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INFLUENCE OF WATER REGIME ON THE CHEMICAL KINETICS
OF SOILS AND RICE GROWTH

A Thesis

By

Prasanta Kumar Patra

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

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Approved by:

1. Dr. N. N. Goswami (Chairman)
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6. Dr. Aloke Dey (Member)

(Dr. O. P. Kathuria)

N. N. Goswami 9/10/87
H. U. Neue
M. B. Kamath
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M. N. Sinha
9.10.87
O. P. Kathuria
9.10.87

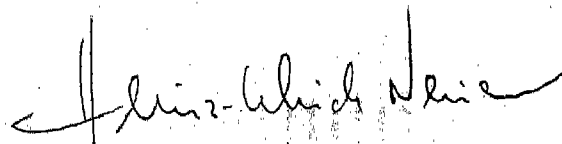
Dr. H. U. Neue
Soil Chemist and Head

Department of Soils
The International Rice Research Institute
Los Baños, Laguna, Philippines

June 11, 1987

CERTIFICATE

This is to certify that the thesis entitled "INFLUENCE OF WATER REGIME ON THE CHEMICAL KINETICS OF SOILS AND RICE GROWTH" submitted to the Faculty of the Post Graduate School, Indian Agricultural Research Institute, New Delhi, by Prasanta Kumar Patra, 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.


(H. U. Neue)
Co-Chairman
Advisory Committee

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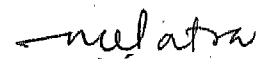
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INTRODUCTION

Rice constitutes nearly 20% of the total world food grain production and in Asia it is the most dominant food grain (92%). Over 52 M ha or nearly 40% of the world's wetland rice soils is rainfed (Barker and Herdt, 1979). The corresponding figure in India is 18 m ha or nearly 49% of the country's total rice lands (Nanda and Coffman, 1979). Rice yield in these vast area of otherwise fertile soils is very low and this depresses India's national average yield to 1.9 t/ha (Palacpac, 1982). Despite its importance, progress in increasing production of rainfed lowland rice has been very slow (Swaminathan, 1986).

Depending upon the rainfall distribution these soils may have various types of water regimes viz. continuously flooded, alternately flooded and dried, alternate flooding and drying with severe drought at some stage of rice growth or continuously flooded with deep water stagnation throughout the rice growing season. Poor rice yield in these intermittently dried and reflooded soils have mostly been attributed to water stress (IRRI, 1982; O'Toole and De Datta, 1986), weed competition (Moody et al., 1986) and disease-pest problems (Khush, 1977; Reddy et al., 1986). Submerging a dry soil brings about a series of chemical reactions in soil, pH changes; decrease in redox potential (Eh); changes in electrical conductivity (EC); denitrification of NO_3^- -N; accumulation of NH_4^+ -N; nitrogen fixation; reduction of Mn(IV), Fe(III) and $\text{SO}_4^{=}$; changes in the availability of N, P, K, S, Ca, Mg, Fe, Mn, Zn, Cu and Si; production of CO_2 , H_2S and organic acids (Ponnamperuma, 1972). With drying the reactions are reversed (Ponnamperuma, 1985). Some of the

soil chemical conditions become adverse to rice growth upon flooding while others become adverse on drying. However, in certain problem soils like zinc- and/or sulfur- deficient soils and iron- toxic soils beneficial effects of drying and reflooding have been reported.

From a soil chemist's point of view, rainfed lowland rice culture can be seen as managing a soil that is vulnerable to extremes -- from a near dry to submerged condition. Nutrient availability and thus crop growth in these soils is largely controlled by the balance of mineralization-immobilization, oxidation-reduction and toxicities and deficiencies associated with chemical and electrochemical changes due to variable soil moisture conditions caused by alternate flooding and drying (Goswami et al., 1986). The nature and severity of the problems depend upon soil properties and the time and duration of drying (Ponnamperuma and Ikehashi, 1979).

Ponnamperuma (1985) has successfully demonstrated the effect of the chemical kinetics of soils on growth and mineral nutrition of rice crop under continuously flooded condition. The chemical kinetics of soils under variable moisture conditions and plant analyses might constitute a valuable diagnostic tool to identify the adverse chemical factors responsible for poor crop growth.

Although a large volume of literature has accumulated about nutrient availability and pattern in submerged soils (Ponnamperuma, 1972; 1985), data on the chemical kinetics of soils under these variable moisture conditions is scanty.

Keeping the soil flooded with 3 to 5 cm standing water has been the common practice in rice cultivation. However, maintaining the field under saturated condition without any standing water could also be equally effective. This practice would result in saving of water which can be utilized to bring more area under irrigation. Information on the effect of this type of water regime (continuous saturation) on the chemical kinetics and rice growth is, however, meager.

Heavy loss of nitrogen under alternately flooded and dried conditions of rainfed lowlands is well documented and many recent reviews have appeared on this subject (Keeney and Sahrawat, 1986; Reddy and Patrick, 1986). However, no concerted effort has been made to understand the availability of other nutrients under variable water regime conditions of rainfed lowlands.

Study of the nutrient kinetics and growth of rice under variable moisture conditions is important for understanding the growth constraints of rainfed environments. An increased understanding of the problems might help to formulate appropriate soil and crop management strategies. This might also assist the plant breeders to breed rice varieties which can perform well under the conditions of rainfed lowlands.

The present investigation was therefore, undertaken to compare the chemical kinetics and rice growth in different Philippine rice soils of widely varying characteristics under different water regimes. Its major goals were to find out the effect of soil drying and reflooding on the availability of nutrients in soil and to identify the chemical factors limiting rice growth and yield. To achieve these goals a series of experiments was conducted with the following objectives:

1. To study the influence of eighteen water regimes on the chemical kinetics in relation to mineral nutrition, growth and yield of rice in a near neutral fertile soil (experiment 1).
2. To study the influence of nine water regimes on the chemical kinetics in relation to mineral nutrition, growth and yield of rice in a potentially iron-toxic acid soil (experiment 2).
3. To study the influence of water regimes on the chemical kinetics in relation to mineral nutrition, growth and yield of rice in three different soils (experiment 3).
4. To study the influence of water regimes on the mineral nutrition, growth and yield of rice in six different sulfur-deficient soils (experiment 4).
5. To study the influence of water regimes on the chemical kinetics in relation to mineral nutrition, growth and yield of rice in four different soils (experiment 5).
6. To study the influence of water regimes and nitrogen application methods on the growth, mineral nutrition and yield of rice in a near neutral fertile field (experiment 6).

REVIEW OF LITERATURE

When a dry soil is flooded a series of changes are set in motion and when dried again the chemical reactions are reversed. These changing patterns of chemical reactions due to alternate flooding and drying have profound effects on nutrient availability and rice growth and yield. To single out an edaphic factor or factors limiting rice growth, a thorough characterization of the plant roots' chemical environment is needed.

The soil solution which is a solution of organic and inorganic solutes, ions and gases, is the aqueous chemical environment of plant-roots. Thus, soil solution is the immediate source of nutrients to the plants. Some researchers (Adams and Lund, 1966; Bennett and Adams, 1970; Geraldson, 1970; Gilliam and Wright, 1977) have indicated that the soil solution rather than a solution obtained from a dry soil through extraction procedure in soil testing is more closely associated with plant growth. Adams (1974) has shown that a number of ionic effects on root growth, including Al and NH_3 toxicity and Ca deficiency are the same in culture solution as for in situ soil solutions. He concluded that soil solution compositions define adequately the chemical environment of plant roots. Such evidence of the value of soil solution data in studies of soil plant relations suggest that the soil electro-chemical properties and the availability of nutrient ions may best be assessed through the characterization of soil solutions.

Determination of the soil solution composition have been seriously hampered, however, by two experimental factors, 1) the difficulties involved in trying to conveniently obtain a representative sample of the soil solution from a moist soil; and 2) the analytical problems involved in measuring trace quantities of many ions of interest in the very small volume of extracted solution.

Methods of Obtaining Soil Solution

Many efforts have been made to obtain unaltered soil solutions. Richards (1941) grouped them into five categories: 1) displacement; 2) centrifugation; 3) suction; 4) compaction and 5) molecular adsorption. The latter two methods suffer from serious deficiencies and were discarded soon after being proposed. Displacement on the other hand, has been used successfully by numerous investigators to obtain unaltered soil solutions and is considered as the reference method by which other methods are compared and tested.

Displacement

Credit for general acceptance of the displacement procedure goes to Parker (1921). He described his soil solution displacement method as follows: "The method consists of packing the moist soil in a cylinder provided with an outlet at the bottom. The displacing liquid is then poured on top of the soil column and as it penetrates the soil it displaces some of the soil solution which forms a zone of saturation below the displacing liquid. This zone increases in depth as it is continually forced downward by the pressure of the liquid above. When

the saturated zone reaches the bottom of the soil column the clear soil solution, free of the displacing liquid, drops from the soil as gravitational water." This displacement procedure has been used widely for collection of soil solution. (Adams and Lund, 1966; Adams et al., 1980; Benians et al., 1977; Bennett and Adams, 1970; Curtin and Smillie, 1983; Wolt and Graveel, 1986).

The principal problem with this procedure is the need for packing the soil into a column prior to displacement. If the soil is not sufficiently packed the displacing solution will mix with the soil solution and if packed too firmly it becomes impervious.

Centrifugation

Water may be caused to move through and out of soil by centrifugation. The main use of centrifugation appears to have been the determination of the moisture equivalent of soil apparently initiated by Briggs and McLane (1907) and later used by other workers (Olmstead, 1937; Russel and Richards, 1938). Chemical analysis of the water obtained seems to have been precluded because of the lack of analytical methods applicable to concentrations of not more than 10 ppm of cations in a volume of 5 mililiters. A successful centrifuge method was developed much later (Davies and Davies, 1963) and recent improvements in this method suggest that it can be used with less bother than the column displacement method (Adams et al., 1980; Elkhatib et al., 1986; Gilman, 1976; Mubarak and Olsen, 1976; Reynolds, 1984; Whelan and Barrow, 1980; Yamasaki and Kishita, 1972).

The main problem of the centrifuge method is that it yields very small amount of solution and cannot be used for soils having very low moisture content. In a Denbighshire soil no soil solution could be extracted by centrifuge method below a moisture content of 32% (Davies and Davies, 1963).

In a bid to increase the amount of soil solution collection Yamasaki and Kishita (1972) and Gilman (1976) increased the size of the centrifuge tube and could increase the volume of solution collection to some degree but the solution volume remained a problem for analysis of those ions which are very low in concentration in soil solution. Mubarak and Olsen (1976) and others (Elkhatib et al., 1986; Whelan and Barrow, 1980;) combined the methods of displacement and centrifugation to get sufficient amount of soil solution. They centrifuged the soil with an immiscible high density (chloroform, trichloroethylene) liquid and then separated the soil solution appearing on the top of the liquid and after filtration used for chemical analysis.

But unfortunately even after the improvement of the centrifugation method through the use of immiscible liquid, the volume of solution collection remained low. Results indicate that even when improved method of Mubarak and Olsen (1976) was used only about 1 ml of soil solution was extracted from 10 g soil (with 30% moisture content) after 2 hours of centrifugation at 48,300 G.

Suction

The removal of water from soil by suction is a common procedure accomplished by connecting the liquid phase of water in soil with liquid water at low pressure. The mechanism for maintaining this pressure

difference between extracted water and water in the soil is usually a porous ceramic wall or other membrane which, when wet, is readily permeable to water but not to air. It is known that the composition of soil solution varies with water content (Bower and Goertzen, 1955; Reitemeier, 1946) and the distribution of ions within the liquid phase of the soil is not uniform. Appraisal therefore, of the ionic composition of the soil solution must take into account the water content or soil suction, at the time of sampling, particularly if the soil suction is high. Much of the water, however, is held at low soil suction in large pores where composition variations are small and ion distribution approach uniformity. The suction method of soil solution sampling relates primarily to soil water that is held at these low soil suctions (Reeve and Doering, 1965).

The suction method proposed by Briggs and McCall (1904) is useful for extracting solution from soil in situ when the soil water suction is less than 1 bar . It can be used in the laboratory, greenhouse as well as in the field. Many types of suction samplers have been used ranging from very simple devices to elaborate schemes. Most of these samplers utilize ceramic porous cup tips (Alberts et al., 1977; Barbarick et al., 1979; Bishop et al., 1978; Reeve and Doering, 1965), plastic porous tips (Hossner and Philips, 1973) and glass filter tips (Long, 1978) through which solution sample is drawn. The procedure involves evacuating an embeded porous cup by suction and allowing soil water to move into the evacuated cup. Then normal air pressure is used to force the water in the porous cup of a tube to a collection bottle. Use of vacuum suction directly through the hole at the bottom of the pots in the greenhouse has also been successfully tried (Holcomb et al., 1982).

In situ suction method offers several advantages over other methods viz. (1) sampling is done at exactly the same physical location; (2) sampling may be unattended; and 3) in situ sampling is less destructive. The latter is particularly important in sampling the soil solution in the area of roots (Long, 1978). Alberts et al. (1977) have rated suction method as the only practical way to obtain in situ samples of the soil solution over time under field conditions.

However, several workers have questioned the effectiveness of suction method of obtaining a true soil solution. One objection to ceramic cups is that most of them have ion exchange properties and may remove some ions as water passes through the cup walls (England, 1974). Another objection has been that new ceramic cups yield several milligrams per liter of Ca, Mg and Na (Wolff, 1967).

The above two problems of ceramic cups can be avoided by use of glass filter (Long, 1978) and plastic filter (Hossner and Phillips, 1973). But Mubarak and Olsen (1976) have pointed out the chance of shifting the equilibria sufficiently in the soil to change the solution composition due to application of vacuum.

From the review of the literature on the methods of extraction of soil solution it is clear that four methods are being widely used viz. displacement by distilled water, centrifugation of soil, combination of displacement and centrifugation by the use of immiscible liquid with soil and the suction method. Critical appraisal of the data suggest that the soil solution extracted through the above four methods do not vary much with respect to their chemical composition (Barbarick et al., 1979). But the main point of consideration for selecting a particular

method is the efficiency of the method to extract a sufficient amount of soil solution for routine analysis. Although the combined displacement and centrifugation method of soil solution extraction through use of trichloroethylene could yield relatively larger volume of solution, the problem of the contamination of the soil solution with oxygen remains the stumbling block in its use for this purpose. Therefore displacement method, with some modifications can be used to collect soil solution directly from pots containing growing plants..

