 290 | 309 | 309 |
| | Wet | 295 | 291 | 345 | 335 | 266 | 182 | 230 |
| | Flooded | 300 | 137 | -20 | -61 | -60 | -43 | -45 |
| Maahas A | Moist | 212 | 267 | 310 | 298 | 231 | 181 | 237 |
| | Wet | 188 | 277 | 301 | 284 | 212 | 173 | 227 |
| | Flooded | 198 | -41 | -41 | -60 | -86 | -62 | -84 |
| Pila | Moist | 250 | 271 | 280 | 266 | 205 | 168 | 223 |
| | Wet | 224 | 285 | 273 | 261 | 198 | 162 | 216 |
| | Flooded | 212 | 98 | 19 | 7 | -49 | -20 | -27 |
| Burabod | Moist | 303 | 337 | 358 | 366 | 337 | 386 | 390 |
| | Wet | 335 | 324 | 346 | 339 | 305 | 316 | 352 |
| | Flooded | 303 | 102 | 54 | 34 | -11 | 20 | 22 |

Appendix Table 27. Kinetics of solution pH in 4 soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | | |
|----------|---------------------------------|-------|------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | pH | | | | | | |
| Luisiana | Moist | 4.69 | 4.60 | 4.22 | 4.10 | 4.19 | 4.21 | 4.57 |
| | Wet | 4.64 | 4.79 | 4.21 | 4.36 | 4.92 | 5.22 | 5.12 |
| | Flooded | 4.63 | 5.54 | 6.35 | 6.52 | 6.51 | 6.50 | 6.53 |
| Maahas A | Moist | 6.74 | 5.98 | 5.95 | 6.17 | 6.40 | 6.51 | 6.52 |
| | Wet | 6.76 | 5.95 | 6.03 | 6.33 | 6.55 | 6.56 | 6.57 |
| | Flooded | 6.83 | 6.90 | 6.97 | 6.95 | 6.99 | 7.12 | 7.16 |
| Pila | Moist | 7.27 | 6.94 | 6.99 | 7.15 | 7.10 | 7.02 | 7.04 |
| | Wet | 7.34 | 6.93 | 7.11 | 7.13 | 7.10 | 7.09 | 7.17 |
| | Flooded | 7.35 | 7.03 | 7.13 | 7.14 | 6.85 | 6.85 | 6.89 |
| Burabod | Moist | 3.69 | 3.69 | 3.77 | 3.77 | 3.64 | 3.64 | 3.62 |
| | Wet | 3.76 | 3.73 | 3.77 | 3.82 | 3.73 | 3.70 | 3.72 |
| | Flooded | 3.82 | 4.53 | 5.38 | 5.71 | 5.74 | 5.84 | 5.85 |

Appendix Table 28. Kinetics of solution EC in 4 soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | | |
|----------|------------------------------|--------------------------|------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | EC (dS m ⁻¹) | | | | | | |
| Luisiana | Moist | 0.97 | 0.61 | 0.86 | 1.18 | 0.74 | 0.68 | 0.37 |
| | Wet | 0.77 | 0.55 | 1.04 | 0.95 | 0.11 | 0.08 | 0.06 |
| | Flooded | 0.74 | 0.93 | 2.42 | 2.51 | 1.62 | 1.34 | 1.10 |
| Maahas A | Moist | 2.39 | 3.33 | 3.12 | 2.42 | 1.63 | 1.38 | 1.20 |
| | Wet | 2.18 | 3.00 | 3.07 | 1.81 | 0.73 | 0.78 | 0.88 |
| | Flooded | 2.61 | 3.65 | 3.49 | 3.26 | 2.88 | 2.97 | 2.64 |
| Pila | Moist | 3.25 | 2.80 | 2.73 | 2.47 | 2.63 | 3.21 | 2.55 |
| | Wet | 3.44 | 2.37 | 2.48 | 1.60 | 1.33 | 1.64 | 1.09 |
| | Flooded | 3.19 | 3.26 | 3.26 | 3.22 | 2.46 | 2.70 | 2.69 |
| Burabod | Moist | 3.33 | 2.84 | 2.39 | 2.43 | 1.90 | 1.70 | 1.85 |
| | Wet | 3.18 | 2.42 | 2.27 | 1.78 | 1.28 | 1.26 | 1.12 |
| | Flooded | 3.00 | 2.87 | 2.43 | 1.18 | 0.68 | 0.66 | 0.72 |

Appendix Table 29. Kinetics of solution P_{CO₂} in 4 soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | | |
|----------|------------------------------|-----------------------|------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | P _{CO} (kPa) | | | | | | |
| Luisiana | Moist | 31.9 | 17.1 | 23.3 | 15.9 | 21.9 | 10.9 | 17.1 |
| | Wet | 37.9 | 10.4 | 28.2 | 21.1 | 10.3 | 11.4 | 7.2 |
| | Flooded | 28.8 | 42.9 | 57.7 | 44.7 | 31.2 | 24.6 | 19.4 |
| Maahas A | Moist | 3.1 | 1.5 | 1.6 | 1.5 | 2.0 | 2.2 | 2.7 |
| | Wet | 3.5 | 2.5 | 1.8 | 2.0 | 2.8 | 4.1 | 4.2 |
| | Flooded | 2.1 | 14.0 | 12.1 | 13.8 | 13.6 | 12.8 | 10.3 |
| Pila | Moist | 2.4 | 1.5 | 0.9 | 0.7 | 1.0 | 1.1 | 1.4 |
| | Wet | 2.1 | 2.3 | 1.6 | 2.0 | 3.2 | 2.4 | 2.0 |
| | Flooded | 2.0 | 7.6 | 8.1 | 10.0 | 17.4 | 22.2 | 19.5 |
| Burabod | Moist | nd | nd | nd | nd | nd | nd | nd |
| | Wet | nd | nd | nd | nd | nd | nd | nd |
| | Flooded | nd | 52.3 | 72.1 | 44.8 | 34.6 | 26.9 | 22.7 |

nd - not determined

Appendix Table 30. Kinetics of water-soluble NH_4^+ -N in 4 soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | | |
|----------|---------------------------------|---|------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | NH_4^+ -N (mg L^{-1}) | | | | | | |
| Luisiana | Moist | 19.6 | 18.5 | 19.1 | 7.8 | 1.4 | 1.2 | 0.4 |
| | Wet | 15.8 | 15.9 | 20.6 | 7.8 | 0.4 | 1.0 | 0.1 |
| | Flooded | 15.0 | 23.5 | 37.9 | 42.7 | 39.8 | 35.0 | 27.4 |
| Maahas A | Moist | 13.4 | 2.7 | 0.6 | 0.8 | 0.6 | 1.1 | 0.4 |
| | Wet | 13.6 | 1.0 | 0.8 | 0.6 | 0.3 | 0.7 | 0.2 |
| | Flooded | 13.0 | 26.5 | 24.5 | 12.3 | 1.7 | 1.9 | 2.0 |
| Pila | Moist | 18.8 | 0.6 | 0.6 | 0.8 | 0.8 | 1.3 | 0.7 |
| | Wet | 18.8 | 1.3 | 1.1 | 0.9 | 0.7 | 0.9 | 0.5 |
| | Flooded | 26.8 | 10.9 | 13.4 | 14.8 | 2.2 | 1.2 | 1.8 |
| Burabod | Moist | 87.9 | 79.9 | 66.3 | 45.2 | 1.7 | 1.1 | 1.0 |
| | Wet | 82.7 | 67.4 | 61.3 | 38.2 | 0.5 | 0.6 | 0.5 |
| | Flooded | 78.1 | 59.5 | 48.9 | 35.6 | 27.7 | 29.5 | 30.8 |

Appendix Table 31. Kinetics of NO_3^- -N in the solutions of 4 soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | | |
|----------|---------------------------------|---|-------|-------|-------|-------|-------|-------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | NO_3^- -N (mg L^{-1}) | | | | | | |
| Luisiana | Moist | 7.9 | 7.1 | 59.7 | 67.1 | 117.7 | 73.0 | 36.8 |
| | Wet | 4.9 | 3.8 | 60.9 | 44.7 | 7.1 | 0.4 | 0.2 |
| | Flooded | 6.1 | 0.5 | nd | nd | nd | nd | nd |
| Maahas A | Moist | 12.0 | 232.2 | 215.8 | 141.6 | 65.0 | 20.3 | 2.9 |
| | Wet | 13.3 | 211.8 | 209.0 | 55.0 | 0.4 | 0.1 | nd |
| | Flooded | 0.3 | 0.2 | 0.1 | nd | nd | nd | nd |
| Pila | Moist | 43.4 | 197.4 | 171.2 | 116.3 | 195.2 | 258.9 | 206.6 |
| | Wet | 55.4 | 134.4 | 139.2 | 39.5 | 38.8 | 75.4 | 26.2 |
| | Flooded | 31.3 | 53.9 | 0.1 | nd | nd | nd | nd |
| Burabod | Moist | 1.4 | 0.7 | 0.4 | nd | nd | nd | nd |
| | Wet | 1.2 | 0.3 | 0.2 | nd | nd | nd | nd |
| | Flooded | 1.5 | 0.4 | nd | nd | nd | nd | nd |

nd - non-detectable.

Appendix Table 32. Kinetics of water-soluble P in 4 soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | | |
|----------|------------------------------|-------------------------|------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | P (mg L ⁻¹) | | | | | | |
| Luisiana | Moist | 0.04 | 0.07 | 0.01 | 0.04 | nd | nd | 0.07 |
| | Wet | 0.08 | 0.04 | nd | nd | nd | nd | 0.07 |
| | Flooded | 0.08 | 0.02 | 0.01 | 0.03 | nd | 0.01 | 0.08 |
| Maahas A | Moist | 0.59 | 0.27 | 0.19 | 0.09 | 0.09 | 0.08 | 0.23 |
| | Wet | 0.56 | 0.45 | 0.22 | 0.14 | 0.16 | 0.13 | 0.19 |
| | Flooded | 0.59 | 0.51 | 0.43 | 0.15 | 0.09 | 0.07 | 0.21 |
| Pila | Moist | 3.30 | 1.95 | 1.70 | 1.40 | 1.55 | 1.58 | 1.89 |
| | Wet | 3.68 | 2.13 | 2.20 | 2.30 | 2.22 | 2.20 | 2.41 |
| | Flooded | 3.75 | 2.39 | 2.06 | 1.70 | 1.44 | 1.63 | 1.75 |
| Burabod | Moist | 0.39 | 0.09 | 0.08 | 0.10 | 0.09 | 0.17 | 0.30 |
| | Wet | 0.29 | 0.06 | 0.05 | 0.02 | 0.01 | nd | 0.13 |
| | Flooded | 0.34 | 0.07 | 0.09 | 0.15 | 0.31 | 0.31 | 0.45 |

nd - non-detectable.