Chemical Kinetics

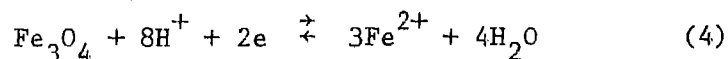
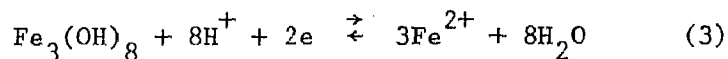
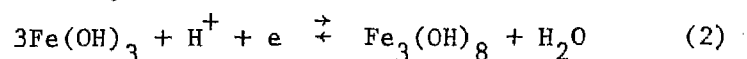
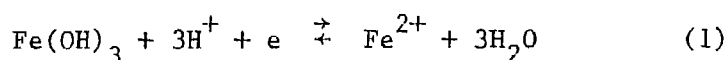
Redox potential and pH

Changes in the redox potential (Eh) and pH are the most striking electrochemical changes caused by variable moisture regimes in soils. When a dry soil is flooded, gas exchange between soil and air is drastically curtailed. Oxygen and other atmospheric gases can enter the soil only by molecular diffusion in the interstitial water. This process is 10,000 times (Greenwood, 1961) slower than diffusion in gas filled pores. Thus within a few hours of soil submergence, microorganisms use up the oxygen present in the water or trapped in the soil and render a flooded soil practically devoid of molecular oxygen and as a result the Eh or pE falls sharply during the first few days and decreases asymptotically to a value characteristic of the soil after 8-12 weeks of submergence (Bora and Goswami, 1980; Kumar et al., 1981; Naphade and Ghildyal, 1973; Ponnampuruma, 1972, 1978, 1985).

The rate and magnitude of the Eh decrease depend on the kind and amount of organic matter added (Beye, 1977; Beye et al., 1978; IRRI, 1976; Katyal, 1977; Ponnampuruma, 1972), nature and content of electron

acceptor (Ponnamperuma, 1972; Yu, 1985), temperature (Gupta, 1974) and duration of submergence. Presence of organic matter, a low content of NO_3^- and MnO_2 and a temperature of 30-35°C favor Eh decrease, and a value as low as -0.25V can be attained within 2 weeks of flooding (Ponnamperuma, 1985). The solutions of submerged soils generally have Eh values of -60 to +170 mV. Ponnamperuma (1978) suggested that the optimum Eh for rice is +10 to +120 mV at pH 7.0. Regardless of their original pH values, most soils reach pHs of 6.5 to 7.2 within 1 month after flooding and remain at that level until dried. This phenomenon has been extensively discussed in various reviews (Bora and Goswami, 1980; Kumar et al., 1981; Naphade and Ghildyal, 1973; Patrick and Reddy, 1978; Ponnamperuma, 1972; 1978; 1982; 1985; Yu, 1985). The overall effect of flooding is to increase the pH in acid soils and decrease the pH in alkaline and calcareous soils. These changes are related to the active iron concentrations and the partial pressure of CO_2 .

The pH of acid soils increase when $\text{Fe}(\text{OH})_3$ and similar compounds are reduced according to the following reactions



The decrease in pH of alkaline soils following submergence may be explained by several chemical and biological changes. Microbial decomposition of organic matter produces CO_2 , which reacts with H_2O to form carbonic acid, which dissociates into H^+ and HCO_3^- ions. The

decreased pH of alkali and calcareous soils upon submergence can be attributed to $\text{Na}_2\text{CO}_3\text{-H}_2\text{O-CO}_2$ and $\text{CaCO}_3\text{-H}_2\text{O-CO}_2$ systems, respectively (Ponnamperuma, 1985).

$$\text{pH} = 6.0 - 2/3 \log {}^P\text{CO}_2 \text{ (calcareous soil)} \quad (5)$$

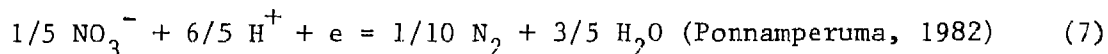
$$\text{pH} = 7.85 + \log (\text{alkalinity}) - \log {}^P\text{CO}_2 \text{ (sodic soil)} \quad (6)$$

This remarkable consequence of flooding amounts to self liming operation and results in an optimum pH range for the availability of most nutrients. Aluminum toxicity is quickly eliminated in most acid soils when they are flooded, because almost all exchangeable aluminum is precipitated by pH 5.5. It should be noted, however, that this pH changes requires about 2 weeks of flooding. Rice may die from aluminum and/or iron toxicity if transplanted at the start of flooding in some acid sulfate soils (Nhung and Ponnamperuma, 1966). Delaying transplanting for 2 to 3 weeks after flooding may eliminate this danger without lime applications.

Ponnamperuma (1978) suggested about 6.6 is the optimum pH (measured in the solution of the submerged soil) for rice. At that pH, microbial release of nitrogen and phosphorus, and the availability of phosphorus are high, the supplies of copper, zinc and molybdenum are adequate; and the concentrations of substances that interfere with nutrient uptake or poison the rice plant, such as aluminum, manganese, iron, carbon dioxide, and organic acids are below the toxic level. However, the rates of denitrification and sulfate reduction are higher at pH 6.6 than at lower values.

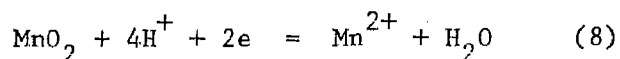
After the disappearance of oxygen in flooded soils, the need for electron acceptors by facultative anaerobic microorganisms results in the reduction of several oxidized soil components and reduce the oxidation number of the oxidized atom. Table 1 shows the major oxidation-reduction systems operating in flooded soils and the standard electrode potentials at pH 7 for these systems.

As the oxygen is depleted from the soil, NO_3^- is utilized by facultative anaerobes and is rapidly reduced according to the following reactions:



Nitrate reduction begins before complete removal of oxygen, but removal of all NO_3^- does not occur until all oxygen has been depleted.

After all the nitrates are consumed, anaerobic microorganisms reduce Mn(IV) to Mn(II). The reactions are:



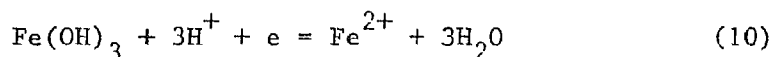
$$\text{pE} = 20.80 + 1/2 \text{pMn}^{2+} - 2\text{pH} \quad (\text{Ponnamperuma et al., 1969}) \quad (9)$$

Table 1. Sequential reduction of some electron acceptors in paddy soils.

Redox reactions		Eo at pH 7 (V)	Actually measured Eh (V)
$O_2 + 4H^+ + 4e$	$= 2H_2O$	0.82	0.65-0.3
$NO_3^- + 2H^+ + 2e^-$	$= NO_2^- + H_2O$	0.54	0.5-0.2
$MnO_2 + 4H^+ + 2e$	$= Mn^{2+} + 2H_2O$	0.43	0.4-0.2
$FeOOH + 3H^+ + e$	$= Fe^{2+} + 2H_2O$	0.17	0.3-0.1
Organic systems		-0.03-(-0.2)	0-(-0.2)
$SO_4^{2-} + 9H^+ + 6e^-$	$= HS^- + 4H_2O$	-0.16	0-(-0.15)
$2H^+ + 2e$	$= H_2$	-0.44	-0.15-(-0.3)
Methane fermentation		-	-0.2-(-0.3)

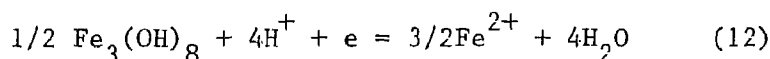
Source: Liu Zhi-Guang (1985).

The next inorganic redox system to be reduced is ferric iron, which is not reactive as long as either O_2 or NO_3^- is present in the soil solution. The reactions for this described by Ponnamperuma (1982) are:



or

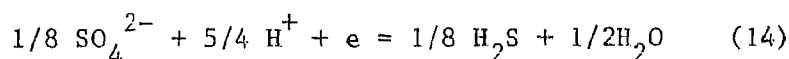
$$pE = 17.87 + pFe^{2+} - 3pH \quad (11)$$



or

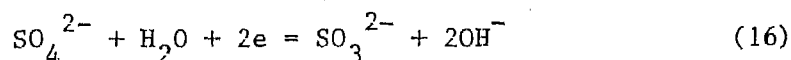
$$pE = 23.27 + 3/2 pFe^{2+} - 4pH \quad (13)$$

Sulfate ions are reduced to SO_3^{2-} and S^{2-} ions by true anaerobic bacteria. The reactions for these are (Ponnamperuma, 1972).



or

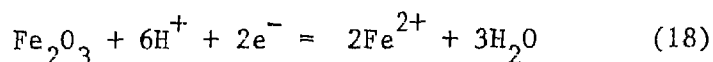
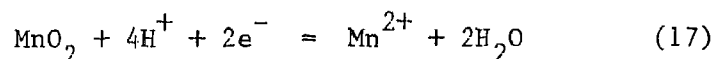
$$pE = 5.12 - 1/8 pSO_4^{2-} + 1/8 pH_2S - 5/4 pH \quad (15)$$



After SO_4^{2-} are reduced, CO_2 is reduced to CH_4 . Other reduction reactions take place in more intensely reduced soils but at Eh values not normally found in flooded rice soils.

The effect of redox potential and pH on the reactions, and especially on the final chemical equilibria of a flooded soil, is much greater when these parameters are acting together than when acting

alone. Microbial reduction processes, as distinguished from chemical processes, are favored by a near neutral pH. For example, Moraghan and Patrick (1974) found that ferric iron reduction in a flooded soil with pH controlled at 7 proceeded faster than at pH 5. Yet the soluble and exchangeable Fe^{+2} concentration of a reduced flooded soil was always much higher at pH 5 than at pH 7 (Gotoh and Patrick, 1974). The reason for this apparent discrepancy is that reduced manganese and iron produced microbially at near neutral pH rapidly undergo secondary reactions and are precipitated as various oxide, hydroxides, and carbonates where as at low pH the reduced cations remain in solution or on the exchange complex. This effect of low pH in increasing solubility can be predicted from the reduction equations for manganese dioxide and iron oxide:



Low pH also inhibits both denitrification (Bremner and Shaw, 1958; Nommik, 1956; Wijler and Delwiche, 1954) and sulfate reduction (Cappenberg, 1975; Zobell, 1958) in soil.

Electrical conductivity

The electrical conductivity (EC) of the solution of most soils increases after submergence, attains a maximum and declines to a fairly stable value which varies with the soil (Bora and Goswami, 1980; Kumar

et al., 1981; Ponnampetuma, 1972; 1978; 1982; 1985). The increase is due to mobilization of Fe^{2+} and Mn^{2+} ; formation of NH_4^+-N , HCO_3^- and RCOO^- ; and displacement of cations from soil colloids by Fe^{2+} , Mn^{2+} and NH_4^+ . The subsequent decrease is caused by precipitation of Fe^{2+} as $\text{Fe}_3(\text{OH})_8$; FeCO_3 (Ponnampetuma, 1978; Schwab and Lindsay, 1983) and FeS , Mn^{2+} as MnCO_3 , loss of CO_2 and conversion of RCOO^- to CH_4 . Thus, there is a close correlation between the kinetics of these ions and changes in EC (Ponnampetuma, 1978).

In normal submerged soils the peak EC's are of the order of 2 to 4 dS m^{-1} . But sandy soils rich in organic matter and some acid sulfate soils may attain values exceeding 4 dS m^{-1} , the harmful limit for rice. An EC of 2 dS m^{-1} favors rice growth (IRRI, 1963). Cations displaced by Fe^{2+} , Mn^{2+} and NH_4^+ while the soil is in the reduced state may be lost in percolating water. On drying, oxidation of Fe^{2+} and NH_4^+ acidifies the soil (Ponnampetuma, 1985).

Effect of soil drying on pH, Eh and EC

All the above reactions are reversed when a flooded soil is dried and reoxidized (Sanchez, 1976). The pH level returns to its original value. The speed of reoxidation depends on the rate of water losses from the soils. In clayey puddled soils the process may last for several months, whereas, in well aggregated soils reoxidation begins within a few days of drainage.

Nitrogen

The key N transformations in a flooded soil system include (1) mineralization of organic N; (2) NH_3 volatilization; (3) nitrification of NH_4^+ ; (4) denitrification; and (5) N_2 fixation.

Mineralization of organic nitrogen. Most of the nitrogen in soils is organically bound with a very small amount present in the inorganic form. Since rice plant can take up only inorganic N, the mineralization of organic N to NH_4^+ is the key process in the nitrogen nutrition of lowland rice (Broadbent, 1978; 1979; Kai and Wada, 1979; Keeney and Sahrawat, 1986; Patrick, 1982; Sahrawat, 1983a, b; Savant and De Datta, 1982). Even in well fertilized lowland rice fields, rice utilizes 50-75% of soil N through mineralization (Broadbent, 1978; IAEA, 1978; Koyama, 1981; Sahrawat, 1983b).

In a flooded soil, both mineralization and immobilization processes occur simultaneously with their rates and magnitude influenced by soil and environmental factors (Broadbent, 1978; Patrick, 1982; Savant and De Datta, 1982). Both oxidative and reductive deamination processes contribute to ammonification in flooded soils (Keeney and Sahrawat, 1986). Lack of oxygen supply generally inhibits nitrification and greatly influences the rate of ammonification. The important environmental factors that affect mineralization-immobilization are temperature, soil moisture regime and soil characteristics including pH, organic matter content, C/N ratio, and amount and quality of organic residues (Keeney and Sahrawat, 1986).

Studies emphasize the importance of temperature on the rate of net N mineralization in flooded soils (Broadbent, 1978; Dei and Yamasaki, 1979; Sahrawat, 1983a; Savant and De Datta, 1982). Net mineralization

of soil organic N in four-Philippine soils under anaerobic incubation increased with an increase in temperature from 15 to 45°C (IRRI, 1974). In a study of 39 diverse lowland rice soils in the Philippines, Sahrawat (1982) found that the mean rate of NH_4^+ production increased from 5.6 to 14.0 mg NH_4^+ -N/kg dry soil/day when the incubation temperature was increased from 30 to 40°C.

Immobilization is also a temperature dependent microbial process and under conditions favorable for N immobilization (application of high C/N ratio residues), it also increases with an increase in temperature (Keeney and Sahrawat, 1986).

Drying and reflooding of soil enhances the N-mineralization rate (Birch, 1960; Reddy and Patrick, 1975; Shiga and Ventura, 1976; Shioiri, 1948). For example, a marked effect of soil drying was observed in four permanently waterlogged Histosols in the Philippines (Sahrawat, 1981). However, alternately wetting and drying the soil also increases immobilization of NH_4^+ -N (Reddy and Patrick, 1975; Yoshida and Padre, 1975).

Among the soil characteristics, organic matter and total N content account for the most variation in NH_4^+ production under anaerobic incubations. Sahrawat (1983a) reported that for lowland rice soils in the Philippines anaerobic incubation was highly correlated with total N ($r = 0.94^{**}$), organic carbon ($r = 0.91^{**}$) and C/N ratio ($r = -0.46^{**}$) but was not significantly correlated with CEC, clay or pH. Multiple regression analysis of CEC, pH and clay on mineralizable N accounted only for 36% of the variability. While soil properties such as pH, clay and CEC may be related to N mineralization, their individual

contribution to this process could not be clearly quantified because of the numerous interactive effects and cross correlations of these properties (Keeney and Sahrawat, 1986). Liming has been reported to increase the availability of N in flooded soils and its availability to lowland rice (Abichandani and Patnaik, 1961; Borthakur and Majumder, 1968; Ponnamperna, 1958). The effect of pH per se cannot be evaluated from such studies. Ammonification seems to operate under a wide pH range in flooded soils, although the tendency of pH to approach neutrality might be an important factor (Keeney and Sahrawat, 1986; Patrick, 1982; Sahrawat, 1980, 1983a).

Ammonia volatilization. Loss of nitrogen through NH_3 volatilization from soils including flooded soils has been a subject of several comprehensive review (Fillery and Vlek, 1986; Hauck, 1979; Keeney and Sahrawat, 1986; Mikkelsen and De Datta, 1979; Patrick, 1982; Savant and De Datta, 1982; Terman, 1979; Vlek and Craswell, 1981). The review here will be restricted to cover the salient principles relevant to NH_3 volatilization from flooded rice fields.

Of the several factors that affect NH_3 volatilization, the pH of the flood water has been recognized as the single most important determinant (Mikkelsen et al., 1978). However, its importance in aquatic systems and its sensitivity to CO_2 concentration as a result of photosynthetic activity has long been recognized (Park et al., 1958). The pH of the floodwater of a flooded soil follows diurnal fluctuations and may increase or decrease by two units during the 24-hour period in response to photosynthetic activity of biota and temperature (Mikkelsen et al., 1978). High bicarbonates in a system with constant removal of

CO_2 may greatly increase the pH which can increase NH_3 volatilization of surface applied fertilizer or of NH_4^+ which diffuses into the water layer. The fluctuation in the floodwater pH is further governed by the buffering capacity of the flooded soil-water system.

Floodwater pH is the result of interactions of several floodwater properties including concentration of dissolved CO_2 and NH_3 , pH buffering capacity, alkalinity, temperature and biotic activity. Several other factors involving the soil (pH, CEC, P^{CO_2} , buffering capacity and alkalinity) and the environment (temperature and wind velocity, etc.) as well as the nature and amount of fertilizer N applied and size of plant canopy affect NH_3 volatilization loss from a flooded soil (Savant and De Datta, 1982).

In general, losses of NH_3 are higher in alkaline and calcareous soils and increase with an increase in soil pH, temperature and solar radiation but decrease with an increase in CEC of the soil and cultural and management practices including the presence of rice canopy and activities which decrease the amount of NH_3 in solution. Also, higher NH_3 volatilization losses are reported from urea fertilizer compared to other NH_4^+ sources because hydrolysis of urea provides alkalinity which can maintain or initiate NH_3 volatilization loss (Keeney and Sahrawat, 1986).

Nitrification. Nitrification is a microbially mediated reaction involving the oxidation of NH_4^+ to NO_3^- . In recent years, several reviews have appeared in the literature (Belser, 1979; Focht and Verstraete, 1977; Patrick and Reddy, 1976; Patrick and Wyatt, 1964; Reddy and Patrick, 1986; Sah and Mikkelsen, 1983a,b; Schmidt, 1982;

Yoshida and Padre, 1975) on the microorganisms involved in nitrification and the factors influencing the process in soil. In flooded rice soils nitrification can potentially occur in (1) the water column above the soil; (2) the surface oxidized soil layer; (3) the oxidized rhizosphere of rice; and (4) in intermittently drained flooded soils. In flooded rice soil, the substrate for nitrification is provided from (1) ammonification of organic nitrogen, and (2) application of inorganic fertilizer. Ammonium formed during mineralization is rapidly partitioned into (1) NH_4^+ adsorbed on the cation exchange complex, and (2) equilibrium NH_4^+ in soil solution. In 38 submerged Louisiana (USA) soils about 20% of the NH_4^+ was found in water soluble form while the remaining NH_4^+ was adsorbed on the exchange complex (Reddy and Patrick, 1986). Application of external sources of NH_4^+ can offset the equilibrium between these two fractions. Ammonium present in the soil solution is subjected to movement in two directions, namely (1) upward movement into the surface oxidized soil layer and floodwater, and (2) movement toward plant roots. This movement of NH_4^+ is accomplished by massflow and diffusion (Reddy and Patrick, 1986).

Ammonium nitrogen diffusing into the floodwater and into the oxidized soil layer is highly unstable because of rapid oxidation to NO_3^- . Since the process of nitrification depends on the metabolism of the nitrifying organisms, it is imperative that the organisms be present in adequate number to achieve rapid oxidation of NH_4^+ . Generally, fertilized soils have larger populations of nitrifiers compared to unfertilized soils (Ardakani et al., 1974) and surface

application of NH_4^+ fertilizers in lowland soils can potentially enhance the activity of nitrifying organisms. The rate of nitrification is also rapid in water containing dissolved CO_2 , compared to CO_2 free water (Reddy and Graetz, 1981).

Nitrification of NH_4^+ in the floodwater and in the oxidized soil layer was observed by several research workers (Broadbent and Tusneem, 1971; Patrick and Gotoh, 1974; Reddy and Rao, 1983; Reddy et al., 1976; Takai and Uehara, 1973; Yoshida and Padre, 1975). In soils with low organic matter content, the oxidized soil layer is usually thick and most of the nitrification occurs in this zone such that no NH_4^+ diffuses into the floodwater (Reddy and Patrick, 1986). In soils with high organic matter content, the oxidized layer is thin, and under these conditions, NH_4^+ tends to diffuse into the flood water. Nitrification was evidenced by the significant concentration of NO_3^- formed in the floodwater of an organic soil (Reddy and Rao, 1983).

Another potential active site of nitrification in lowland rice soil is the rhizosphere. The diffusive flux of O_2 from the rice roots to the adjacent soil can create an oxidized environment around the root tips. This oxidized soil rhizosphere can potentially support nitrification of NH_4^+ diffused from surrounding reduced zones (Reddy and Patrick, 1986). However, no experimental evidence has been reported on the significance of this process in the rice rhizosphere.

Denitrification. Under O_2 free conditions, many microorganisms can utilize NO_3^- as a terminal electron acceptor. The pathway involving the reduction of NO_3^- to gaseous end products ($\text{NO}_3^- \rightarrow \text{NO}_2^- \rightarrow \text{HNO} \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \rightarrow \text{N}_2$) is usually known as denitrification,

and the pathway of reduction to NH_4^+ ($\text{NO}_3^- \rightarrow \text{NH}_2\text{OH} \rightarrow \text{NH}_4^+$) is known as dissimilatory reduction. The intermediate N oxides of this process can also be used as electron acceptors. In recent years, several reviews on this process have appeared (Delwiche and Bryan, 1976; Firestone, 1982; Knowles, 1981; Payne, 1981; Reddy and Patrick, 1986; Stouthamer et al., 1980). Dissimilatory reduction of NO_3^- to NH_4^+ can potentially occur in soils and sediments high in organic matter which are anaerobic for long periods, including and continuously flooded lowland soils (Keeney et al., 1971; Koike and Hattori, 1978; Sorensen, 1978). Denitrification, on the other hand, can be a major pathway of NO_3^- loss from soils where temporary reduced conditions exist or soils which are less intensively reduced (soils with low organic matter content). Denitrification has been shown to be a dominant process in soils with Eh values of 200 to 300 mV, while NO_3^- reduction to NH_4^+ can occur in soils with Eh values of <-100 mV (Buresh and Patrick, 1981; Patrick, 1960).

Nitrification-denitrification reactions can also occur in soils subjected to alternate flooding and drying conditions. Ammonium accumulates during flooding; then when soil is dried NH_4^+ is nitrified and NO_3^- accumulates. Upon reflooding NO_3^- can be potentially lost through denitrification. Severe N loss has been shown to occur in soils subjected to alternate flooded and dried conditions (MacRae et al., 1967; Patrick and Wyatt, 1964; Reddy and Patrick, 1975; 1976; Sah and Mikkelsen 1983a, b; Sahrawat, 1979; 1981; Ventura and Watanabe, 1978).

Studies on the influence of water regime on growth and yield of rice, however, showed that mid season soil drying followed by reflooding increased yield and nitrogen uptake instead of depressing them (IRRI, 1975; Castro and Lantin, 1976). Patrick et al. (1967) reported that draining and flooding a nitrogen rich field increased rice yield. In a study in greenhouse as well as in field, Khind and Ponnampereuma (1981) have reported that alternate wetting and drying of Maahas clay soil (Tropudalf) carrying a vigorously growing rice crop does not cause appreciable denitrification.

Nitrogen fixation. Heterotrophic nitrogen fixation in paddy soils is of significance because these soils by virtue of their high moisture content and nutrient availability, offer favorable conditions for the activities of nitrogen-fixing microorganisms. Soil submergence accelerates nitrogen fixation (Ponnampereuma, 1972; Yoshida and Ancajas, 1973; Rao, 1976; Yamamuro, 1986) which is further enhanced by organic matter addition (MacRae and Castro, 1967; Matsuguchi, 1979; Rao, 1976; Rao et al., 1973). Alternate wetting and drying reduces N fixation (Nayek and Rao, 1981).

Phosphorus

Phosphorus is not directly involved in oxidation-reduction reactions in the redox potential range encountered in submerged soils, but because of its reactivity with a number of redox elements its behavior is significantly affected by flooding. Perhaps, the most important effect of the anaerobic condition on phosphate is the increased availability of phosphate to wetland rice whether measured by

soluble phosphorus in the soil solution, or plant uptake. Phosphorus is generally more available in anaerobic soil than in aerobic soil (Aoki, 1941; Mitsui, 1960). When a soil is flooded the concentration of water and acid soluble P usually increase to a peak or plateau and then decrease (Ponnamperuma, 1972; 1985).

Phosphate chemistry in flooded soil is linked to iron chemistry and conditions that increase solubility of iron in the soil usually increase phosphorus solubility (Patrick and Reddy, 1978). Phosphorus is chemically associated with iron in two major forms in an aerobic soil as insoluble iron-phosphate compounds such as strengite ($\text{FePO}_4 \cdot 2\text{H}_2\text{O}$) and as the more soluble phosphate compounds such as calcium and magnesium phosphates.

The increase in availability of phosphate under flooded conditions has been attributed to the following factors:

1. reduction of ferric phosphate to more soluble ferrous phosphate (Aoki, 1941; Patrick et al., 1973; Ponnamperuma, 1955; Subrahmanyan, 1937) which is a major source of available phosphate for wetland rice (Chang, 1976).
2. release of occluded phosphate (Chang and Jackson, 1957) and phosphate sorbed on amorphous iron and manganese oxides (Jenne, 1977) following soil reduction.
3. the hydrolysis of some iron and aluminum-bonded phosphates in acid soils (due to increase in pH following flooding) resulting in a release of some fixed phosphorus at higher soil pH (Muljadi et al., 1966; Stumm and Morgan, 1970).

4. desorption of $\text{Fe}(\text{OH})_3$ bound P following reduction of $\text{Fe}(\text{III})$ oxides (Mandal and Mandal, 1973; Patrick and Khalid, 1974).
5. solvent action of inorganic acids on soil phosphates (Subrahmanyam, 1937)
7. the increased mineralization of organic phosphorus in acid soils, caused by increasing the pH between 6 and 7 (Sanchez, 1976).
7. the increased solubility of apatite in calcareous soils when the pH decreases to 6 or 7 (Khan and Mandal, 1973; Ponnampetuma, 1965).
8. the greater diffusion of phosphate ions in a larger volume of soil solution (Ponnampetuma, 1972; Turner and Gilliam, 1976).

In some soils there are no clear peaks of soil solution phosphorus concentration on flooding while others show a measurable peak and a subsequent decrease. These decreases have been attributed to refixation of soil solution phosphorus as calcium bonded phosphates (Patrick and Mahapatra, 1968; Ponnampetuma, 1972).

The relative importance of these various mechanisms is not clear. What is clear is that in most soils there is a marked increase in soil solution phosphorus beyond the 0.1 to 0.2 ppm level, which is considered adequate for rice growth (Hossner et al., 1973).

The magnitude of this P increase varies with soil properties. One would expect it to be greater in soils high in ferric phosphates or reductant soluble phosphates. Ponnampetuma (1972), however, found largest increases in sandy soils low in iron, while clayey soils high in iron did not produce large increases.