Appendix Table 33. Kinetics of water-soluble K in 4 soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | | |
|----------|------------------------------|-------------------------|------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | K (mg L ⁻¹) | | | | | | |
| Luisiana | Moist | 10.7 | 8.7 | 10.0 | 6.0 | 1.5 | 0.5 | 0.6 |
| | Wet | 9.0 | 7.2 | 10.7 | 4.0 | 0.3 | 0.1 | 0.1 |
| | Flooded | 8.7 | 8.5 | 9.7 | 10.2 | 8.2 | 7.0 | 5.8 |
| Maahas A | Moist | 45.0 | 56.0 | 52.5 | 37.5 | 24.5 | 22.0 | 16.2 |
| | Wet | 43.5 | 51.5 | 52.2 | 30.7 | 15.5 | 14.2 | 14.8 |
| | Flooded | 46.7 | 61.7 | 62.0 | 51.7 | 39.5 | 33.0 | 30.5 |
| Pila | Moist | 23.0 | 17.7 | 17.5 | 14.2 | 15.7 | 16.3 | 15.2 |
| | Wet | 23.0 | 17.2 | 17.5 | 13.2 | 13.0 | 12.9 | 11.3 |
| | Flooded | 21.7 | 22.5 | 23.5 | 21.5 | 11.2 | 2.7 | 1.0 |
| Burabod | Moist | 51.0 | 40.2 | 31.7 | 14.2 | 1.2 | 1.1 | 0.4 |
| | Wet | 50.7 | 34.5 | 29.7 | 14.0 | 0.3 | 0.2 | 0.1 |
| | Flooded | 45.2 | 28.2 | 18.7 | 12.2 | 8.9 | 8.4 | 7.3 |

Appendix Table 34. Kinetics of water-soluble Ca in 4 soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | | |
|----------|---------------------------------|--------------------------|-------|-------|-------|-------|-------|-------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | Ca (mg L ⁻¹) | | | | | | |
| Luisiana | Moist | 52.5 | 27.5 | 51.2 | 87.5 | 63.7 | 52.5 | 35.0 |
| | Wet | 41.3 | 25.0 | 77.5 | 65.0 | 4.0 | 2.4 | 8.6 |
| | Flooded | 38.8 | 51.2 | 121.2 | 118.8 | 70.0 | 54.4 | 60.0 |
| Maahas A | Moist | 141.2 | 250.0 | 230.0 | 161.9 | 98.7 | 91.9 | 72.5 |
| | Wet | 123.8 | 227.5 | 227.5 | 110.0 | 41.2 | 36.9 | 55.0 |
| | Flooded | 162.5 | 303.7 | 275.0 | 246.3 | 248.8 | 176.3 | 171.2 |
| Pila | Moist | 497.5 | 452.5 | 417.5 | 372.5 | 417.5 | 490.0 | 447.5 |
| | Wet | 542.5 | 385.0 | 385.0 | 227.5 | 222.5 | 225.0 | 166.3 |
| | Flooded | 477.5 | 587.5 | 592.5 | 575.0 | 440.0 | 512.5 | 572.5 |
| Burabod | Moist | 340.0 | 331.2 | 248.8 | 317.5 | 318.7 | 257.5 | 300.0 |
| | Wet | 340.0 | 280.0 | 246.7 | 201.2 | 201.7 | 183.3 | 185.0 |
| | Flooded | 320.0 | 262.5 | 185.0 | 58.8 | 25.6 | 20.9 | 35.1 |

Appendix Table 35. Kinetics of water-soluble Mg in 4 soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | | |
|----------|---------------------------------|--------------------------|-------|-------|-------|-------|-------|-------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | Mg (mg L ⁻¹) | | | | | | |
| Luisiana | Moist | 26.8 | 12.8 | 26.8 | 43.6 | 28.8 | 24.7 | 11.9 |
| | Wet | 21.3 | 11.4 | 31.5 | 33.8 | 3.9 | 2.6 | 1.9 |
| | Flooded | 19.6 | 25.1 | 77.4 | 83.6 | 49.1 | 38.7 | 35.6 |
| Maahas A | Moist | 112.5 | 183.0 | 176.0 | 130.9 | 74.9 | 54.0 | 45.4 |
| | Wet | 100.2 | 167.8 | 172.8 | 87.9 | 29.8 | 28.7 | 32.6 |
| | Flooded | 128.4 | 232.1 | 232.5 | 225.9 | 247.9 | 211.0 | 199.6 |
| Pila | Moist | 143.8 | 121.6 | 114.3 | 100.0 | 113.8 | 129.7 | 107.3 |
| | Wet | 153.4 | 102.0 | 109.7 | 66.5 | 60.5 | 63.5 | 41.7 |
| | Flooded | 151.0 | 159.4 | 174.0 | 178.2 | 139.9 | 164.6 | 175.0 |
| Burabod | Moist | 78.2 | 72.2 | 54.8 | 60.9 | 56.5 | 47.7 | 51.3 |
| | Wet | 69.4 | 57.4 | 52.3 | 41.8 | 34.4 | 26.9 | 21.7 |
| | Flooded | 61.8 | 53.0 | 35.7 | 13.8 | 6.5 | 5.2 | 5.4 |

Appendix Table 36. Kinetics of water-soluble Fe in 4 soils under moist, wet and flooded conditions.

| Treatment | | Weeks | | | | | | |
|-----------|-----------------|--------------------------|--------|--------|--------|--------|--------|--------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | Fe (mg L ⁻¹) | | | | | | |
| Luisiana | Moist | 0.10 | 0.10 | 0.05 | 0.07 | 0.12 | 0.10 | 0.05 |
| | Wet | 0.10 | 0.10 | 0.09 | 0.07 | 0.15 | 0.60 | 0.70 |
| | Flooded | 0.10 | 34.50 | 339.00 | 393.00 | 212.00 | 162.00 | 151.00 |
| Maahas A | Moist | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.27 | 0.25 |
| | Wet | 0.12 | 0.12 | 0.15 | 0.10 | 0.15 | 0.55 | 0.40 |
| | Flooded | 0.20 | 16.57 | 21.00 | 36.00 | 40.50 | 26.00 | 24.00 |
| Pila | Moist | 0.10 | 0.12 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| | Wet | 0.10 | 0.18 | 0.14 | 0.18 | 0.10 | 0.10 | nd |
| | Flooded | 0.10 | 0.10 | 0.20 | 0.25 | 0.82 | 1.92 | 2.37 |
| Burabod | Moist | 8.50 | 0.32 | 0.20 | 0.22 | 0.35 | 0.25 | 0.27 |
| | Wet | 8.40 | 6.70 | 0.44 | 1.32 | 1.50 | 2.23 | 1.23 |
| | Flooded | 7.10 | 322.50 | 377.00 | 121.00 | 56.00 | 46.00 | 61.00 |

Appendix Table 37. Kinetics of water-soluble Mn in 4 soils under moist, wet and flooded conditions.

| Treatment | | Weeks | | | | | | |
|-----------|-----------------|--------------------------|-------|--------|--------|-------|-------|-------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | Mn (mg L ⁻¹) | | | | | | |
| Luisiana | Moist | 26.80 | 9.47 | 8.00 | 16.32 | 11.30 | 6.75 | 3.07 |
| | Wet | 20.50 | 8.65 | 12.22 | 20.02 | 1.35 | 2.15 | 1.85 |
| | Flooded | 19.90 | 39.50 | 125.00 | 121.50 | 48.00 | 28.00 | 22.00 |
| Maahas A | Moist | 2.12 | 0.18 | nd | 0.05 | nd | 0.15 | 0.60 |
| | Wet | 1.95 | 0.10 | nd | nd | 0.10 | 0.25 | 0.40 |
| | Flooded | 2.72 | 45.00 | 43.50 | 36.00 | 31.50 | 12.15 | 8.57 |
| Pila | Moist | 0.32 | nd | nd | nd | nd | 0.07 | nd |
| | Wet | 0.31 | nd | nd | nd | nd | nd | nd |
| | Flooded | 0.32 | 1.35 | 8.90 | 19.50 | 25.00 | 35.00 | 32.00 |
| Burabod | Moist | 5.07 | 4.98 | 3.72 | 4.25 | 3.98 | 3.10 | 3.12 |
| | Wet | 4.52 | 4.00 | 3.41 | 2.87 | 2.33 | 1.27 | 0.63 |
| | Flooded | 3.92 | 3.95 | 2.62 | 0.95 | 0.48 | 0.42 | 0.45 |

nd - non-detectable

Appendix Table 38. Kinetics of water-soluble Zn in 4 soils under moist, wet and flooded conditions.

| Soil | Treatment Water regime | Weeks | | | | | | |
|----------|---------------------------|--------------------------|------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | Zn (mg L ⁻¹) | | | | | | |
| Luisiana | Moist | 0.15 | 0.10 | 0.12 | 0.24 | 0.14 | 0.13 | 0.07 |
| | Wet | 0.14 | 0.09 | 0.18 | 0.18 | 0.05 | 0.05 | 0.04 |
| | Flooded | 0.18 | 0.14 | 0.05 | 0.06 | 0.04 | 0.04 | 0.04 |
| Maahas A | Moist | 0.04 | 0.05 | 0.06 | 0.04 | 0.04 | 0.04 | 0.06 |
| | Wet | 0.05 | 0.05 | 0.05 | 0.04 | 0.03 | 0.03 | 0.02 |
| | Flooded | 0.07 | 0.06 | 0.05 | 0.05 | 0.05 | 0.03 | 0.03 |
| Pila | Moist | 0.04 | 0.06 | 0.04 | 0.03 | 0.03 | 0.03 | 0.02 |
| | Wet | 0.03 | 0.04 | 0.05 | 0.02 | 0.03 | 0.03 | 0.02 |
| | Flooded | 0.03 | 0.07 | 0.04 | 0.03 | 0.03 | 0.02 | 0.01 |
| Burabod | Moist | 0.74 | 0.74 | 0.54 | 0.52 | 0.45 | 0.44 | 0.44 |
| | Wet | 0.68 | 0.57 | 0.50 | 0.36 | 0.17 | 0.27 | 0.18 |
| | Flooded | 0.56 | 0.45 | 0.07 | 0.03 | 0.02 | 0.04 | 0.03 |

Appendix Table 39. Kinetics of water-soluble Cu in 4 soils under moist, wet and flooded conditions.

| Soil | Treatment Water regime | Weeks | | | | | | |
|----------|---------------------------|--------------------------|------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | Cu (mg L ⁻¹) | | | | | | |
| Luisiana | Moist | .040 | .010 | .015 | .020 | .012 | .015 | .010 |
| | Wet | .035 | .010 | .013 | .015 | .007 | .010 | .007 |
| | Flooded | .030 | .018 | .020 | .010 | .007 | .007 | nd |
| Maahas A | Moist | .020 | .022 | .013 | .010 | .010 | .007 | .007 |
| | Wet | .020 | .015 | .017 | .003 | .010 | .007 | .005 |
| | Flooded | .013 | .057 | .020 | .007 | .013 | nd | nd |
| Pila | Moist | .070 | .043 | .040 | .033 | .035 | .025 | .030 |
| | Wet | .080 | .038 | .040 | .030 | .035 | .022 | .020 |
| | Flooded | .075 | .058 | .055 | .037 | .023 | .010 | .010 |
| Burabod | Moist | .265 | .178 | .130 | .150 | .142 | .130 | .120 |
| | Wet | .240 | .140 | .110 | .095 | .077 | .064 | .047 |
| | Flooded | .225 | .068 | .020 | .010 | .010 | .010 | nd |

nd - non-detectable

Appendix Table 40. Kinetics of water-soluble Na in 4 soils under moist, wet and flooded conditions.

| Soil | Treatment Water regime | Weeks | | | | | | |
|----------|---------------------------|--------------------------|-------|-------|-------|-------|-------|-------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | Na (mg L ⁻¹) | | | | | | |
| Luisiana | Moist | 28.7 | 21.5 | 24.5 | 26.5 | 15.8 | 16.5 | 9.2 |
| | Wet | 26.0 | 20.2 | 29.0 | 21.5 | 4.5 | 2.5 | 1.5 |
| | Flooded | 24.7 | 25.0 | 31.7 | 31.7 | 23.2 | 19.8 | 15.5 |
| Maahas A | Moist | 172.5 | 237.5 | 199.0 | 169.0 | 148.0 | 164.0 | 135.0 |
| | Wet | 172.5 | 237.5 | 196.0 | 140.0 | 90.0 | 100.0 | 101.0 |
| | Flooded | 193.7 | 262.5 | 247.5 | 240.0 | 297.0 | 305.0 | 299.0 |
| Pila | Moist | 81.2 | 63.0 | 59.5 | 55.0 | 62.0 | 73.0 | 64.0 |
| | Wet | 84.7 | 56.5 | 58.5 | 42.2 | 40.8 | 43.2 | 32.0 |
| | Flooded | 77.5 | 82.7 | 83.2 | 84.0 | 66.0 | 67.0 | 64.0 |
| Burabod | Moist | 96.7 | 97.7 | 78.2 | 89.0 | 63.0 | 64.2 | 59.0 |
| | Wet | 90.5 | 82.8 | 73.0 | 57.8 | 25.7 | 20.7 | 15.3 |
| | Flooded | 83.7 | 83.7 | 66.2 | 42.7 | 25.7 | 25.2 | 24.0 |

Appendix Table 41. Kinetics of water-soluble Si in 4 soils under moist, wet and flooded conditions.

| Soil | Treatment Water regime | Weeks | | | | | | |
|----------|---------------------------|--------------------------|------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | Si (mg L ⁻¹) | | | | | | |
| Luisiana | Moist | 13.0 | 9.9 | 14.3 | 7.9 | 4.4 | 5.6 | 5.5 |
| | Wet | 12.8 | 9.9 | 19.4 | 7.5 | 2.4 | 2.6 | 1.2 |
| | Flooded | 13.1 | 6.8 | 5.0 | 3.9 | 3.8 | 4.1 | 2.5 |
| Maahas A | Moist | 20.6 | 28.3 | 28.4 | 21.9 | 18.1 | 16.5 | 15.2 |
| | Wet | 20.9 | 28.7 | 28.5 | 21.9 | 14.5 | 12.7 | 9.1 |
| | Flooded | 21.2 | 23.3 | 22.5 | 21.8 | 19.2 | 17.9 | 13.7 |
| Pila | Moist | 23.6 | 27.4 | 25.7 | 21.9 | 25.3 | 25.6 | 23.8 |
| | Wet | 24.9 | 28.9 | 29.4 | 27.4 | 29.5 | 28.2 | 27.0 |
| | Flooded | 24.1 | 30.1 | 33.7 | 26.6 | 27.3 | 27.9 | 22.7 |
| Burabod | Moist | 32.0 | 40.5 | 38.0 | 28.4 | 16.2 | 31.0 | 33.2 |
| | Wet | 31.7 | 39.5 | 41.2 | 29.6 | 6.4 | 7.2 | 4.4 |
| | Flooded | 31.5 | 38.9 | 23.1 | 17.9 | 15.6 | 21.0 | 22.0 |

Appendix Table 42. Kinetics of water-soluble oxidizable matter in four soils under moist, wet and flooded conditions.

| Soil | Treatment Water regime | Weeks | | | | | | |
|----------|---------------------------|---------------------------|------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | OxM (me L ⁻¹) | | | | | | |
| Luisiana | Moist | 13.1 | 1.3 | 2.1 | 1.3 | 1.3 | 0.9 | 0.9 |
| | Wet | 13.6 | 1.5 | 2.2 | 1.1 | 1.0 | 0.9 | 0.8 |
| | Flooded | 13.9 | 14.4 | 20.9 | 22.1 | 15.4 | 10.9 | 10.0 |
| Maahas A | Moist | 7.8 | 2.2 | 2.4 | 1.3 | 1.1 | 2.1 | 1.1 |
| | Wet | 12.7 | 2.1 | 2.5 | 0.6 | 0.7 | 4.3 | 0.7 |
| | Flooded | 12.6 | 7.8 | 5.7 | 5.4 | 6.0 | 5.9 | 6.3 |
| Pila | Moist | 15.2 | 4.8 | 4.5 | 2.5 | 1.9 | 4.3 | 1.4 |
| | Wet | 15.6 | 5.8 | 5.1 | 1.9 | 1.9 | 4.4 | 1.3 |
| | Flooded | 14.3 | 9.3 | 6.9 | 5.5 | 3.8 | 4.7 | 6.4 |
| Burabod | Moist | 16.2 | 9.9 | 4.0 | 1.6 | 2.0 | 2.6 | 2.1 |
| | Wet | 15.5 | 6.9 | 3.2 | 1.2 | 1.1 | 1.1 | 1.1 |
| | Flooded | 15.6 | 21.9 | 21.9 | 14.0 | 10.2 | 11.6 | 11.6 |

Appendix Table 43. Kinetics of water-soluble Al in two acidic soils under moist, wet and flooded conditions.

| Soil | Treatment Water regime | Weeks | | | | | | |
|----------|---------------------------|--------------------------|------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 | 12 |
| | | Al (mg L ⁻¹) | | | | | | |
| Luisiana | Moist | 0.4 | 0.1 | 0.4 | 1.1 | 0.7 | 0.6 | 0.2 |
| | Wet | 0.2 | 0.1 | 0.5 | 0.7 | 0.1 | 0.2 | 0.1 |
| | Flooded | 0.2 | nd | nd | nd | nd | nd | nd |
| Burabod | Moist | 36.0 | 27.0 | 18.5 | 24.0 | 30.2 | 24.0 | 28.0 |
| | Wet | 31.5 | 18.0 | 16.0 | 13.0 | 15.3 | 11.0 | 9.0 |
| | Flooded | 27.0 | 4.0 | nd | nd | nd | nd | nd |

nd - non-detectable.

Appendix Table 44. Analysis of variance for mineral nutrient concentration in 8 week old shoot of IR43 grown in three soils under three moisture regimes.

| Source of variation | df | Mean Squares | | | | | | | | | | |
|---------------------|----|--------------|-----------|---------|-----------|----------|------------------|-----------|----------|-----------|--------|--------|
| | | N | P | K | Ca | Mg | SiO ₂ | Na | Fe | Mn | Zn | Cu |
| Replication | 3 | 0.010ns | 0.00015ns | 0.082* | 0.00015ns | 0.0004ns | 0.14ns | 4497ns | 252ns | 4258ns | 11ns | 12ns |
| Treatment | 8 | 1.306** | 0.00365** | 2.514** | 0.00474** | 0.1018** | 27.48** | 977986** | 96136** | 2315210** | 619** | 430** |
| Soil (S) | 2 | 2.721** | 0.01123** | 9.235** | 0.01488** | 0.0957** | 72.18** | 1101940** | 98646** | 8257000** | 1493** | 426** |
| Moisture (M) | 2 | 1.004** | 0.00183** | 0.550** | 0.00125** | 0.2684** | 29.32** | 1527150** | 134975** | 228988** | 718** | 1000** |
| S x M | 4 | 0.749** | 0.00077** | 0.136** | 0.00143** | 0.0216** | 4.22** | 641424** | 75463** | 387423** | 132* | 148** |
| Error | 24 | 0.018 | 0.00006 | 0.025 | 0.00014 | 0.0007 | 0.14 | 2072 | 390 | 3445 | 38 | 7 |
| CV (%) | | 4.62 | 3.75 | 5.02 | 5.51 | 5.94 | 4.37 | 10.54 | 8.87 | 7.52 | 18.38 | 11.06 |

*,** Significant at the 0.05 and 0.01 level of probability, respectively.

ns Non-significant at the 0.05 level of probability.