The pH of the soil has an effect on phosphorus solubility. An increase in pH considered without regard to redox conditions will increase the solubility of ferric phosphate and aluminum phosphate and decrease the solubility of calcium-phosphate (Lindsay and Moreno, 1960). Under reducing conditions, however, maximum phosphate solubility occurs under low pH conditions (Patrick et al. 1973). This apparent anomaly is due to the role of iron oxyhydroxides (both ferric and ferrous) in binding phosphate. Under aerobic conditions maximum solubility of iron phosphate occurs under high pH conditions while under anaerobic conditions maximum iron solubility occurs at low pH. The soluble ferrous iron cannot remove phosphate from solution at the low pH. If the pH is increased under reducing conditions the formation of insoluble ferrous oxide and hydroxides and vivianite $[\text{Fe}_3(\text{PO}_4)_2 \cdot 2\text{H}_2\text{O}]$ results in phosphate removal from soil solution (Patrick et al., 1973).

Flooding causes a marked change in the distribution of the different phosphorus fractions. The reductant soluble and Ca-P fractions decrease, where as the Fe-phosphate fraction increases (Goswami and Banerjee, 1978; Gupta et al., 1972; Khan and Mandal, 1973; Patrick and Mahapatra, 1968; Sadanandan et al., 1980; Sharma et al., 1980; Singhanian and Goswami, 1978; Singlachar and Samaniego, 1973). The increase in iron-bonded phosphorus can be explained as precipitation of phosphorus by Fe^{+3} upon drying and under subsequent flooding this newly formed $\text{Fe}^{+3}\text{-P}$ will be reduced to $\text{Fe}^{+2}\text{-P}$ (Chang and Chu, 1961; Mahapatra and Patrick, 1969) or interconversion of Al-P formed at the initial stage to Fe-P with time (Chang and Chu, 1961; Singhanian and Goswami, 1978). In calcareous soils the long term effect of flooding

will be the transformation of Ca-P into Fe-P. This may result in lower phosphorus availability, not to flooded rice, but to subsequent upland crops growing in rotation with rice, because of the low solubility of Fe-P at the high pH levels of aerobic calcareous soils (Sanchez, 1976).

Flooding also alters the process of P fixation. Patrick and Khalid (1974) showed that under reduced conditions less P was sorbed at concentrations in the soil solution below 1 ppm P and more phosphorus at high concentration. They concluded that the differences in phosphate-fixation and release pattern under aerobic and anaerobic conditions can be attributed to the reduction of ferric oxyhydroxide to gel like ferrous compounds with greater surface area. All the soils in question had low phosphorus fixation capacities. In high-fixing Ultisols and Oxisols the magnitude of this phenomenon is probably different. Although no direct evidence is available, the lack of marked increase in water soluble or extractable phosphorus upon flooding such soils observed by Ponnampetuma (1972) implies no major decrease in phosphorus fixation.

There are conflicting reports on the effect of soil drying on phosphorus availability in soils. Paul and Delong (1949) observed that drying a soil subsequent to flooding generally decreased the solubility of both native and added phosphate whereas Savant et al. (1970) observed that submergence followed by drying of soils prior to resubmergence increased availability of native phosphorus in acid soils. Yuan et al. (1960) showed that prolonged alternate wetting and drying reduced the percentage of phosphate in the aluminum form and increased the iron form, thereby increasing availability of phosphorus.

Alternate wetting and drying increases phosphorus fixation, the amount of phosphorus in Fe-P and in reductant soluble Fe-P fractions at the expense of soluble and Al-P fractions (Barrow and Shaw, 1980; Bora and Goswami, 1980; Haynes and Swift, 1985; Mandal and Khan, 1975; Patrick and Mikkelsen, 1971; Sah and Mikkelsen, 1986; Singh and Dixit, 1983; Singhanian and Goswami, 1978).

Potassium, calcium and magnesium

Potassium, Ca^{2+} and Mg^{2+} are not directly affected by soil reduction. The large quantities of NH_4^+ -N, Fe^{2+} and Mn^{2+} ions released upon flooding may displace substantial quantities of Ca^{2+} , Mg^{2+} and K^+ from the exchange sites into the soil solution (Islam and Islam, 1973; Islam and Ullah, 1973; Kadrekar, 1976; Ponnampuruma, 1965; Sharma et al., 1977; Silverman and Munoz, 1980, Subramanian and Rajagopalan, 1980).

Alternate wetting and drying influences potassium availability in soil. Singh and Ram (1976) and others (Biswas, 1974; Goswami and Banerjee, 1978; Kadrekar and Kibe, 1973)) have found that alternate wetting and drying increased exchangeable potassium of soil, and potassium uptake by rice.

Sulfur

At low Eh, sulfate ions are reduced to SO_3^{2-} and S^{2-} by bacteria of the genus Desulfovibrio. This dissimilatory biological reduction of sulfate (SO_4^{2-}) under anoxic conditions, utilizes organic matter as the energy source (Jenitzky and Whittig, 1964; Ogata and Bower, 1965).

The products formed as a result of SO_4^{2-} reduction depend on a number of conditions, including pH, oxidation-reduction potentials, iron levels and the microbial population (Deverel et al., 1986). Pyrite (FeS_2) and amorphous iron sulfides have long been considered to be primary end products. Availability of reactive iron may, however, limit pyrite formation (Berner, 1984).

Highly reducing conditions are necessary for SO_4^{2-} reduction to occur in soils. Harter and McLean (1965) found S^{2-} formation at redox potential (Eh) below -75 mV. Takai and Kamura (1966) reported SO_4^{2-} reduction in waterlogged soils having Eh ranging from 0 to -190 mV. Connel and Patrick (1968) found that little or no S^{2-} was produced at Eh above -150 mV and outside a pH range of 6.5 to 8.5.

Sulfate reduction was found to follow first order kinetics (Deverel et al., 1986). In soils having high SO_4^{2-} concentration, the amounts and reactivity of organic carbon source appears to be the rate limiting factor (Berner, 1984; Trudinger, 1979; Westrich and Berner, 1984) while in low SO_4^{2-} soil it appears that SO_4^{2-} concentration can be rate limiting. Boudreau and Westrich (1984), however, showed SO_4^{2-} reduction to be independent of SO_4^{2-} concentration when greater than 3 μM .

The magnitude of sulfate reduction also depends on soil properties; acid soils first show an increase in soil solution SO_4^{2-} because of the release of sorbed SO_4^{2-} (as pH increases) followed by a slow decrease, depending on the intensity of soil reduction (Harvard and Reisenauer, 1966), while in neutral or alkaline soils regardless of initial SO_4^{2-} content all the SO_4^{2-} is lost within 4 weeks of submergence (Ponnamperuma, 1985). High pH favors SO_4^{2-} reduction (Gupta, 1974; Ponnamperuma, 1982).

Sulfate reduction may cause S deficiency in soils low in available S (Nearpass and Clark, 1960; Wang, 1976). Zinc deficiency may occur due to precipitation of ZnS and H_2S toxicity in soils low in iron and in acid sulfate soils (Dhillon et al., 1975; Maskina, 1976; Ponnampereuma, 1972; Sinha et al., 1975).

Drying and remoistening, release available sulfate in soil solution due to mineralization of organic sulfur (McLaren et al., 1985; Mukhopadhyay and Mukhopadhyay, 1980).

Iron

The most conspicuous change caused by flooding a dry soil is reduction of Fe (III) to Fe (II) and the accompanying increase in the solubility of iron. This is a consequence of the anaerobic metabolism of bacteria (Ottow, 1982) and appears to be chiefly a chemical reduction of Fe (III) by bacterial metabolites (Bloomfield, 1951; Motomura, 1961), although direct reduction coupled with respiration may also be involved (Kamura et al., 1963; Ottow and Glathe, 1971). The kinetics of Fe^{2+} production in flooded soils follow a roughly asymptotic curve (Gupta, 1974; Ponnampereuma et al., 1967; Takai, 1963). As much as 50% of the free iron oxides in a soil may be reduced within a few weeks of submergence depending on the temperature, the organic matter content and the crystallinity of the oxides (Mandal, 1960; Takkar, 1969).

The distribution of reduced iron between the solid and solution phases is controlled by pH, organic matter content, CEC of the soil and precipitation reactions (Ponnampereuma, 1985; Sahwab and Lindsay, 1983). During soil submergence the concentration of water-soluble Fe^{2+}

increases to a peak value and then declines or reaches a plateau. Those changes vary with the pH and organic matter content of the soil, the content and reactivity of the Fe(III) oxides, and the salt content of the soil (Ponnamperuma, 1972; 1985). Average concentration of water soluble Fe^{2+} are highest ($>3000 \text{ mg/l}$) in acid sulfate soils with a high content of reactive Fe(III) hydrous oxides and lowest ($<1 \text{ mg/L}$) in alkaline soils low in organic matter. Iron deficiency is often observed in flooded high pH soils (Ponnamperuma, 1985). Application of organic materials enhances the reduction of Fe(III) in high pH soils, but the prevailing high pH inhibits attainment of high concentrations of Fe^{2+} in soil solution. Low temperature (Cho and Ponnamperuma, 1971) or the presence of nitrate (Yamane, 1978) retards the release of water-soluble Fe^{2+} but does not prevent the later building up of high concentrations.

The increase in concentration of water-soluble Fe^{2+} in the initial phase of reduction and its subsequent decrease after the peak has been related to a number of Fe(III)-Fe(II) redox systems operating in a submerged soil (Collins and Buol, 1970; Gotoh and Patrick, 1974; Pasricha and Ponnamperuma, 1976; Ponnamperuma, 1982; 1985; Ponnamperuma et al., 1967; Sajwan and Lindsay, 1986) and formation of FeCO_3 (Sajwan and Lindsay, 1986; Schwab and Lindsay, 1983).

The increase in the solubility of iron is an important benefit of flooding rice soil because oxygen secretion by rice roots increases the rice plant's apparent Fe-requirement (Ponnamperuma, 1975a) but an excess of Fe^{2+} harms rice directly (Tanado and Yoshida, 1978) and indirectly by impeding N and K uptake (Yamada, 1959). Toxic Fe^{2+} concentrations occur in strongly acid soils. Iron toxicity is corrected by adding lime

or MnO_2 or by prolonged submergence. Iron deficiency may occur even in flooded soils if pH and pE are high, as in alkaline soils low in organic matter. It is corrected by applying organic matter, Fe-salts or H_2SO_4 (Randhawa et al., 1978).

Manganese

Almost coincident with the disappearance of nitrate is the reduction of the higher oxides of manganese, which is brought about by bacterial metabolites and by biological redox pathways (Mann and Quastel, 1946; Takai, 1963). The reduction of oxides and hydroxides of manganese occurs at a higher Eh than Fe(III) oxides and therefore it precedes that of Fe(III). Following reduction, the concentration of water soluble Mn^{2+} increases, reaches peaks as high as 90 mg/l and declines or plateaus to 10-20 mg/l depending on the type of soils (Ponnamperuma, 1972; 1985). The peaks are sharp and appear early in acid soils high in Mn and organic matter. Alkaline soils or soils low in manganese seldom contain more than 10 ppm Mn^{2+} in the soil solution. The decline in concentration after the peak is due to the precipitation of MnCO_3 at low redox (Ponnamperuma, 1972; 1985; Schwab and Lindsay, 1983) and precipitation of Mn_3O_4 at higher redox (Schwab and Lindsay, 1983).

Most flooded soils contain sufficient manganese for rice growth. However, the eluviation of Mn^{2+} in the lower profiles due to movement of soluble Mn^{2+} down the profile may cause Mn deficiency in sandy soils (Mitsui, 1960). Although flooding increases the solubility of Mn^{2+} , Mn deficiency in wetland rice may occur in sodic and calcareous

soils low in organic matter, and in sandy soils (Ponnamperuma, 1985). No evidence of manganese toxicity has been reported in flooded conditions. In fact flooding eliminates manganese toxicity in acid aerobic soils because the solubility of Mn^{2+} compounds is vastly decreased when the pH increases to about 7. However acid upland soils may have the problem (Ponnamperuma, 1975a,b).

Boron, copper, molybdenum and zinc

The forms of boron, copper, molybdenum and zinc present in flooded soils do not undergo oxidation-reduction reactions (Sanchez, 1976) but they are indirectly affected by pH changes, iron or sulfate reduction and the production of organic complexing agents. The reduction of iron and manganese oxides, the production of organic complexing agents, and the decrease in pH of alkaline soils are expected to increase the solubility of zinc and copper while the formation of sulfides, carbonates, hydroxides and reaction with soluble silica in solution may lower the concentration of zinc in particular (Forno et al., 1975a, b; Randhawa et al., 1978; Sajwan and Lindsay, 1986; Singh and Prasad, 1982; Sinha et al., 1975; Yoshida et al., 1971). Apparently, zinc deficiency in flooded soils may be the result of combined effects of high pH, high bicarbonate levels, sulfide production, low available zinc content and impeded internal drainage (Dhillon et al., 1975; Kittrick, 1976; Maskina, 1976; Ponnamperuma, 1972; Sinha et al., 1975; Yoshida et al., 1971). Prolonged soil submergence increases the solubility of copper and molybdenum and depresses that of zinc (IRRI, 1970; Katyal and Ponnamperuma, 1974). A negative phosphorus-zinc interaction similar to

that observed in aerobic soils is known to occur in rice soils (Mandal and Halder, 1980; Patrick and Mikkelsen, 1971).

Silica

The concentration of monomeric silica $[\text{Si}(\text{OH})_4]$ in the soil solution increases slightly with flooding and decreases thereafter (Mortimer, 1941; Ponnampetuma, 1965). Subrahmanyam (1937) and Ponnampetuma (1955) suggested that increased availability of silica is a benefit of flooding soils for rice. The increase is apparently due to the release of occluded silicon by reduction of iron oxides. Silica uptake increases photosynthesis and resistance to insects and diseases (Yoshida, 1975) and is agronomically essential to rice (Lian, 1976).

Experiment 1

Influence of Eighteen Water Regimes on the Chemical Kinetics and Rice Growth in a Fertile Lowland Soil

Since variable water regime conditions influence nutrient availability (Goswami et al., 1986) and the nature and severity of the problems depend on soil properties and the time and duration of drying (Ponnamperuma and Ikehashi, 1979) this greenhouse experiment was conducted at the Soils Department of The International Rice Research Institute to study the effect of 18 different water regimes on the chemical kinetics of soil solution, and mineral nutrition, growth and yield of rice (IR54).