Appendix Table 45. Analysis of variance for mineral nutrient uptake by 8 week old shoot of IR43 grown in three soils under three moisture regimes.

| Source of variation | df | Mean Squares | | | | | | | | | | |
|---------------------|----|--------------|--------|----------|--------|---------|------------------|---------|--------|--------|---------|----------|
| | | N | P | K | Ca | Mg | SiO ₂ | Na | Fe | Mn | Zn | Cu |
| Replication | 3 | 0.007ns | 5ns | 0.0006ns | 68ns | 355ns | 0.06ns | 7.3ns | 0.7ns | 22ns | 0.033ns | 16948ns |
| Treatment | 8 | 0.171** | 3029** | 0.9343** | 1305** | 13300** | 5.89** | 141.8** | 12.0** | 1686** | 0.590** | 468572** |
| Soil (S) | 2 | 0.049** | 3875** | 1.8827** | 867** | 1887** | 10.97** | 97.5** | 4.9** | 4099** | 0.363** | 80088** |
| Moisture (M) | 2 | 0.101** | 346** | 0.0107ns | 725** | 26827** | 1.53** | 315.7** | 19.0** | 215** | 0.855** | 794029** |
| S x M | 4 | 0.267** | 3948** | 0.9219** | 1815** | 12244** | 5.53** | 77.1** | 12.0** | 1215** | 0.771** | 500085** |
| Error | 24 | 0.005 | 39 | 0.0066 | 36 | 283 | 0.06 | 3.7 | 0.3 | 14 | 0.027 | 7123 |
| CV (%) | | 9.75 | 11.92 | 9.82 | 11.61 | 14.64 | 10.77 | 21.94 | 11.49 | 18.52 | 19.40 | 13.50 |

*,** Significant at the 0.05 and 0.01 levels of probability, respectively.

ns Non-significant at the 0.05 level of probability.

Appendix Table 46. Analysis of variance for mineral nutrient concentration in mature straw of IR43 grown in three soils under three moisture regimes.

| Source of variation | df | Mean Squares | | | | | | | | | |
|---------------------|----|--------------|------------|-----------|-----------|-----------|------------------|-------------|-----------|-------------|----------|
| | | N | P | K | Ca | Mg | SiO ₂ | Na | Fe | Mn | Cu |
| Replication | 3 | 0.006 ns | 0.00012 ns | 0.047 ns | 0.0002 ns | 0.0002 ns | 1.0 ns | 96883 ns | 2724 ns | 13850 ns | 5.2 * |
| Treatment | 8 | 1.716 ** | 0.00853 ** | 4.246 ** | 0.0231 ** | 0.2259** | 23.2 ** | 20456600 ** | 610059 ** | 6156380 ** | 123.3 ** |
| Soil (S) | 2 | 2.496 ** | 0.00164 ** | 14.852 ** | 0.0644 ** | 0.2509 ** | 38.6 ** | 54746300 ** | 503746 ** | 21282300 ** | 68.1 ** |
| Moisture (M) | 2 | 2.473 ** | 0.03049 ** | 0.527 ** | 0.0030 ** | 0.5186 ** | 40.1 ** | 16717600 ** | 952845 ** | 707640 ** | 217.0 ** |
| S x M | 4 | 0.947 ** | 0.00100 ** | 0.802 ** | 0.0125 ** | 0.0670 ** | 7.0 ** | 5181320 ** | 491823 ** | 1317790 ** | 104.1 ** |
| Error | 24 | 0.003 | 0.00007 | 0.025 | 0.0005 | 0.0014 | 0.4 | 60925 | 1088 | 5530 | 1.7 |
| CV (%) | | 4.71 | 6.94 | 7.22 | 8.59 | 8.17 | 4.52 | 10.55 | 9.39 | 6.44 | 7.18 |

*,** Significant at the 0.05 and 0.01 levels of probability, respectively.

ns Non-significant at the 0.05 level of probability.

Appendix Table 47. Analysis of variance for total nutrient uptake by IR43 at harvest (straw plus grain) from three soils under three moisture regimes.

| Source of variation | df | Mean Squares | | | | | | | | | |
|---------------------|------|--------------|----------|----------|----------|-----------|------------------|-----------|---------|-----------|----------|
| | | N | P | K | Ca | Mg | SiO ₂ | Na | Fe | Mn | Cu |
| Replication | 3 | 0.0128 ns | 1806 ** | 0.08 * | 204 ns | 1022 ns | 4.8 * | 83 ns | 42 ns | 300 ns | 1.74 ** |
| Treatment | 8 | 0.4569 ** | 29831 ** | 5.09 ** | 26904 ** | 198542 ** | 85.3 ** | 50638 ** | 1503 ** | 46819 ** | 29.17 ** |
| Soil (S) | 2 | 1.3359 ** | 36198 ** | 15.77 ** | 49051 ** | 127797 ** | 123.2 ** | 137868 ** | 144 ns | 142385 ** | 5.64 ** |
| Moisture (M) | 2 | 0.2368 ** | 6164 ** | 0.12 ** | 14971 ** | 441448 ** | 51.7 ** | 30828 ** | 3951 ** | 8329 ** | 43.66 ** |
| S x M | 4 | 0.1274 ** | 38481 ** | 2.24 ** | 21798 ** | 112461 ** | 83.2 ** | 16928 ** | 960 ** | 18281 ** | 33.70 ** |
| Error | 24 | 0.0052 | 297 | 0.02 | 405 | 969 | 1.1 | 342 | 52 | 154 | 0.21 |
| CV (%) | 4.56 | 7.34 | 7.06 | 9.86 | 7.50 | 7.94 | 12.58 | 17.52 | 12.73 | 10.25 | |

*, ** Significant at the 0.05 and 0.01 levels of probability, respectively.

ns non-significant at the 0.05 level of probability.

Appendix Table 48. Analysis of variance for height, tiller number and yields of IR43 in four soils under three moisture regimes.

| Source of variation | df | Mean Squares | | | | |
|---------------------|----|-----------------------------|---------------------------------|--------------------------------------|-------------|-------------|
| | | Height of 8 week old plants | Tiller No. of 8 week old plants | Dry Matter Yield of 8 week old shoot | Grain yield | Straw yield |
| Replication | 3 | 19 ns | 1.3 ns | 4.1 ns | 9.5 ns | 1.2 ns |
| Treatment | 11 | 1217 ** | 242.1 ** | 635.6 ** | 6103.4 ** | 3927.7 ** |
| Soil (S) | 3 | 1802 ** | 435.6 ** | 1268.1 ** | 2868.6 ** | 7784.1 ** |
| Moisture (M) | 2 | 923 ** | 21.3 * | 52.9 ** | 9811.2 ** | 622.2 ** |
| S x M | 6 | 1022 ** | 219.0 ** | 513.5 ** | 6484.9 ** | 3101.3 ** |
| Error | 33 | 15 | 4.4 | 5.4 | 12.9 | 20.2 |
| CV (%) | | 4.18 | 11.57 | 11.35 | 7.18 | 7.12 |

*,** Significant at the 0.05 and 0.01 level of probability, respectively.

^{ns} non-significant at the 0.05 level of probability.

A Method of Collecting Representative
Solutions from Moderately Reduced Unsaturated Soils

Equilibrium saturation extracts serve well as the representative solutions of unsaturated soils. To ensure equilibration, the unsaturated soils should either be kept saturated for enough time or the quickly drained saturation extracts be recycled about 3 times through the soils (Kundu et al 1987). Since allowing the unsaturated soils under saturated conditions overnight is suspected to cause soil reduction, the recycling method is recommended for collecting representative solutions from aerobic soils. This method, however, is not expected to work satisfactorily for moderately reduced soils as the solutions may get oxidized through the process of recycling.

It was presumed that keeping unsaturated soils under saturated conditions for about 12 hours would cause moderate reduction of aerobic soil but might not cause further reduction of moderately reduced soil. For testing this hypothesis, one preliminary experiment was conducted in which the changes in redox conditions of six unsaturated soils with time after saturation was monitored.

Procedure

Twelve kilogram portions of each soil were placed in 3 separate 16 liter glazed porcelain pots fitted with drainage tubes at bottom. Soils in all the pots were brought to the

field capacity moisture regime by adding required amount of demineralized water. Two bright platinum electrodes were installed in each pot at 12 cm depth. While one pot for each soil was maintained at around field capacity, the other two pots were maintained at two wetter than the field capacity moisture regimes by supplying 2 to 3 irrigations daily. Two weeks after these treatments started, Eh of the soils in situ were measured and found to have achieved three different redox conditions for each soil.

Soils in all the pots were then made saturated (with no standing water on soil surface) by adding water and the initial Eh values were recorded. Subsequently, soil Eh in all the pots were recorded at 4, 8 and 16 hours after the saturation.

Results

Table 49 shows that regardless of the initial status, redox conditions of the Maahas A and Pila soils were not appreciably changed by 16 hours of saturation. In the Luisiana soil also, the change was not so well marked. In case of the other three soils (the Burabod, Rotonda and Maahas B soils), Eh drops due to 16 hours' saturation were clearly marked under the initially aerobic regime and very less marked under the moderately reduced conditions.

Conclusion

Results of this preliminary experiment indicate that keeping the moderately-reduced unsaturated soils under saturated condition for about 16 hours would not alter their redox status.

Since it is not certain whether the soils under the well-drained wet regimes would maintain aerobic or moderately-reduced conditions, it was considered safe to collect the equilibrium saturation extracts from the wet Burabod soil after keeping it saturated for 8 hours and from the other soils (Luisiana, Maahas A, Pila, Rotonda and Maahas B under the wet regimes) after 12 hours of saturation.

Appendix Table 49. Changes in Eh of six soils with time after saturation.

| Soils | Time after saturation (hours) | | | |
|----------|-------------------------------|-----|-----|-----|
| | 0 | 4 | 8 | 16 |
| | ----- Eh (mV) ----- | | | |
| Luisiana | 450 | 435 | 424 | 416 |
| | 235 | 200 | 192 | 191 |
| | 176 | 167 | 161 | 154 |
| Maahas A | 552 | 556 | 549 | 512 |
| | 385 | 388 | 397 | 396 |
| | 95 | 93 | 98 | 98 |
| Pila | 304 | 304 | 301 | 297 |
| | 90 | 78 | 84 | 67 |
| | 15 | 22 | 27 | 23 |
| Burabod | 596 | 574 | 481 | 395 |
| | 295 | 280 | 275 | 268 |
| | 269 | 263 | 254 | 233 |
| Rotonda | 630 | 620 | 593 | 561 |
| | 479 | 455 | 426 | 402 |
| | 204 | 202 | 209 | 200 |
| Maahas B | 433 | 377 | 365 | 350 |
| | 419 | 396 | 365 | 343 |
| | 234 | 205 | 201 | 200 |

Appendix Table 50. Kinetics of Eh in six soils under moist, wet and flooded conditions.

| Treatment | | Weeks | | | | | | | | | | |
|-----------|--------------|---------|------|------|------|------|------|------|------|------|------|------|
| Soil | Water regime | 2 | 3 | 4 | 5 | 6 | 7 | 9 | 11 | 13 | 14 | 15 |
| | | Eh (mV) | | | | | | | | | | |
| Luisiana | Moist | 377 | 346 | 475 | 396 | 491 | 468 | 470 | 448 | 459 | 467 | 325 |
| | Wet | 289 | 353 | 435 | 263 | 449 | 413 | 424 | 417 | 332 | 416 | 329 |
| | Flooded | -237 | -267 | -306 | -322 | -312 | -341 | -286 | -291 | -282 | -313 | -248 |
| Maahas A | Moist | 475 | 501 | 595 | 511 | 522 | 468 | 546 | 520 | 429 | 520 | 401 |
| | Wet | 339 | 243 | 376 | 248 | 366 | 320 | 318 | 456 | 10 | 434 | 245 |
| | Flooded | 223 | 119 | 30 | -65 | -52 | -128 | -146 | -219 | -212 | -236 | -187 |
| Pila | Moist | 158 | 151 | 230 | 266 | 322 | 350 | 428 | 427 | 443 | 518 | 436 |
| | Wet | 148 | 169 | 96 | 184 | 155 | 121 | 146 | 208 | 258 | 264 | 226 |
| | Flooded | -181 | -232 | -279 | -263 | -262 | -278 | -283 | -290 | -259 | -335 | -223 |
| Burabod | Moist | 132 | -19 | 122 | 479 | 502 | 550 | 560 | 539 | 563 | 585 | 499 |
| | Wet | 133 | -21 | -90 | -52 | -42 | 53 | 399 | 317 | -57 | 501 | 445 |
| | Flooded | -239 | -276 | -296 | -287 | -278 | -286 | -255 | -265 | -287 | -288 | -228 |
| Rotonda | Moist | 281 | 416 | 521 | 497 | 523 | 523 | 539 | 547 | 465 | 607 | 516 |
| | Wet | 220 | 201 | 166 | 52 | 205 | 223 | 249 | 73 | 33 | 350 | 256 |
| | Flooded | -174 | -236 | -284 | -297 | -284 | -298 | -296 | -319 | -324 | -327 | -275 |
| Maahas B | Moist | 323 | 431 | 493 | 464 | 466 | 515 | 516 | 510 | 482 | 560 | 478 |
| | Wet | 331 | 396 | 391 | 362 | 377 | 445 | 449 | 413 | 440 | 461 | 419 |
| | Flooded | -112 | -153 | -203 | -231 | -219 | -230 | -236 | -245 | -309 | -332 | -307 |

Appendix Table 51. Kinetics of solution Eh in six soils under moist, wet and flooded conditions.

| Treatment | | Weeks | | | | | |
|-----------|-----------------|---------------------|-----|-----|-----|------|------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 |
| | | ----- Eh (mV) ----- | | | | | |
| Luisiana | Moist | 325 | 339 | 305 | 338 | 325 | 294 |
| | Wet | 279 | 222 | 291 | 315 | 273 | 291 |
| | Flooded | 211 | -25 | -54 | -71 | -75 | -48 |
| Maahas A | Moist | 291 | 266 | 259 | 308 | 234 | 179 |
| | Wet | 282 | 260 | 249 | 295 | 221 | 139 |
| | Flooded | 283 | 82 | 63 | 26 | -27 | -19 |
| Pila | Moist | 120 | 303 | 220 | 236 | 185 | 127 |
| | Wet | 86 | 288 | 217 | 200 | 170 | 135 |
| | Flooded | 59 | 115 | 78 | 34 | -32 | -36 |
| Burabod | Moist | 440 | 548 | 447 | 452 | 341 | 350 |
| | Wet | 410 | 421 | 331 | 435 | 463 | 353 |
| | Flooded | 387 | 15 | 17 | 21 | -10 | 0 |
| Rotonda | Moist | 242 | 364 | 330 | 266 | 274 | 214 |
| | Wet | 205 | 254 | 139 | 251 | 220 | 142 |
| | Flooded | 213 | 32 | -41 | -85 | -124 | -109 |
| Maahas B | Moist | 80 | 323 | 274 | 272 | 193 | 205 |
| | Wet | 70 | 321 | 343 | 269 | 200 | 195 |
| | Flooded | 60 | 9 | -20 | -50 | -77 | -67 |

Appendix Table 52. Kinetics of solution pH in six soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | |
|----------|---------------------------------|-------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 |
| | | pH | | | | | |
| Luisiana | Moist | 5.24 | 5.21 | 4.30 | 4.32 | 4.29 | 4.35 |
| | Wet | 5.40 | 5.92 | 4.40 | 4.26 | 4.44 | 4.47 |
| | Flooded | 5.46 | 6.49 | 6.91 | 6.62 | 6.64 | 6.54 |
| Maahas A | Moist | 6.30 | 5.83 | 5.99 | 6.01 | 6.08 | 6.30 |
| | Wet | 6.30 | 6.24 | 5.96 | 6.03 | 6.37 | 6.58 |
| | Flooded | 6.27 | 6.46 | 6.52 | 6.65 | 6.82 | 6.84 |
| Pila | Moist | 7.37 | 6.88 | 6.70 | 6.92 | 6.98 | 7.13 |
| | Wet | 7.35 | 6.82 | 6.71 | 6.83 | 6.96 | 6.87 |
| | Flooded | 7.51 | 6.99 | 6.82 | 6.82 | 6.83 | 6.75 |
| Burabod | Moist | 3.78 | 3.74 | 3.88 | 4.12 | 4.11 | 3.97 |
| | Wet | 3.78 | 4.33 | 4.58 | 4.20 | 3.82 | 3.86 |
| | Flooded | 3.86 | 5.70 | 5.92 | 6.06 | 6.12 | 6.09 |
| Rotonda | Moist | 6.15 | 5.68 | 5.20 | 5.66 | 5.91 | 5.95 |
| | Wet | 6.22 | 6.23 | 5.70 | 5.91 | 6.13 | 6.12 |
| | Flooded | 6.21 | 6.47 | 6.50 | 6.72 | 6.94 | 6.96 |
| Maahas B | Moist | 6.52 | 5.95 | 6.01 | 6.15 | 6.25 | 6.31 |
| | Wet | 6.51 | 6.02 | 6.05 | 6.20 | 6.47 | 6.53 |
| | Flooded | 6.60 | 6.76 | 6.73 | 6.82 | 6.86 | 6.93 |

Appendix Table 53. Kinetics of solution EC in six soils under moist, wet and flooded conditions.

| Treatment | | Weeks | | | | | |
|-----------|-----------------|-----------|------|------|------|------|------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 |
| | | EC (dS/m) | | | | | |
| Luisiana | Moist | 1.69 | 1.95 | 3.13 | 2.87 | 3.66 | 2.63 |
| | Wet | 1.80 | 1.77 | 3.39 | 3.54 | 3.75 | 2.79 |
| | Flooded | 1.90 | 2.94 | 2.19 | 1.86 | 1.69 | 1.32 |
| Maahas A | Moist | 3.20 | 3.56 | 2.88 | 3.20 | 3.42 | 2.34 |
| | Wet | 3.34 | 3.49 | 3.68 | 3.46 | 1.75 | 1.10 |
| | Flooded | 3.33 | 2.89 | 2.30 | 1.86 | 3.66 | 2.73 |
| Pila | Moist | 2.64 | 2.80 | 3.65 | 3.93 | 3.54 | 2.96 |
| | Wet | 2.71 | 3.70 | 3.16 | 2.82 | 2.28 | 2.00 |
| | Flooded | 2.66 | 3.41 | 3.47 | 3.23 | 3.13 | 2.12 |
| Burabod | Moist | 2.83 | 2.67 | 2.21 | 1.21 | 1.19 | 0.73 |
| | Wet | 2.81 | 3.23 | 2.69 | 2.11 | 1.71 | 1.41 |
| | Flooded | 2.84 | 3.11 | 1.61 | 1.19 | 1.15 | 0.90 |
| Rotonda | Moist | 1.40 | 1.95 | 2.45 | 1.76 | 1.55 | 1.57 |
| | Wet | 1.25 | 2.39 | 1.66 | 1.09 | 0.97 | 0.82 |
| | Flooded | 1.34 | 2.18 | 2.51 | 2.58 | 2.28 | 1.99 |
| Maahas B | Moist | 1.98 | 2.53 | 2.63 | 2.12 | 1.97 | 1.91 |
| | Wet | 2.04 | 3.07 | 2.81 | 2.40 | 1.39 | 1.28 |
| | Flooded | 2.12 | 2.91 | 2.56 | 2.26 | 2.47 | 1.85 |

Appendix Table 54. Kinetics of water-soluble oxidizable matter in six soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | |
|----------|---------------------------------|---------------------------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 |
| | | OxM (me L ⁻¹) | | | | | |
| Luisiana | Moist | 16.4 | 1.1 | 2.0 | 0.8 | 1.0 | 0.5 |
| | Wet | 19.1 | 3.2 | 2.6 | 0.9 | 0.9 | 0.9 |
| | Flooded | 18.8 | 23.0 | 15.8 | 14.7 | 11.9 | 11.1 |
| Maahas A | Moist | 3.3 | 1.5 | 1.9 | 0.8 | 1.2 | 0.8 |
| | Wet | 3.5 | 1.9 | 2.5 | 0.8 | 0.9 | 0.8 |
| | Flooded | 3.1 | 8.9 | 1.8 | 2.3 | 2.4 | 3.0 |
| Pila | Moist | 17.4 | 6.4 | 6.7 | 2.7 | 2.4 | 2.0 |
| | Wet | 19.5 | 6.4 | 5.1 | 2.6 | 3.1 | 2.3 |
| | Flooded | 16.7 | 12.0 | 6.0 | 6.9 | 4.5 | 5.1 |
| Burabod | Moist | 22.2 | 7.8 | 4.4 | 1.1 | 1.1 | 1.2 |
| | Wet | 22.2 | 10.6 | 6.7 | 2.1 | 2.0 | 1.7 |
| | Flooded | 22.2 | 23.6 | 20.2 | 16.6 | 14.8 | 13.5 |
| Rotonda | Moist | 7.5 | 2.3 | 2.6 | 0.5 | 1.6 | 0.7 |
| | Wet | 7.5 | 3.4 | 2.0 | 1.0 | 1.5 | 0.8 |
| | Flooded | 6.4 | 7.2 | 6.9 | 6.7 | 6.6 | 7.0 |
| Maahas B | Moist | 12.0 | 1.4 | 1.6 | 0.7 | 0.9 | 1.0 |
| | Wet | 13.0 | 2.6 | 2.0 | 1.1 | 1.2 | 0.6 |
| | Flooded | 14.0 | 5.4 | 4.7 | 4.7 | 3.9 | 5.2 |