MATERIALS AND METHODS

Soil

A fertile Maahas soil (Maahas-1, Tropaqualf) collected from Block M-14 of the IRRI farm was used. Some of the characteristics of the soil are presented in Table 2.

Design

The experiment was laid out in randomized complete block design with three replications.

Treatments

- i. Continuously flooded with 3-5 cm standing water (CF)
- ii. Continuously flooded with a drainage of 5 mm/day (D5)
- iii. Continuously flooded with a drainage of 10 mm/day (D10)
- iv. Continuously saturated (CS)
- v. Two weeks soil drying imposed on the day of
transplanting and reflooding (SD 0-2)
- vi. Two weeks soil drying imposed 2 weeks after
transplanting (WAT) and reflooding (SD 2-4)
- vii. Two weeks soil drying imposed at 4 WAT and reflooding (SD 4-6)
- viii. Two weeks soil drying imposed at 6 WAT and reflooding (SD 6-8)
- ix. Two weeks soil drying imposed at 8 WAT and reflooding (SD 8-10)
- x. Two weeks soil drying imposed at 10 WAT and reflooding (SD 10-12)
- xi. Four weeks soil drying imposed on the day of
transplanting and reflooding (SD 0-4)
- xii. Four weeks soil drying imposed at 2 WAT and reflooding (SD 2-6)
- xiii. Four weeks soil drying imposed at 4 WAT and reflooding (SD 4-8)
- xiv. Four weeks soil drying imposed at 6 WAT and reflooding (SD 6-10)
- xv. Four weeks soil drying imposed at 8 WAT and reflooding (SD 8-12)
- xvi. Alternate soil drying and reflooding for 4 weeks
imposed on the day of transplanting and at 8 WAT (SD 0-4/8-1)
- xvii. Alternate soil drying and reflooding for 2 weeks
imposed on the day of transplanting, 4 and 8 WAT (SD 0/4/8)
- xviii. Alternate soil drying and reflooding for 2 weeks
imposed at 2, 6 and 10 WAT (SD 2/6/10)

Table 2. Some characteristics of the soil (Maahas-1)
used in experiment I .

pH (1:1)	6.4
Organic (%) C	2.00
Total N (%)	0.17
Total S (%)	0.09
Available	
N (mg/kg)	152.6
P (Olsen) (mg/kg)	5.5
S (mg/kg)	33.7
Zn (mg/kg)	0.52
Cu (mg/kg)	0.10
Exchangeable	
K (me/100 g)	2.3
Ca (me/100 g)	21.7
Mg (me/100 g)	15.8
Active	
Fe (%)	1.93
Mn (%)	0.12
Water soluble Si (mg/kg)	230.6
CEC (me/100 g)	60.0
Mechanical analysis	
Clay (%)	53
Silt (%)	33
Sand (%)	14
Textural class	Clay

Greenhouse procedure

Bulk soil sample was collected from the field from 0-20 cm depth, air-dried, crushed to 0.6 cm clods and mixed thoroughly. Sixteen liter glazed porcelain pots were thoroughly cleaned, acid washed and rinsed with demineralized water. Each pot was fitted at the bottom with a glass tube wrapped in glass wool and then covered with a layer of quartz sand (Ottawa, Industrial Sand Co., Illinois) for recycling or sampling the soil solution (Fig. 1).

Twelve kg portion of the soil was mixed with N, P and K at the rate of 100, 25 and 75 mg/kg soil respectively and put carefully in each pot. Urea, KH_2PO_4 and KCl were used as source of N, P and K. The pot was filled with demineralized water and the percolating water collected by allowing it to flow under gravity. Collected soil solution was then returned to the pot. The soil solution from each pot was thus recycled 3 times to ensure equilibration between the solid and liquid phase and then the appropriate water regime treatments were imposed. A tensiometer and 2 bright platinum electrodes were placed at 10 cm depth in each pot for in situ measurement of soil moisture tension and soil Eh respectively. The pots were kept bathed in water constantly (leaving 7-8 cm at the top of the pot) in concrete tank to minimize fluctuations in temperature (Plate 1).

A hypodermic needle was fixed at the end of the drainage tube and kept open in the pots receiving drainage treatment. The flow of water through the needle was adjusted with a pinch-clamp to get desired drainage rates. The collected drainage water was discarded.

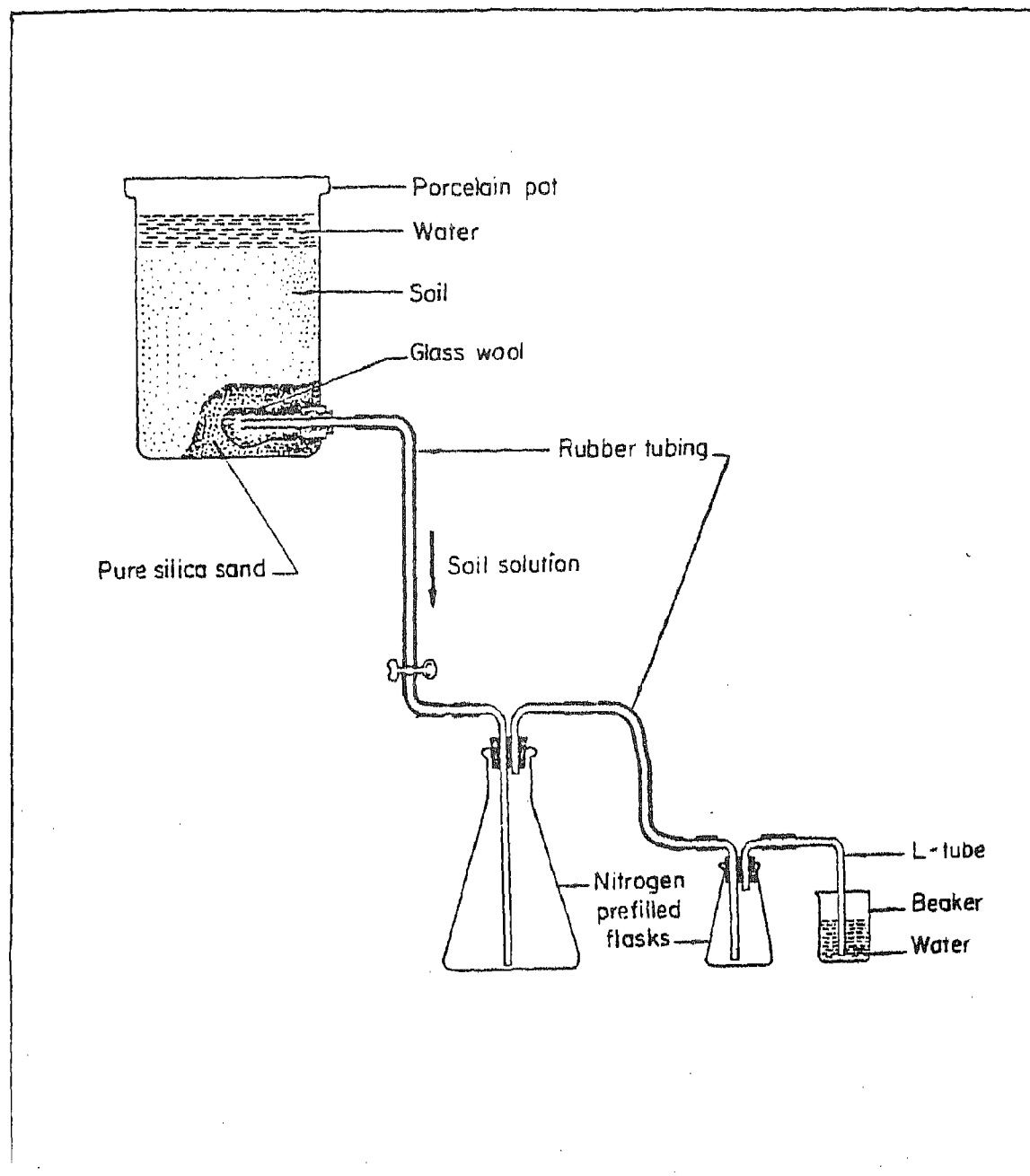


Fig. 1. Set-up for sampling soil solution.



Plate 1. Experimental set-up in the greenhouse.

In the saturated water regime treatment, sufficient water was added to the pot to just saturate the soil and have only a very thin film of water over it but no standing water was allowed on the top of the soil. The pots were watered four times a day to compensate for evapotranspiration.

The flooded pots were irrigated with demineralized water when needed to maintain 3-5 cm of standing water.

For soil drying treatments, the designated pots were drained on the day of start of the drying treatment and the drained water was stored in glass bottles for irrigating the same pot later. The pots were allowed to dry up to 0.3 bar tension. When the tensiometer reached the 0.3 bar tension mark, the pots were watered with calculated amount of water to saturate the soil.

Seeds of IR54 were selected by immersing them in 1.12 g cm^{-3} specific gravity salt solution. The seeds floating on the solution were discarded and those remaining at the bottom of the container were selected. The seeds were washed thoroughly with running tap water and incubated for 48 hours before placing on nylon netted floats in tap water. The seedlings were grown for 2 weeks in tap water.

Six of these seedlings were transplanted in each pot. Before transplanting the seedlings were given a "root-dip" in 2% ZnO suspension. After one week, two weakest seedlings were uprooted from each pot and buried in the soil of the same pot.

Soil solution was collected by gravity through the drainage tube (Fig. 1) into 125 ml nalgene and 50 ml pyrex Erlenmeyer flasks previously flushed with nitrogen. Soil solution was collected from dry

soil by saturating the soil with demineralized water. A water head was imposed as in flooded pots before collecting in sampling flasks.

Soil solution was collected from each pot at 0, 2, 4, 6, 8, 10, 12 and 14 weeks after transplanting of rice.

Two plants were harvested from each pot at 8 WAT and the remaining two plants were grown to maturity and grain and straw yields were recorded.

Growth observation and yield data

Plant growth was followed by measuring plant height and counting tiller number at different stages. Dry matter yield of shoot at 8 WAT, and grain and straw yields at harvest were also determined.

Analytical Procedures

Soil analyses

1. Preparation of soil sample

Sub samples were collected from the homogenized bulk soils, air dried, passed through 2 mm sieve and quartered to a final weight of about 1 kg. A portion was ground further to pass through an 80-mesh sieve. The prepared samples were then analyzed.

2. Analyses

- a. Soil pH was determined using 1:1 soil water ratio using a glass electrode (Black et al., 1965).
- b. Organic carbon was determined following wet digestion method of Walkley and Black (1934) using o-phenanthroline-ferrous complex indicator (Allison, 1965).

- c. Total nitrogen was analyzed after wet digestion with concentrated H_2SO_4 (Bremner, 1965) using a Tecator Kjeltrec Autoanalyzer.
- d. Available nitrogen was determined after incubating soil anaerobically for 2 weeks, extracting NH_4^+-N by 2(M) KCl (Waring and Bremner, 1965) and distilling in a Tecator Auto Analyzer.
- e. Available phosphorus was estimated by the Olsen method (1954) using ascorbic acid (Watanabe and Olsen, 1965).
- f. Exchangeable K^+ , Ca^{2+} and Mg^{2+} were determined after extraction with neutral molar ammonium acetate using a Perkin Elmer 5000 atomic absorption spectrophotometer (Black, 1965).
- g. Available Zn and Cu were estimated using the 0.05 N HCl method (Ponnamperuma et al., 1981).
- h. Available sulfur was extracted using 500 ppm P (Ensminger, 1954). Sulfate-S was determined by the methylene blue method (Johnson and Nishita, 1952).
- i. Total sulfur was estimated by digesting soil with sodium hypobromide (Tabatabai and Bremner, 1970) and determining sulfate-S colorimetrically by methylene blue method (Johnson and Nishita, 1952).
- j. Available Si was determined by water extraction and subsequent analysis using molybdenum blue method (Hesse, 1971).
- k. Active iron and manganese were determined using sodium hydrosulfite and EDTA extraction method (Asami and Kudama, 1959).

1. Cation exchange capacity was determined at pH 7.0 using 1 molar ammonium acetate (Black, 1965).

m. Mechanical analysis was done by the pipette method (Black, 1965).

Soil solution analyses

The pH, Eh and EC were determined simultaneously in the electrometric cell using 125 ml sample (IRRI, 1964) fitted with glass electrode, a saturated calomel reference electrode, two bright platinum electrodes and a conductivity cell (Fig. 2). These analyses were performed under anaerobic conditions immediately after collection of the soil solution. The temperature of the soil solution samples was maintained at 25°C by keeping them in a thermostat controlled water bath.

After the electrochemical measurements a portion of soil solution was placed in Benzene- Isobutanol mixture for P analysis. A portion of the soil solution was acidified with few drops of 6 N HCl to prevent oxidation of Fe^{2+} and Mn^{2+} and to prevent ammonia volatilization. This acidified soil solution was used for the analyses of NH_4^+ , K^+ , Ca^{2+} , Mg^{2+} , Fe^{2+} , Mn^{2+} and Si(OH)_4 . Zinc concentration of the soil solution was measured immediately without acidification.

a. Ammonium-N was determined by distillation with 50% NaOH using Kjeltéc Auto Analyzer 1030.

b. Ferrous iron, Mn^{2+} , Zn^{2+} and Mg^{2+} were determined directly by Atomic Absorption spectrophotometry and K^+ and Ca^{2+} by emission spectrophotometry, using a Perkin Elmer 5000 Atomic Absorption Spectrophotometer.