Appendix Table 55. Kinetics of water-soluble NH_4^+ -N in six soils under moist, wet and flooded conditions.

| Treatment | | Weeks | | | | | |
|-----------|-----------------|---|-------|-------|------|------|------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 |
| | | ----- NH_4^+ -N (mg L^{-1}) ----- | | | | | |
| Luisiana | Moist | 47.5 | 45.4 | 24.9 | 8.2 | 1.0 | 1.0 |
| | Wet | 56.4 | 45.0 | 28.1 | 3.1 | 1.1 | 0.8 |
| | Flooded | 62.0 | 73.8 | 75.8 | 74.2 | 64.7 | 52.1 |
| Maahas A | Moist | 18.9 | 1.6 | 1.1 | 1.5 | 0.6 | 1.1 |
| | Wet | 16.5 | 8.0 | 1.3 | 1.3 | 0.4 | 0.5 |
| | Flooded | 23.0 | 22.4 | 19.2 | 12.7 | 1.0 | 1.1 |
| Pila | Moist | 46.5 | 13.6 | 5.9 | 1.7 | 0.8 | 1.2 |
| | Wet | 39.3 | 14.2 | 6.6 | 3.8 | 2.9 | 0.9 |
| | Flooded | 42.3 | 33.8 | 39.6 | 33.8 | 14.2 | 2.5 |
| Burabod | Moist | 164.8 | 115.0 | 103.5 | 56.8 | 25.2 | 31.9 |
| | Wet | 168.0 | 125.2 | 119.6 | 95.8 | 30.2 | 11.5 |
| | Flooded | 175.3 | 109.0 | 87.7 | 68.3 | 63.3 | 54.2 |
| Rotonda | Moist | 16.6 | 6.0 | 1.8 | 0.3 | 0.1 | 0.3 |
| | Wet | 16.4 | 14.7 | 10.4 | 0.21 | 0.0 | 0.4 |
| | Flooded | 14.7 | 28.2 | 37.2 | 28.0 | 1.1 | 0.8 |
| Maahas B | Moist | 12.5 | 1.8 | 0.5 | 0.2 | 0.8 | 0.4 |
| | Wet | 14.5 | 0.9 | 0.9 | 0.4 | 0.0 | 0.0 |
| | Flooded | 11.9 | 18.9 | 21.0 | 17.6 | 1.7 | 0.9 |

Appendix Table 56. Kinetics of NO_3^- -N in the solutions of six soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | |
|----------|---------------------------------|--|-------|--------|--------|-------|-------|
| | | 0 | 2 | 4 | 6 | 8 | 10 |
| | | ----- NO_3^- -N (mg L ⁻¹) ----- | | | | | |
| Luisiana | Moist | 0.2 | 126.0 | 891.0 | 939.0 | 399.0 | 397.0 |
| | Wet | 0.2 | 69.0 | 921.0 | 1131.0 | 442.0 | 412.0 |
| | Flooded | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maahas A | Moist | 330.0 | 252.0 | 678.0 | 466.0 | 356.0 | 172.0 |
| | Wet | 350.0 | 218.0 | 1123.0 | 814.0 | 30.0 | 1.0 |
| | Flooded | 360.0 | 32.0 | 20.0 | 10.0 | 0.0 | 0.0 |
| Pila | Moist | 20.0 | 150.0 | 1280.0 | 725.0 | 428.0 | 274.0 |
| | Wet | 47.0 | 198.0 | 407.0 | 115.0 | 79.0 | 68.0 |
| | Flooded | 5.0 | 5.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Burabod | Moist | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Wet | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Flooded | 0.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Rotonda | Moist | 9.0 | 129.0 | 515.0 | 199.0 | 74.0 | 58.0 |
| | Wet | 1.0 | 126.0 | 83.0 | 69.0 | 2.0 | 0.0 |
| | Flooded | 19.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maahas B | Moist | 0.1 | 199.0 | 581.0 | 324.0 | 102.0 | 108.0 |
| | Wet | 0.1 | 252.0 | 607.0 | 327.0 | 1.0 | 0.0 |
| | Flooded | 1.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |

Appendix Table 57. Kinetics of water-soluble P in six soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | |
|----------|---------------------------------|-------------------------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 |
| | | P (mg L ⁻¹) | | | | | |
| Luisiana | Moist | 0.43 | 0.72 | 0.16 | 0.15 | 0.19 | 0.18 |
| | Wet | 0.29 | 1.27 | 0.13 | 0.10 | 0.14 | 0.14 |
| | Flooded | 0.45 | 0.01 | 0.04 | 0.02 | 0.08 | 0.08 |
| Maahas A | Moist | 0.45 | 0.33 | 0.19 | 0.22 | 0.37 | 0.25 |
| | Wet | 0.41 | 0.50 | 0.26 | 0.18 | 0.30 | 0.21 |
| | Flooded | 0.60 | 0.46 | 0.31 | 0.19 | 0.29 | 0.26 |
| Pila | Moist | 2.16 | 2.00 | 2.00 | 1.50 | 1.54 | 1.60 |
| | Wet | 2.10 | 2.16 | 2.20 | 2.10 | 2.00 | 1.80 |
| | Flooded | 2.00 | 2.20 | 2.10 | 1.80 | 1.60 | 1.50 |
| Burabod | Moist | 0.38 | 0.08 | 0.19 | 0.04 | 0.39 | 0.08 |
| | Wet | 0.31 | 0.12 | 0.10 | 0.05 | 0.19 | 0.09 |
| | Flooded | 0.45 | 0.25 | 0.47 | 0.47 | 0.85 | 0.74 |
| Rotonda | Moist | 0.78 | 0.48 | 0.62 | 0.41 | 0.55 | 0.94 |
| | Wet | 0.80 | 0.96 | 0.55 | 0.56 | 0.57 | 0.42 |
| | Flooded | 1.07 | 2.85 | 3.07 | 3.10 | 2.11 | 1.37 |
| Maahas B | Moist | 0.29 | 0.20 | 0.22 | 0.10 | 0.17 | 0.20 |
| | Wet | 0.33 | 0.22 | 0.22 | 0.10 | 0.17 | 0.14 |
| | Flooded | 0.27 | 0.18 | 0.23 | 0.17 | 0.23 | 0.24 |

Appendix Table 58. Kinetics of water-soluble Fe in six soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | |
|----------|---------------------------------|--------------------------------------|--------|--------|--------|--------|--------|
| | | 0 | 2 | 4 | 6 | 8 | 10 |
| | | ----- Fe (mg L ⁻¹) ----- | | | | | |
| Luisiana | Moist | 0.10 | 0.15 | 0.25 | 0.10 | 0.15 | 0.15 |
| | Wet | 0.25 | 1.60 | 0.18 | 0.10 | 0.10 | 0.15 |
| | Flooded | 0.40 | 260.00 | 179.00 | 152.00 | 132.00 | 108.00 |
| Maahas A | Moist | 0.20 | 0.10 | 0.10 | 0.30 | 0.10 | 0.10 |
| | Wet | 0.35 | 0.15 | 0.27 | 0.55 | 0.35 | 0.50 |
| | Flooded | 0.50 | 1.00 | 0.95 | 2.15 | 8.30 | 10.10 |
| Pila | Moist | 0.20 | 0.15 | 0.15 | 0.25 | 0.08 | 0.15 |
| | Wet | 0.20 | 0.12 | 0.13 | 0.15 | 0.10 | 0.15 |
| | Flooded | 0.15 | 0.35 | 1.25 | 1.80 | 2.50 | 3.00 |
| Burabod | Moist | 13.30 | 2.10 | 0.45 | 0.15 | 2.07 | 0.35 |
| | Wet | 15.20 | 6.10 | 5.90 | 2.70 | 3.50 | 11.20 |
| | Flooded | 18.40 | 330.00 | 78.00 | 54.00 | 40.00 | 32.00 |
| Rotonda | Moist | 0.45 | 0.15 | 0.13 | 0.10 | 0.25 | 0.10 |
| | Wet | 0.30 | 6.20 | 4.60 | 1.30 | 4.25 | 7.50 |
| | Flooded | 0.30 | 32.80 | 44.00 | 54.00 | 56.00 | 62.00 |
| Maahas B | Moist | 0.35 | 0.15 | 0.10 | 0.05 | 0.08 | 0.10 |
| | Wet | 0.20 | 0.10 | 0.10 | 0.10 | 0.03 | 0.10 |
| | Flooded | 1.20 | 8.50 | 20.00 | 30.00 | 54.00 | 48.00 |

Appendix Table 59. Kinetics of water-soluble Mn in six soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | |
|----------|---------------------------------|--------------------------------------|-------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 |
| | | ----- Mn (mg L ⁻¹) ----- | | | | | |
| Luisiana | Moist | 32.0 | 32.0 | 58.0 | 72.0 | 78.0 | 62.0 |
| | Wet | 36.0 | 34.0 | 62.0 | 84.0 | 72.0 | 52.0 |
| | Flooded | 34.0 | 154.0 | 36.0 | 18.0 | 11.3 | 7.9 |
| Maahas A | Moist | 0.9 | 0.6 | 0.2 | 0.0 | 0.1 | 0.0 |
| | Wet | 0.8 | 0.2 | 0.1 | 0.0 | 0.2 | 0.1 |
| | Flooded | 1.0 | 3.8 | 6.1 | 14.4 | 50.0 | 48.0 |
| Pila | Moist | 1.6 | 2.1 | 0.2 | 0.0 | 0.0 | 0.1 |
| | Wet | 1.3 | 0.5 | 0.3 | 0.2 | 0.6 | 0.1 |
| | Flooded | 1.0 | 11.8 | 28.0 | 34.0 | 34.0 | 28.0 |
| Burabod | Moist | 11.2 | 8.5 | 6.4 | 2.2 | 1.5 | 3.2 |
| | Wet | 13.1 | 9.5 | 7.5 | 5.5 | 6.5 | 5.6 |
| | Flooded | 13.3 | 10.3 | 2.9 | 1.8 | 1.5 | 1.2 |
| Rotonda | Moist | 6.9 | 0.3 | 0.1 | 0.0 | 0.0 | 0.0 |
| | Wet | 5.9 | 10.9 | 6.2 | 0.7 | 3.9 | 7.0 |
| | Flooded | 5.3 | 36.0 | 42.0 | 40.0 | 40.0 | 40.0 |
| Maahas B | Moist | 8.0 | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 |
| | Wet | 9.4 | 0.2 | 0.0 | 0.0 | 0.5 | 0.1 |
| | Flooded | 11.5 | 44.0 | 30.0 | 20.0 | 14.0 | 7.9 |

Appendix Table 60. Kinetics of water-soluble Si in six soils under moist, wet and flooded conditions.

| Treatment | | Weeks | | | | | |
|-----------|-----------------|--------------------------------------|------|------|------|------|------|
| Soil | Moisture regime | 0 | 2 | 4 | 6 | 8 | 10 |
| | | ----- Si (mg L ⁻¹) ----- | | | | | |
| Luisiana | Moist | 12.6 | 10.5 | 15.5 | 12.7 | 8.9 | 9.6 |
| | Wet | 12.4 | 7.9 | 15.5 | 15.9 | 11.8 | 8.8 |
| | Flooded | 12.3 | 9.6 | 6.2 | 5.6 | 5.6 | 5.3 |
| Maahas A | Moist | 23.3 | 25.6 | 26.5 | 25.4 | 22.7 | 19.9 |
| | Wet | 24.3 | 26.4 | 29.4 | 27.4 | 15.7 | 12.0 |
| | Flooded | 25.4 | 23.1 | 22.7 | 19.2 | 17.2 | 14.7 |
| Pila | Moist | 25.6 | 25.8 | 31.1 | 25.2 | 21.5 | 19.4 |
| | Wet | 26.5 | 30.7 | 31.3 | 29.3 | 29.0 | 24.5 |
| | Flooded | 25.3 | 27.7 | 31.9 | 31.4 | 29.2 | 21.9 |
| Burabod | Moist | 35.2 | 28.8 | 28.4 | 18.1 | 11.9 | 11.5 |
| | Wet | 37.5 | 37.7 | 34.4 | 30.3 | 9.5 | 8.8 |
| | Flooded | 39.0 | 21.7 | 19.9 | 16.5 | 17.5 | 17.2 |
| Rotonda | Moist | 22.8 | 28.6 | 30.9 | 22.8 | 16.9 | 12.2 |
| | Wet | 22.9 | 31.4 | 29.1 | 23.5 | 8.8 | 4.7 |
| | Flooded | 22.3 | 27.6 | 31.2 | 27.7 | 11.9 | 11.7 |
| Maahas B | Moist | 26.6 | 23.5 | 23.5 | 21.2 | 19.0 | 18.7 |
| | Wet | 25.9 | 24.5 | 24.9 | 23.9 | 19.1 | 16.5 |
| | Flooded | 25.5 | 21.2 | 24.0 | 24.6 | 22.3 | 20.1 |

Appendix Table 61. Kinetics of water-soluble Zn in six soils under moist, wet and flooded conditions.

| Soil | Treatment Moisture regime | Weeks | | | | | |
|----------|---------------------------------|--------------------------|------|------|------|------|------|
| | | 0 | 2 | 4 | 6 | 8 | 10 |
| | | Zn (mg L ⁻¹) | | | | | |
| Luisiana | Moist | 0.07 | 0.09 | 0.22 | 0.24 | 0.23 | 0.22 |
| | Wet | 0.07 | 0.08 | 0.18 | 0.22 | 0.23 | 0.19 |
| | Flooded | 0.07 | 0.07 | 0.03 | 0.03 | 0.04 | 0.03 |
| Burabod | Moist | 1.00 | 0.80 | 0.69 | 0.46 | 0.48 | 0.67 |
| | Wet | 1.00 | 0.90 | 0.73 | 0.32 | 0.30 | 0.28 |
| | Flooded | 1.02 | 0.45 | 0.02 | 0.02 | 0.03 | 0.03 |

Appendix Table 62. Analysis of variance for mineral nutrient concentration in 8 week old shoot of IR43 grown in six soils under three moisture regimes.

| Source of variation | df | Mean Squares | | | | | | | | | | |
|---------------------|----|--------------|-----------|---------|-----------|----------|------------------|----------|---------|-----------|-------|---------|
| | | N | P | K | Ca | Mg | SiO ₂ | Na | Fe | Mn | Zn | Cu |
| Replication | 2 | 0.068ns | 0.00019ns | 0.018ns | <0.0000 | 0.7ns | 447ns | 88ns | 5660ns | 10ns | 1.2ns | |
| Treatment | 17 | 1.016** | 0.00610** | 0.812** | 0.00210** | 0.0041** | 6.1** | 307743** | 8783** | 613398** | 276** | 172.3** |
| Soil (S) | 5 | 2.397** | 0.01135** | 1.536** | 0.00596** | 0.0054** | 11.1** | 468868** | 13370** | 1481070** | 463** | 246.0** |
| Moisture (M) | 2 | 0.774** | 0.01627** | 1.039** | 0.00029* | 0.0108** | 12.7** | 635479** | 13039** | 369452** | 799** | 481.0** |
| S x M | 10 | 0.374** | 0.00143** | 0.405** | 0.00053** | 0.0020** | 2.3** | 161634** | 5639** | 228352** | 78** | 73.6** |
| Error | 34 | 0.030 | 0.00013 | 0.062 | 0.00008 | 0.0003 | 0.6 | 1044 | 179 | 3001 | 20 | 5.8 |
| CV (%) | | 5.62 | 4.66 | 6.85 | 6.88 | 6.96 | 8.44 | 14.86 | 15.74 | 12.33 | 13.80 | 13.73 |

*,** significant at the 0.05 and 0.01 levels of probability, respectively.

ns non-significant at the 0.05 level of probability.

Appendix Table 63. Analysis of variance for mineral nutrient concentration in mature straw of IR43 grown in six soils under three moisture regimes.

| Source of variation | df | Mean Squares | | | | | | | | | | |
|---------------------|----|--------------|-----------|--------|----------|----------|------------------|------------|---------|------------|--------|---------|
| | | N | P | K | Ca | Mg | SiO ₂ | Na | Fe | Mn | Zn | Cu |
| Replication | 2 | 0.018ns | <0.0001ns | 0.12ns | 0.0004ns | 0.0004ns | 0.02ns | 4909ns | 249ns | 3212ns | 37ns | 6.2ns |
| Treatment | 17 | 1.132** | 0.0027** | 2.15** | 0.0176** | 0.0230** | 21.48** | 6697440** | 49608** | 4580580** | 3988** | 194.0** |
| Soil (S) | 5 | 2.763** | 0.0020** | 5.00** | 0.0417** | 0.0235** | 43.30** | 12875600** | 68746** | 11051400** | 7355** | 272.7** |
| Moisture (M) | 2 | 0.974** | 0.0037** | 2.42** | 0.0052** | 0.0870** | 30.76** | 9139230** | 93108** | 448481** | 4222** | 610.4** |
| S x M | 10 | 0.348** | 0.0029** | 0.67** | 0.0081** | 0.0099** | 8.72** | 3119970** | 31338** | 2171620** | 2258** | 71.4** |
| Error | 34 | 0.016 | 0.0003** | 0.09 | 0.0004 | 0.0006 | 0.88 | 8039 | 266 | 6294 | 38 | 6.7 |
| CV (%) | | 8.77 | 13.46 | 9.84 | 10.77 | 9.42 | 8.06 | 10.68 | 15.43 | 8.30 | 12.35 | 24.81 |

*,** significant at the 0.05 and 0.01 levels of probability, respectively.

ns non-significant at the 0.05 level of probability.

Appendix Table 64. Analysis of variance for height, tiller number and yields of IR43 in six soils under three moisture regimes.

| Source of variation | df | Mean Squares | | | | |
|---------------------|----|-----------------------------|---------------------------------|---------------------------------------|-------------|-------------|
| | | Height of 8 week old plants | Tiller no. of 8 week old plants | Dry matter yield of 8 week old shoots | Grain yield | Straw yield |
| Replication | 2 | <1 ns | 5.6 ns | 2 ns | 68 ns | 28 ns |
| Treatment | 17 | 549 ** | 80.6 ** | 366 ** | 2742 ** | 2055 ** |
| Soil (S) | 5 | 577 ** | 133.1 ** | 367 ** | 1670 ** | 770 ** |
| Moisture (M) | 2 | 1763 ** | 118.9 ** | 1243 ** | 10645 ** | 6044 ** |
| S x M | 10 | 292 ** | 46.7 ** | 191 ** | 1698 ** | 1900 ** |
| Error | 34 | 6 | 6.0 | 5 | 32 | 34 |
| CV (%) | | 2.41 | 12.12 | 9.89 | 11.27 | 8.03 |

*,** significant at the 0.05 and 0.01 levels of probability, respectively.

^{ns} non-significant at the 0.05 level of probability.