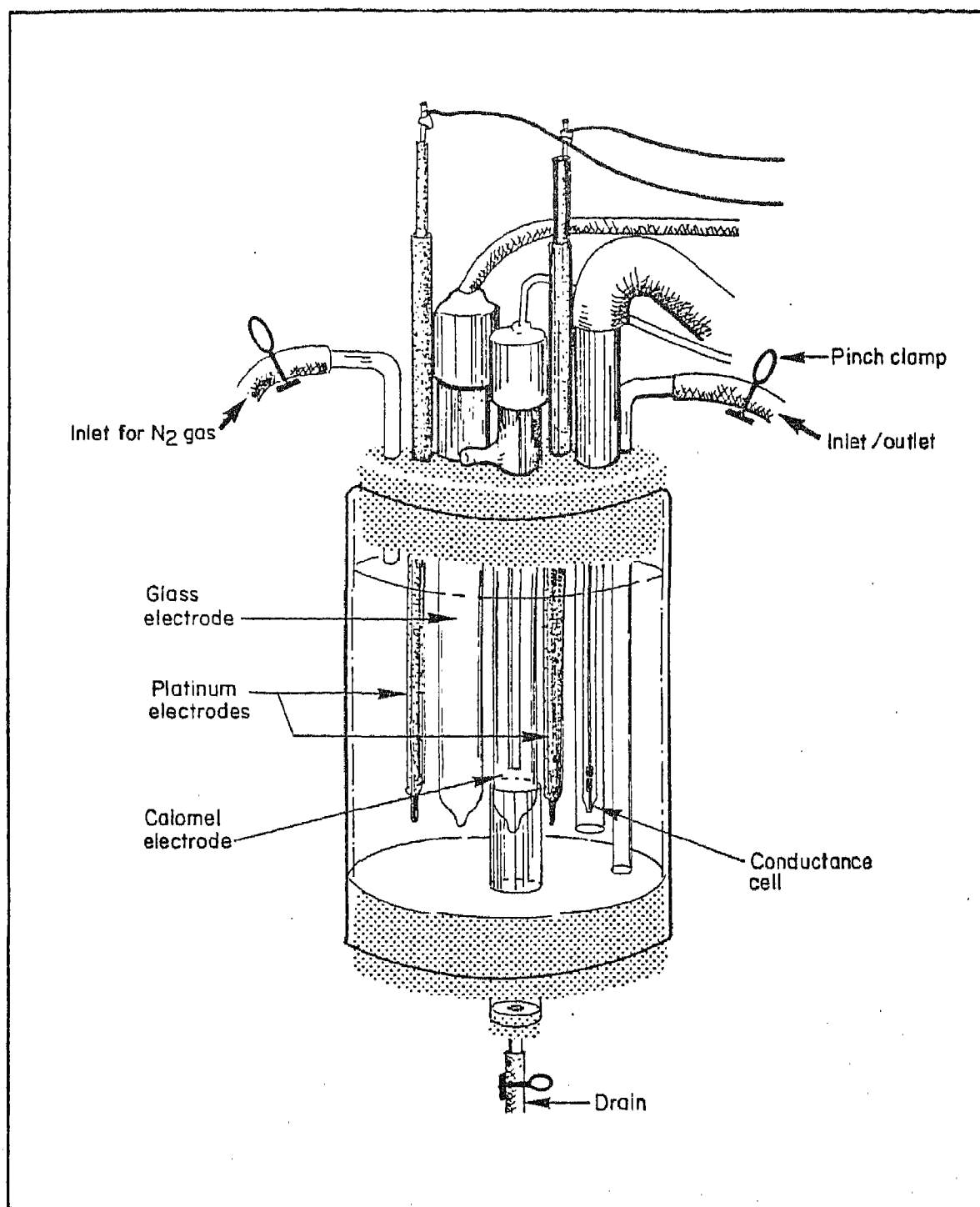


Fig. 2. The electrometric cell.

- c. Phosphorus was determined by isobutanol-benzene extraction method described by Martin and Doty (1949) and modified by Ponnampetuma (1955).

Plant tissue analysis

1. Sample preparation

Shoots, straw and grain samples were dried at 80°C in an oven for 48 hours and ground using a UD cyclone mill. The samples were then placed in paper envelopes and redried before analysis.

2. Analytical procedures

- a. Total nitrogen was determined by wet digestion with concentrated H_2SO_4 and distillation in a Tecator Auto Analyzer.

- b. Total P was determined by the vanado molybdophosphoric method (Yoshida et al., 1976).

- c. K, Ca, Mg, Fe, Mn, Zn and Cu were determined by digestion of the samples in tri-acid mixture (HNO_3 , H_2SO_4 and $HClO_4$), filtering and reading the filtrate for the elements in an atomic absorption spectrophotometer (Perkin Elmer 5000) after suitable dilutions (Yoshida et al., 1976).

- d. Si was determined as crude silica gravimetrically by the method of Yoshida et al. (1976).

Calculations

1. Nutrient uptake by shoot

This was calculated as follows:

1. Uptake of nutrient (g/pot)

$$= [\text{Shoot weight (g/pot)} \times \frac{\% \text{ Nutrient in shoot}}{100}]$$

ii. Uptake of nutrient (mg/pot)

$$= [\text{Shoot weight (g/pot)} \times \frac{\text{ppm nutrient in shoot}}{1000}]$$

2. Nutrient uptake at harvest

This was calculated by adding the uptake of nutrient by grains and by straw at harvest. For example

i. Nutrient uptake (g/pot)

$$= \frac{\% \text{ Nutrient in straw} \times \text{Straw yield (g/pot)}}{100} \\ + \frac{\% \text{ Nutrient in grains} \times \text{Grain yield (g/pot)}}{100}$$

ii. Nutrient uptake (mg/pot)

$$= \frac{\text{ppm Nutrient in straw} \times \text{Straw yield (g/pot)}}{1000} \\ + \frac{\text{ppm Nutrient in grains} \times \text{Grain yield (g/pot)}}{1000}$$

All the data for plant observations, nutrient concentrations in shoots and straw and nutrient uptake by shoot and at harvest were analyzed statistically using an IBM PC XT microcomputer with the help of standard statistical programmes.

RESULTS AND DISCUSSION

Chemical Kinetics of Soil Solution

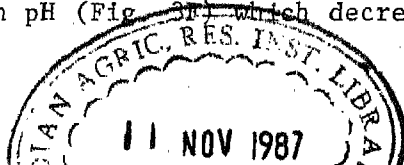
On the sampling dates soil solutions were collected from all the three replications of each treatment and analyzed. The results presented graphically in the following pages are the mean of the three replications.

pH

The pH of soil solution gradually decreased up to 8 weeks after transplanting (WAT) to a value of 6.4 for the CF, D10, D5 and CS treatments and remained stable at that value during the rest of the growing season (Fig. 3A).

The initial drop of soil solution pH under flooded water regime could be due to the formation of CO_2 and organic acids on organic matter decomposition (Ponnamperuma, 1972). The slightly higher soil solution pH in flooded-drained soils (D10 and D5) could be due to removal of these organic acids from the system along with the drainage water.

Soil drying for 2 weeks had only a little depressing effect on the soil solution pH during the dry period which on reflooding started to rise up again to the pH of the flooded soil solution (Fig. 3B, C). Soil drying for 4 weeks had pronounced effect and on reflooding the soil solution pH never recovered to the former level (Fig. 3D, E). Three cycles of soil drying and reflooding of 2 weeks, also had pronounced effect on soil solution pH (Fig. 3F) which decreased to 6.0 during soil drying.



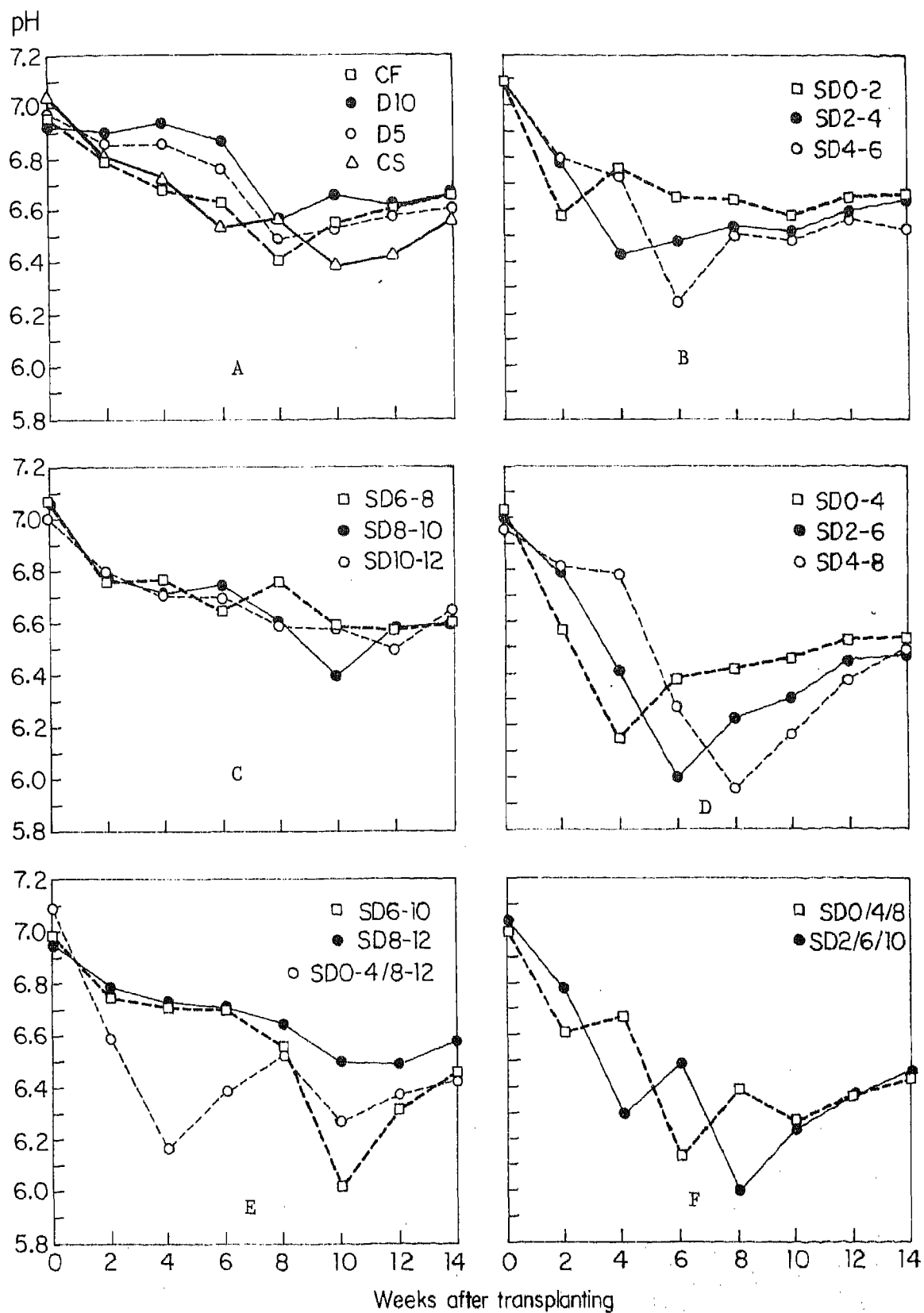


Fig. 3. Influence of eighteen water regimes on kinetics of solution pH in Maahas-1 soil.

Soil drying depressed the soil solution pH probably because of oxidation of NH_4^+-N to NO_2^--N and NO_3^--N and precipitation of Fe and Mn as their respective oxides or hydroxides (Ponnamperuma, 1985). On reflooding the dry soil, the pH did not rise rapidly probably because of the lack of readily available organic matter in soil.

Eh

Soil solution Eh in all treatments decreased to near 0 mV within few hours of flooding the soil as indicated by the soil solution Eh at 0 WAT (Fig. 4). The soil solution Eh in continuously flooded or saturated treatments (CF, D5, D10, CS) continued decreasing and attained a value of around -50 mV two weeks after transplanting (Fig. 4A) and fluctuated thereafter within a value of 0 and -50 mV during the rest of the rice growing periods. Drainage of 5 to 10 mm/day (D5, D10) did not influence the Eh of flooded soil.

Continuously saturated water regime (CS) maintained a little higher soil solution Eh as compared to the flooded water regime probably because of little higher rate of oxygen diffusion due to absence of standing water on the soil surface (Fig. 4A).

Soil drying increased soil solution Eh and reflooding decreased it again (Fig. 4B-F). The soil Eh measured in situ also indicated soil reduction due to flooding and oxidation on soil drying (Fig. 5A-F). However, the soil Eh values were much lower than soil solution Eh under flooded condition while the opposite was true under soil drying conditions. These observations agree closely with those of Ponnamperuma (1972) and Sato and Yamane (1973). The difference between soil and

Eh (mv)

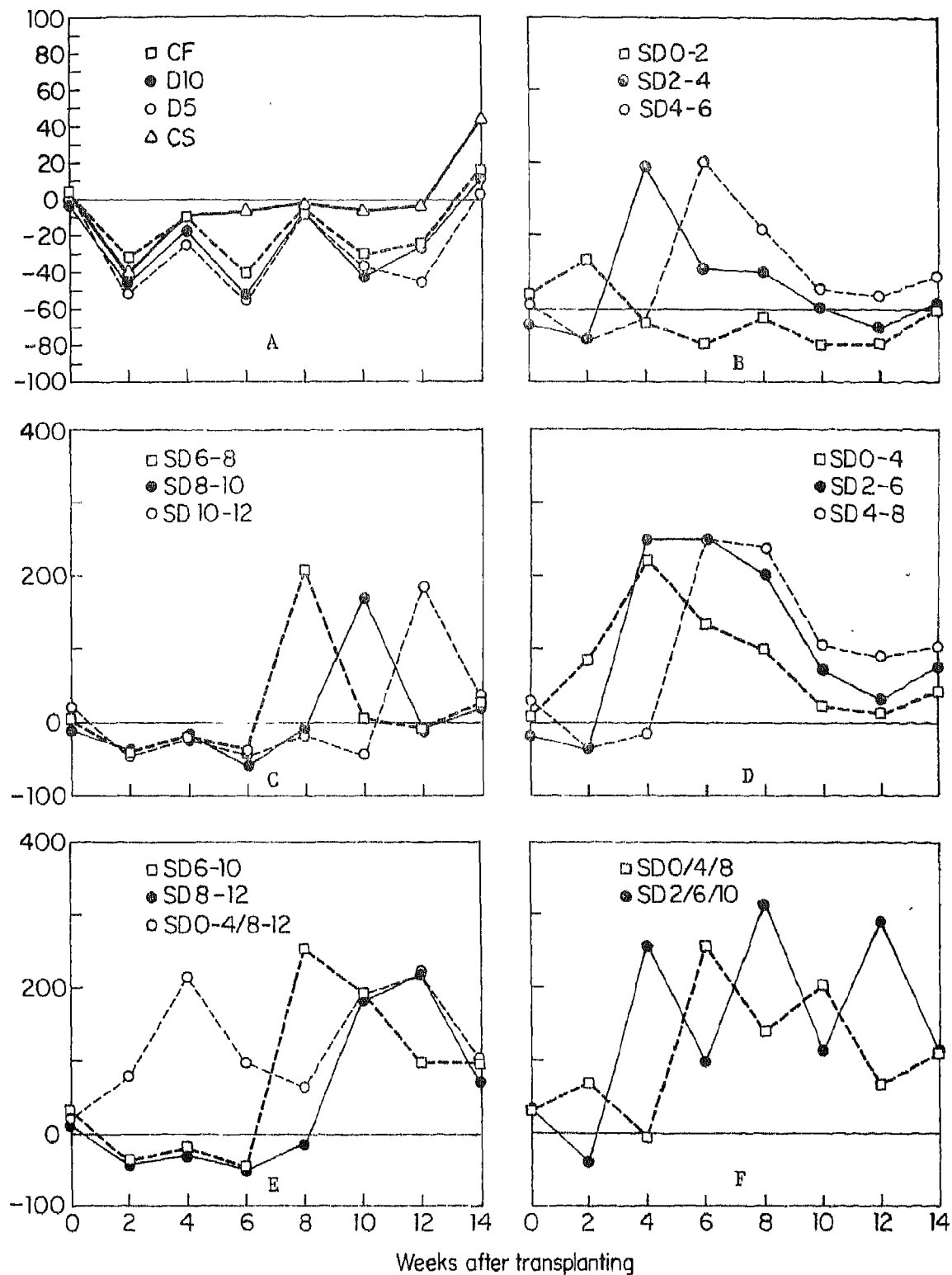


Fig. 4. Influence of eighteen water regimes on kinetics of solution Eh in Maahas-1 soil.

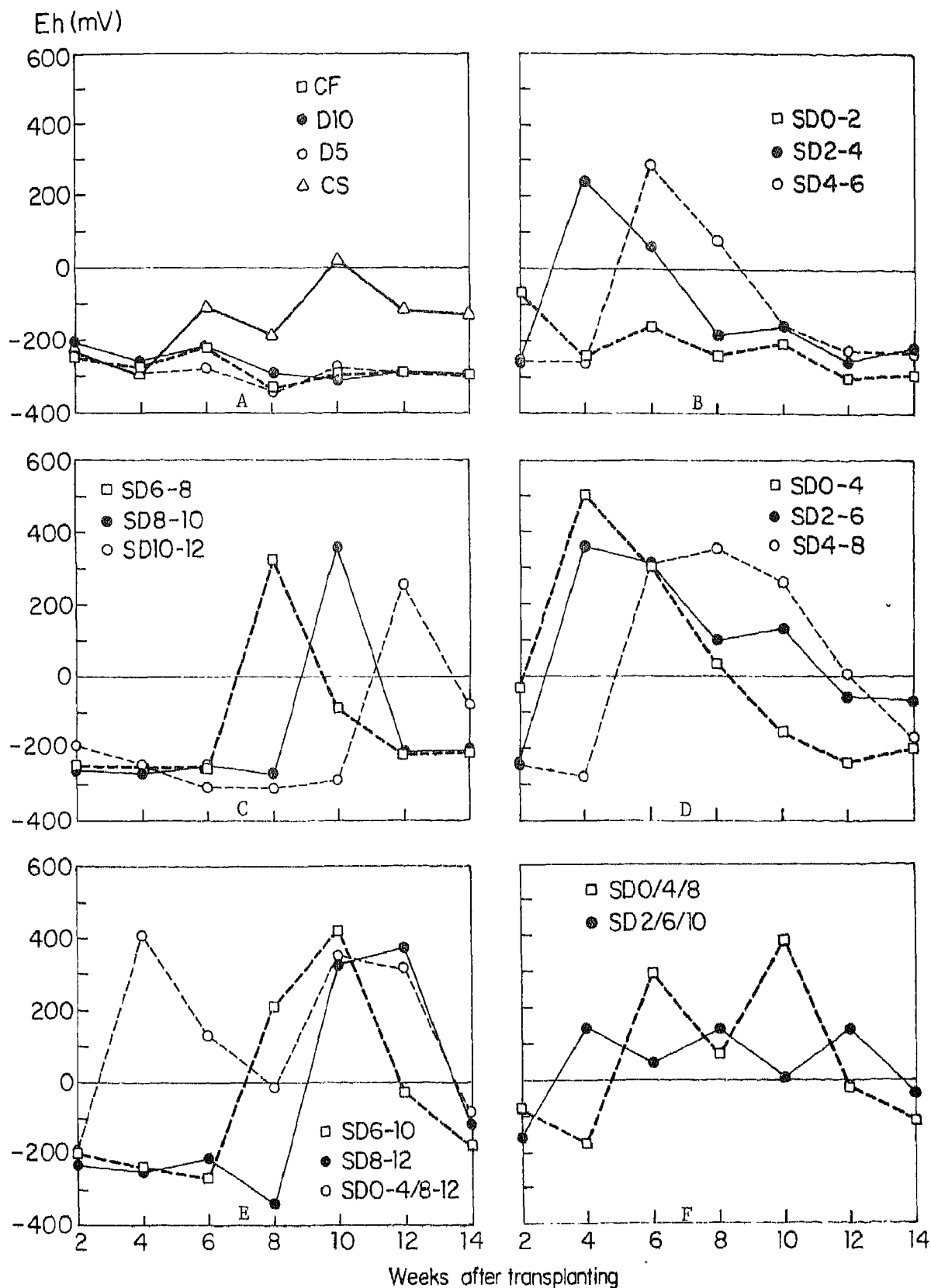


Fig. 5. Influence of eighteen water regimes on kinetics of Eh in Maahas-1 soil.

solution Eh might be, as suggested by Ponnampetuma (1972), due to presence of an oxidant or reductant in the solid phase. Considering the errors involved in the measurement of soil Eh, Ponnampetuma (1972) noted that soil Eh is less meaningful and less reliable than the soil solution Eh. However, it is, worth mentioning here, that the critical redox potential values reported in the literature for identification of the dominant redox systems operating in soils are of soils and not of the soil solutions (Yamane, 1978).

Electrical conductivity (EC)

The EC of soil solution of continuously flooded (CF) and saturated (CS) water regimes increased to a maximum 2 weeks after flooding and decreased for the next 4 weeks to a value of around 2.2 dS/m and remained stable at that value during the rest of the rice growing season (Fig. 6A).

Drainage of 5-10 mm/day of the flooded soil (D5, D10) decreased the EC to lower values due to removal of ions from the system (Fig. 6A). Continuously saturated water regime (CS) also maintained relatively lower EC values although the trend in EC change remained the same as in continuously flooded water regime (CF).

Soil drying for 2 to 4 weeks depressed the soil solution EC during the dry periods. Reflooding the dry soil increased the EC and this increase brought the EC to values higher than the continuous flooded water regime at the given time (Fig. 6B-F).

Ec(dS/m)

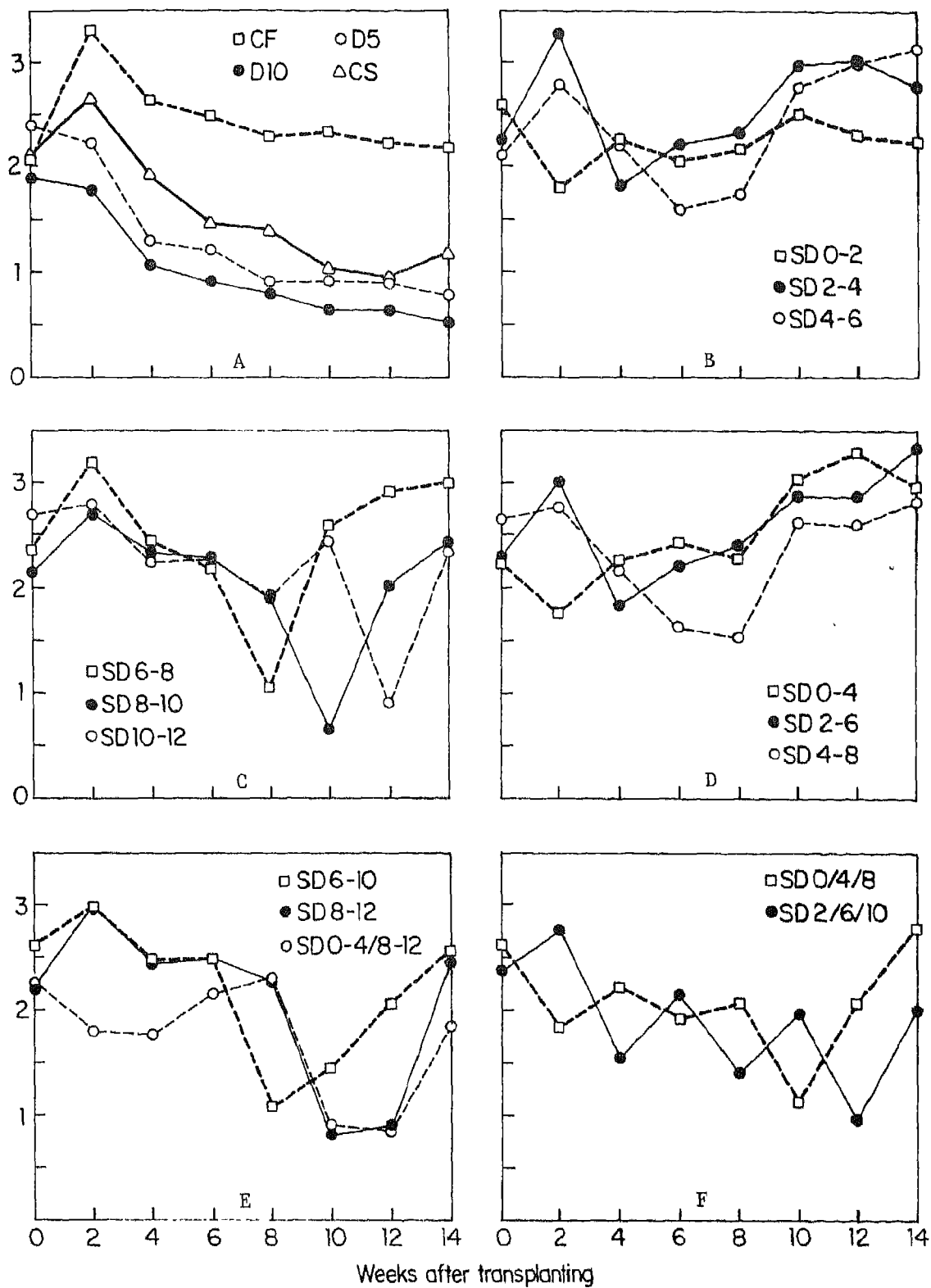


Fig. 6. Influence of eighteen water regimes on kinetics of solution electrical conductivity in Maahas-1 soil.

The initial increase in soil solution EC was due to increase in the concentration of water soluble cations as a consequence of soil reduction (Bora and Goswami, 1980; Ponnampetuma, 1972; 1985). The subsequent decrease in EC was caused by precipitation of Fe^{2+} and Mn^{2+} , loss of CO_2 and conversion of RCOO^- to CH_4 (Ponnampetuma, 1978).

The decrease in EC due to soil drying could be due to escape of CO_2 from soil, oxidation and precipitation of Fe^{2+} , Mn^{2+} and readsorption of K^+ , Ca^{2+} and Mg^{2+} by soil exchange complex.

NH_4^+-N

In all treatments, the soil was treated with 100 mg N/kg soil as urea on the day of flooding (transplanting). Because urea hydrolysis takes time, the NH_4^+-N concentration of the soil solution on the day of first sampling represent the initial water soluble NH_4^+-N concentration of the soil (Fig. 7A-F)). On the second week after flooding the NH_4^+-N concentration of the soil solution decreased because of its movement on to the exchange sites of the soil. A portion of NH_4^+-N might also have been lost by ammonia volatilization (Fillery and Vlek, 1986; Keeney and Sahrawat, 1986; Savant and De Datta, 1982). The later decrease was due to plant uptake and loss of N by denitrification in the oxidized zone and also probably in the rhizosphere (Patrick and Reddy, 1986).