Appendix Table 65. Analysis of variance for mineral nutrient concentration in mature straw (active Fe in flag leaves) of two rices grown with some amendments in Block UK1 under two moisture regimes. IRR1 Farm.

| Source of variation | df | Mean Squares | | | | | | | | | | | |
|---------------------|----|--------------|-----------|----------|------------|------------|------------------|----------|-----------|-----------|----------|--------|----------|
| | | N | P | K | Ca | Mg | SiO ₂ | Total Fe | Active Fe | Mn | Zn | Cu | Na |
| Replication | 3 | 0.0029ns | 0.00086ns | 0.0069ns | 0.000018ns | 0.000147ns | 0.24ns | 200ns | 11.4ns | 1521ns | 2.6ns | 0.25ns | 901ns |
| Moisture (M) | 1 | 0.5418** | 0.15176** | 0.0352** | 0.018213** | 0.004408** | 440.44** | 4504* | 2817.2** | 2039813** | 5702.9** | 0.77ns | 291408** |
| Error (a) | 3 | 0.0009 | 0.00021 | 0.0008 | 0.000012 | 0.000025 | 0.89 | 179 | 15.7 | 1201 | 3.0 | 0.37 | 651 |
| Amendment (A) | 2 | 0.0111ns | 0.00013ns | 0.0540* | 0.000080ns | 0.000477** | 0.44ns | 19ns | 15.4ns | 5433** | 13.6* | 0.36ns | 2977ns |
| M x A | 2 | 0.0272* | 0.00002ns | 0.0452ns | 0.000080ns | 0.000714** | 0.65ns | 25ns | 2.1ns | 4758* | 17.3* | 0.02ns | 1914ns |
| Cultivar (V) | 1 | 0.5504** | 0.00002ns | 1.6502** | 0.000285* | 0.001633** | 21.01** | 325ns | 181.4** | 1250ns | 1395.4** | 0.17ns | 145200** |
| M x V | 1 | 0.3040** | 0.00004ns | 0.0469ns | 0.000414** | 0.000533** | 69.07** | 25ns | 1.8ns | 275ns | 0.6ns | 9.99** | 38533** |
| A x V | 2 | 0.0108ns | 0.00075ns | 0.0002ns | 0.000051ns | 0.000039ns | 0.76ns | 77ns | 5.0ns | 714ns | 35.9ns | 0.11ns | 3769ns |
| M x A x V | 2 | 0.0052ns | 0.00082ns | 0.0731* | 0.000198* | 0.000152ns | 1.88* | 39ns | 1.8ns | 514ns | 8.2ns | 0.09ns | 6039* |
| Error (b) | 30 | 0.0069 | 0.00062 | 0.0157 | 0.000046 | 0.000071 | 0.55 | 312 | 10.0 | 987 | 3.5 | 0.11 | 1248 |
| CV (a) % | | 3.48 | 8.30 | 0.92 | 3.89 | 2.56 | 7.65 | 19.41 | 9.74 | 15.37 | 5.53 | 13.88 | 9.10 |
| CV (b) % | | 9.70 | 14.17 | 4.17 | 7.53 | 4.32 | 6.02 | 25.58 | 7.80 | 13.93 | 5.97 | 7.72 | 12.60 |

*,** significant at the 0.05 and 0.01 levels of probability, respectively.

ns non-significant at the 0.05 level of probability.

Appendix Table 66. Analysis of variance for plant height, panicle number, spikelet sterility %, 100 grain weight, grain yield and straw yield of two rices grown with some amendments in Block UK1 under two moisture regimes. IRRI Farm.

| Source of variation | df | Mean Squares | | | | | |
|---------------------|----|--------------|----------------|--------------------|------------------|-------------|-------------|
| | | Plant height | Panicle number | Spikelet sterility | 100 grain weight | Grain yield | Straw yield |
| Replication | 3 | 40.0ns | 4.59ns | 31ns | 0.0056ns | 0.034ns | 0.038ns |
| Moisture | 1 | 6090.7** | 8.33* | 7217** | 3.0050** | 27.938** | 4.544* |
| Error (a) | 3 | 14.3 | 0.76 | 39 | 0.0087 | 0.093 | 0.304 |
| Amendment (A) | 2 | 4.8ns | 1.27ns | 8ns | 0.0041ns | 0.187* | 0.915** |
| M x A | 2 | 2.9ns | 3.46ns | 42ns | 0.0027ns | 0.392** | 0.670** |
| Cultivar (V) | 1 | 3534.6** | 4.81ns | 397** | 0.0077ns | 0.750** | 24.040** |
| M x V | 1 | 686.3** | 154.08** | 1730** | 1.6170** | 17.136** | 11.534** |
| A x V | 2 | 9.0ns | 1.34ns | 53ns | 0.0253* | 0.078ns | 1.072** |
| M x A x V | 2 | 45.1ns | 0.95ns | 76ns | 0.0029ns | 0.030ns | 0.540** |
| Error (b) | 30 | 18.6 | 1.45 | 27 | 0.0048 | 0.054 | 0.096 |
| CV (a) % | | 4.65 | 7.88 | 17.76 | 4.43 | 14.41 | 12.91 |
| CV (b) % | | 5.30 | 10.84 | 14.80 | 3.30 | 11.03 | 7.27 |

*,** significant at the 0.05 and 0:01 levels of probability, respectively.

ns non-significant at the 0.05 level of probability.

Appendix Table 67. Analysis of variance for mineral nutrient concentration in 8 week old shoot of two rices grown in Louisiana upland with some amendments.

| Source of variation | df | Mean Squares | | | | | | | | | | |
|---------------------|----|--------------|-----------|---------|------------|----------|------------------|--------|--------|---------|--------|-------|
| | | N | P | K | Ca | Mg | SiO ₂ | Na | Fe | Mn | Zn | Cu |
| Replication | 3 | 0.112ns | 0.00014ns | 0.198** | <0.00001ns | 0.0002ns | 0.5ns | 2964** | 115ns | 27411** | 7.2ns | 0.5ns |
| Treatment | 11 | 0.308** | 0.00063** | 0.166** | 0.00078** | 0.0021** | 1.3* | 1370** | 2295** | 48233** | 10.7ns | 3.7* |
| Amendment (A) | 5 | 0.525** | 0.00091** | 0.193** | 0.00161** | 0.0029** | 1.4* | 1563** | 3141** | 93127** | 16.9ns | 5.2* |
| Cultivar (V) | 1 | 0.285* | 0.00199** | 0.440** | 0.00006ns | 0.0037* | 3.8** | 2028* | 4033* | 11102* | 2.5ns | 8.3* |
| A x V | 5 | 0.096ns | 0.00008ns | 0.086ns | 0.00009ns | 0.0010ns | 0.8ns | 1046* | 1102ns | 10767** | 6.3ns | 1.4ns |
| Error | 33 | 0.061 | 0.00009 | 0.036 | 0.00007 | 0.0005 | 0.5 | 324 | 573 | 2604 | 9.0 | 1.5 |
| CV (%) | | 10.13 | 6.04 | 6.92 | 6.76 | 8.87 | 7.23 | 16.85 | 12.39 | 9.94 | 9.21 | 7.13 |

*,** significant at the 0.05 and 0.01 levels of probability, respectively.

ns non-significant at the 0.05 level of probability.

Appendix Table 68. Analysis of variance for mineral nutrient concentration in mature straw of two rices grown in Louisiana upland with some amendments.

| Source of variation | df | Mean Squares | | | | | | | | | | |
|---------------------|----|--------------|-----------|---------|-----------|-----------|------------------|---------|---------|----------|-------|--------|
| | | N | P | K | Ca | Mg | SiO ₂ | Na | Fe | Mn | Zn | Cu |
| Replication | 3 | 0.042** | 0.00010ns | 0.021ns | 0.00003ns | 0.00497** | 0.9ns | 3213ns | 909ns | 11024ns | 125* | 8.4ns |
| Treatment | 11 | 0.035** | 0.00021** | 0.199** | 0.00018** | 0.00470** | 0.8ns | 8011** | 10836** | 193688** | 213** | 36.6** |
| Amendment (A) | 5 | 0.048** | 0.00006ns | 0.070ns | 0.00028** | 0.00982** | 0.7ns | 127ns | 23044** | 355052** | 262** | 35.6** |
| Cultivar (V) | 1 | 0.114** | 0.00187** | 1.540** | 0.00039** | 0.00196* | <0.1ns | 80852** | 918ns | 247969** | 21ns | 90.7** |
| A x V | 5 | 0.008ns | 0.00003ns | 0.059ns | 0.00005ns | 0.00012ns | 1.0ns | 1327ns | 611ns | 21468ns | 203** | 26.9** |
| Error | 33 | 0.006 | 0.00005 | 0.028 | 0.00005 | 0.00046 | 0.7 | 1538 | 503 | 15001 | 31 | 4.9 |
| CV (%) | | 8.33 | 11.16 | 6.23 | 10.29 | 9.19 | 8.86 | 10.68 | 19.58 | 11.52 | 6.97 | 11.76 |

*,** significant at the 0.05 and 0.01 levels of probability, respectively.

ns non-significant at the 0.05 level of probability.

Appendix Table 69. Analysis of variance for total Fe, active Fe and crude SiO₂ concentration in flag leaves of two rices grown in Louisiana upland with some amendments.

| Source of variation | df | Mean Squares | | |
|---------------------|----|--------------|-----------|------------------------|
| | | Total Fe | Active Fe | Crude SiO ₂ |
| Replication | 3 | 1975* | 13.6ns | 5.0** |
| Treatment | 11 | 5206** | 314.3** | 16.6** |
| Amendment (A) | 5 | 9004** | 407.0** | 1.7* |
| Cultivar (V) | 1 | 6533** | 1274.1** | 166.9** |
| A x V | 5 | 1143ns | 29.6** | 1.4ns |
| Error | 33 | 583 | 7.9 | 0.6 |
| CV (%) | | 11.56 | 6.23 | 7.51 |

*,** Significant at the 0.05 and 0.01 levels of probability, respectively.

^{ns} non-significant at the 0.05 level of probability.

Appendix Table 70. Analysis of variance for plant height and tiller number (at panicle initiation stage), panicle number, spikelet sterility %, 100 grain weight, grain yield and straw yield of two rices grown in Luisiana upland with some amendments.

| Source of variation | df | Height | Tiller number | Panicle number | Spikelet sterility | 100 Grain weight | Grain yield | Straw yield |
|---------------------|----|--------|---------------|----------------|--------------------|------------------|-------------|-------------|
| Replication | 3 | 29ns | 6.5ns | 2.77ns | 73* | 0.024ns | 0.180* | 0.08ns |
| Treatment | 11 | 422** | 18.5** | 4.85ns | 58** | 0.011ns | 0.733** | 0.28* |
| Amendment (A) | 5 | 84** | 3.8ns | 6.15ns | 42* | 0.007ns | 0.227** | 0.07ns |
| Cultivar (V) | 1 | 3996** | 165.0** | 11.21ns | 271** | 0.076** | 5.096** | 1.57** |
| A x V | 5 | 46ns | 3.9ns | 2.27ns | 31ns | 0.002ns | 0.366** | 0.22ns |
| Error | 33 | 19 | 4.9 | 2.96 | 17 | 0.009 | 0.049 | 0.13 |
| CV (%) | | 5.30 | 10.46 | 11.53 | 9.14 | 4.21 | 7.75 | 8.32 |

*,** Significant at the 0.05 and 0.01 levels of probability, respectively.

^{ns} Non-significant at the 0.05 level of probability.