The NH_4^+-N concentration of soil solution in saturated (CS) and drained flooded soil (D10 and D5) was lower as compared to that under continuous flooded non drained water regime (CF). The lower NH_4^+-N

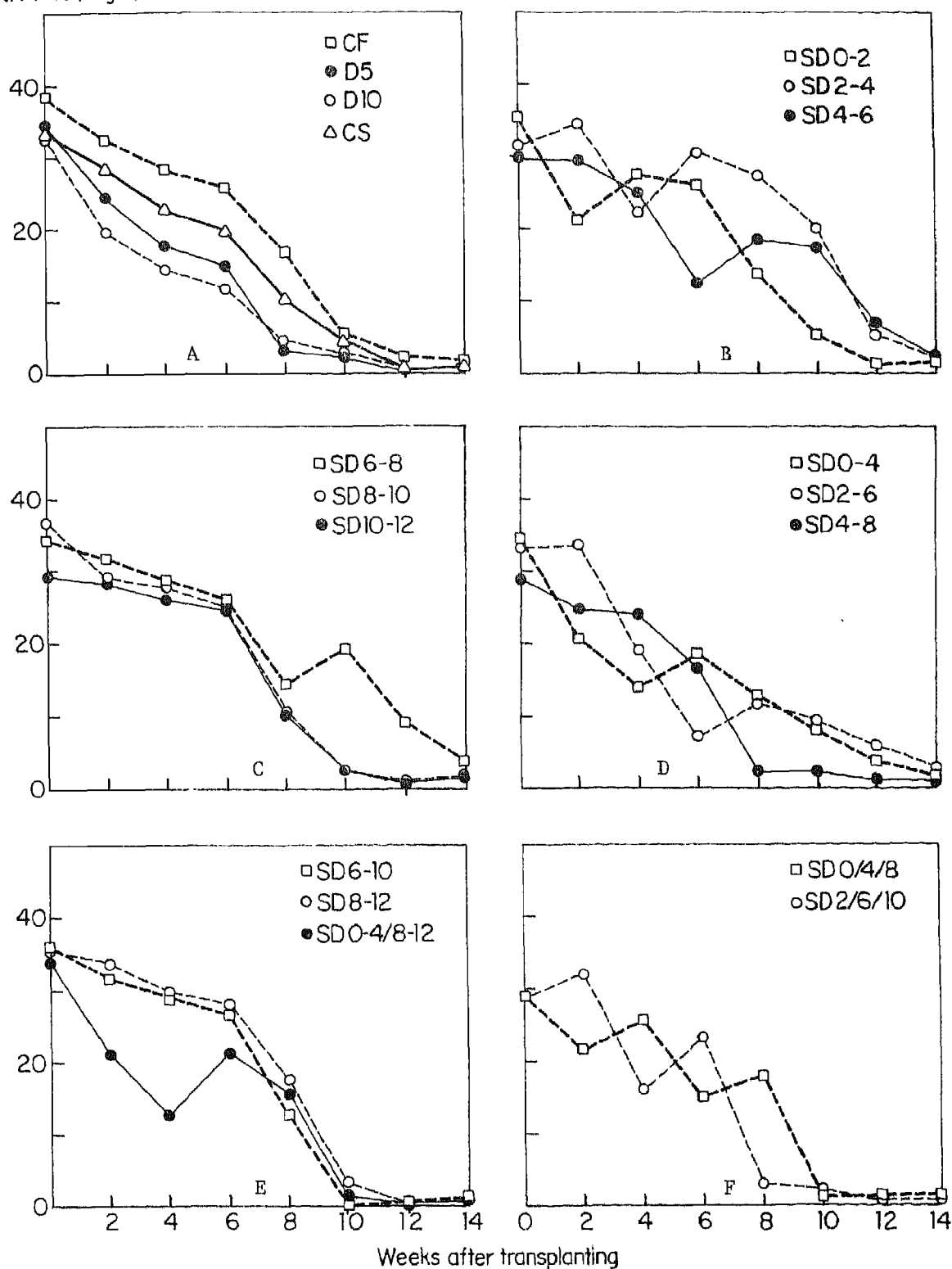
NH₄-N (mg/l)

Fig. 7. Influence of eighteen water regimes on kinetics of water-soluble NH₄⁺-N in Maahas-1 soil.

in saturated water regime (CS) could be due to loss of more N by ammonia volatilization or more adsorption on the exchange sites while the lower NH_4^+ -N in drained water regime might be due to loss of NH_4^+ -N with drainage water.

Soil drying for 2 to 4 weeks decreased the NH_4^+ -N due to its nitrification (Fig. 7B-F). The NO_3^- -N formed on drying seemed to have been lost by denitrification on reflooding. This is one of the major losses that can occur under intermittently dried and reflooded conditions (Patrick and Wyatt, 1964; Sah and Mikkelsen, 1983a; Sahrawat, 1981).

Reflooding the dry soil resulted in formation of NH_4^+ -N in soil solution. This indicates accelerated mineralization of organic N due to soil drying and reflooding (Birch, 1960; Reddy and Patrick, 1975; Shiga and Ventura, 1976).

Phosphorus (P)

In all the treatments phosphorus @25 mg P/kg soil was applied as KH_2PO_4 on the day of flooding. In all the treatments there was a decrease in water soluble P during the next two weeks (Fig. 8A). The P concentration of the soil solution, under continuous flooded condition (CF) increased to a peak 4 weeks after transplanting and started to decrease to a value of around 0.1 ppm-P at 14 weeks after transplanting. Drained flooded (D5 and D10) and saturated (CS) water regime maintained lower P in soil solution compared to flooded one.

Phosphorus (mg/l)

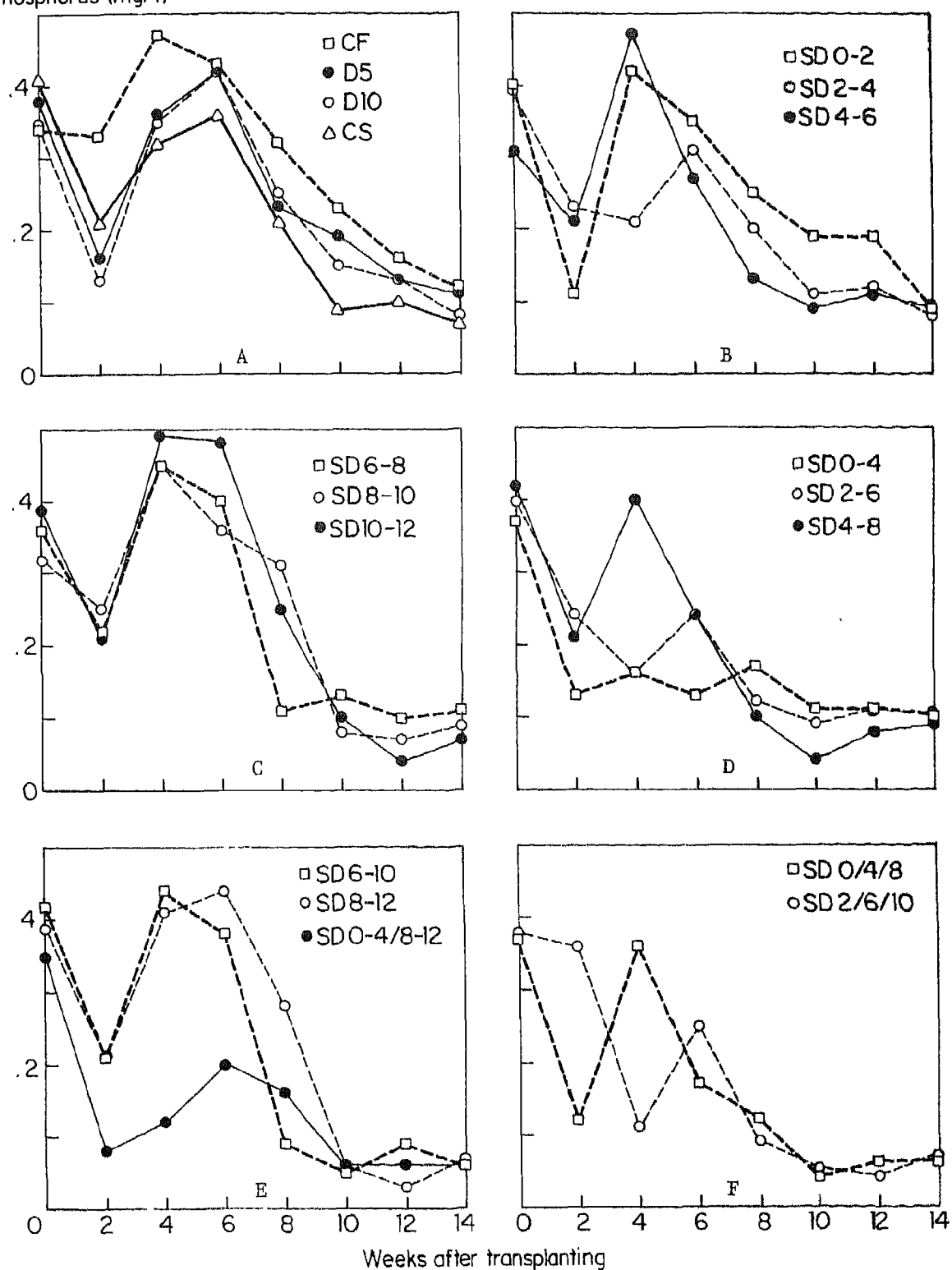


Fig. 8. Influence of eighteen water regimes on kinetics of water-soluble P in Maahas-1 soil.

The initial decrease in soil solution P in flooded water regime could be due to fixation of added fertilizer P where as the peak P concentration in soil solution 4 weeks after flooding could be due to desorption of applied and native P due to reduction of Fe(III) and Mn(IV) oxides (Mandal and Mandal, 1973; Patrick and Khalid, 1974). The later decrease in soil solution P was due to plant uptake, refixation and co-precipitation (Patrick and Mahapatra, 1968; Patrick and Reddy, 1978; Ponnampersuma, 1972; 1985).

Soil drying decreased the P concentration of soil solution and reflooding raised the soil solution P again, although to lower concentration than in the flooded soil (Fig. 8B-F).

Decrease in soil solution P due to soil drying and reflooding could be because of decreased solubility of added and native P (Paul and Delong, 1949) or increased P fixation (Bora and Goswami, 1980; Haynes and Swift, 1985; Sah and Mikkelsen, 1986; Singhanla and Goswami, 1978).

Potassium (K^+)

In all the treatments K @75 mg/kg soil was applied on the day of flooding. In continuously flooded (CF) water regime the K^+ concentration of the soil solution decreased during the first two weeks of flooding, increased for the next two weeks reaching a peak 4 weeks after flooding and declined thereafter (Fig. 9A). Soil solution K^+ concentration in continuously saturated (CS) and drained flooded soils (D5 and D10) followed the same pattern as continuously flooded non drained soil (CF) but with lower values.

Potassium (mg/l)

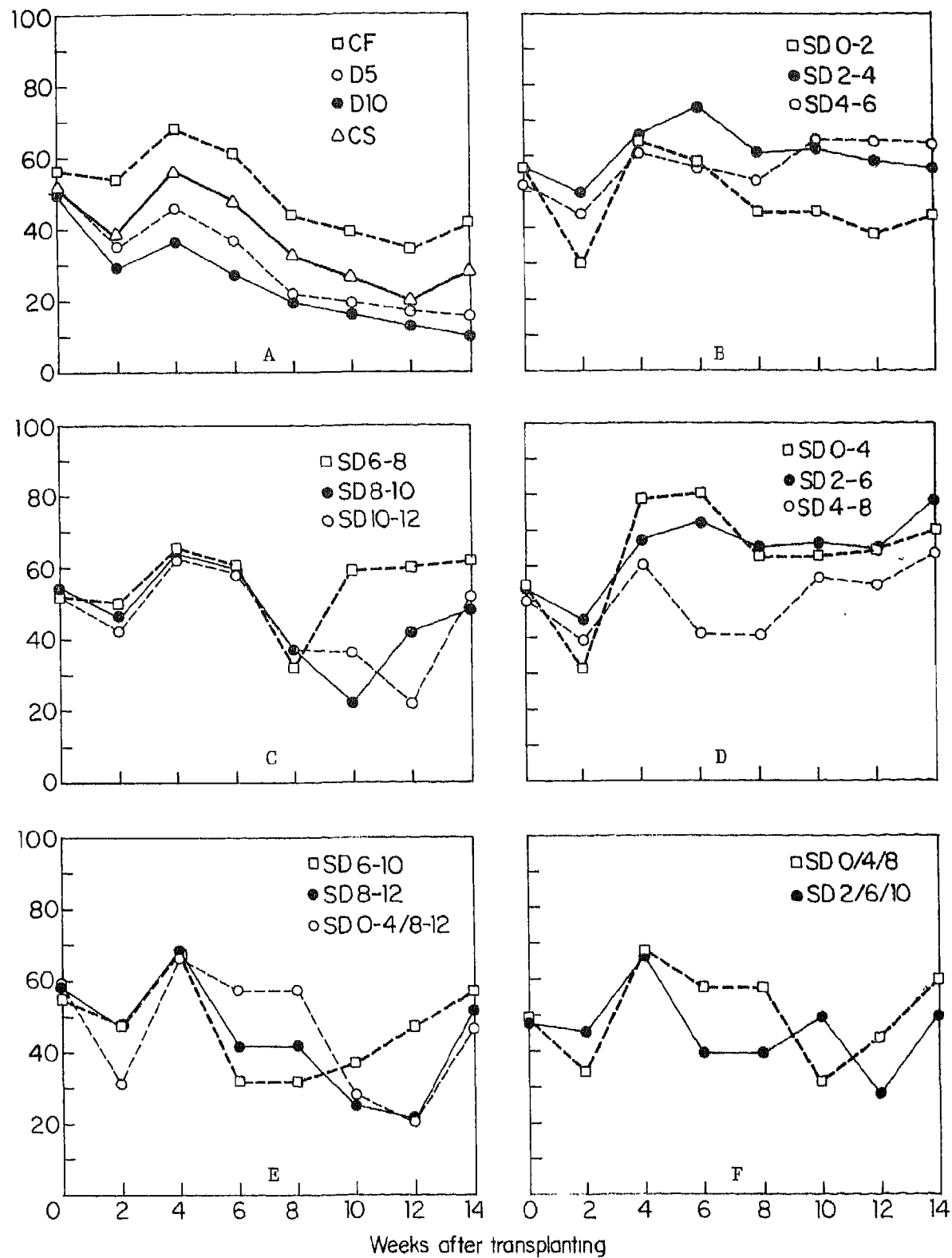


Fig. 9. Influence of eighteen water regimes on kinetics of water-soluble K in Maahas-1 soil.

Soil drying for 2 to 4 weeks decreased the soil solution K^+ concentration during the dry periods but reflooding started to increase it and within 2 weeks time it reached or even surpassed the level of K^+ in continuously flooded water regime (Figs. 9B-F).

The initial decrease in soil solution K^+ in flooded water regime (CF) could be due to fixation of the applied K^+ . The later increase of soil solution K^+ was due to the displacement of K^+ from the exchange complex by NH_4^+-N , Fe^{2+} and Mn^{2+} released on soil reduction due to flooding (Islam and Islam, 1973; Kadrekar, 1976; Subramanian and Rajagopalan, 1980). The increased soil solution K^+ due to alternate flooding and drying confirmed the findings of Kadrekar and Kibe (1973); Singh and Ram (1976) and others (Biswas, 1974; Goswami and Banerjee, 1978).

Calcium (Ca^{2+})

In continuously flooded water regime (CF) peak value of Ca^{2+} concentration in soil solution was obtained two weeks after flooding and thereafter it declined gradually with time (Fig. 10A). Drainage with flooding (D5 and D10) resulted in continuous decline in soil solution Ca^{2+} and this decline was faster with higher drainage rate (D10). In the continuously saturated (CS) water regime soil solution Ca^{2+} concentration showed similar trend as in non drained flooded treatment (CF) but the corresponding concentrations were lower in saturated water regime.

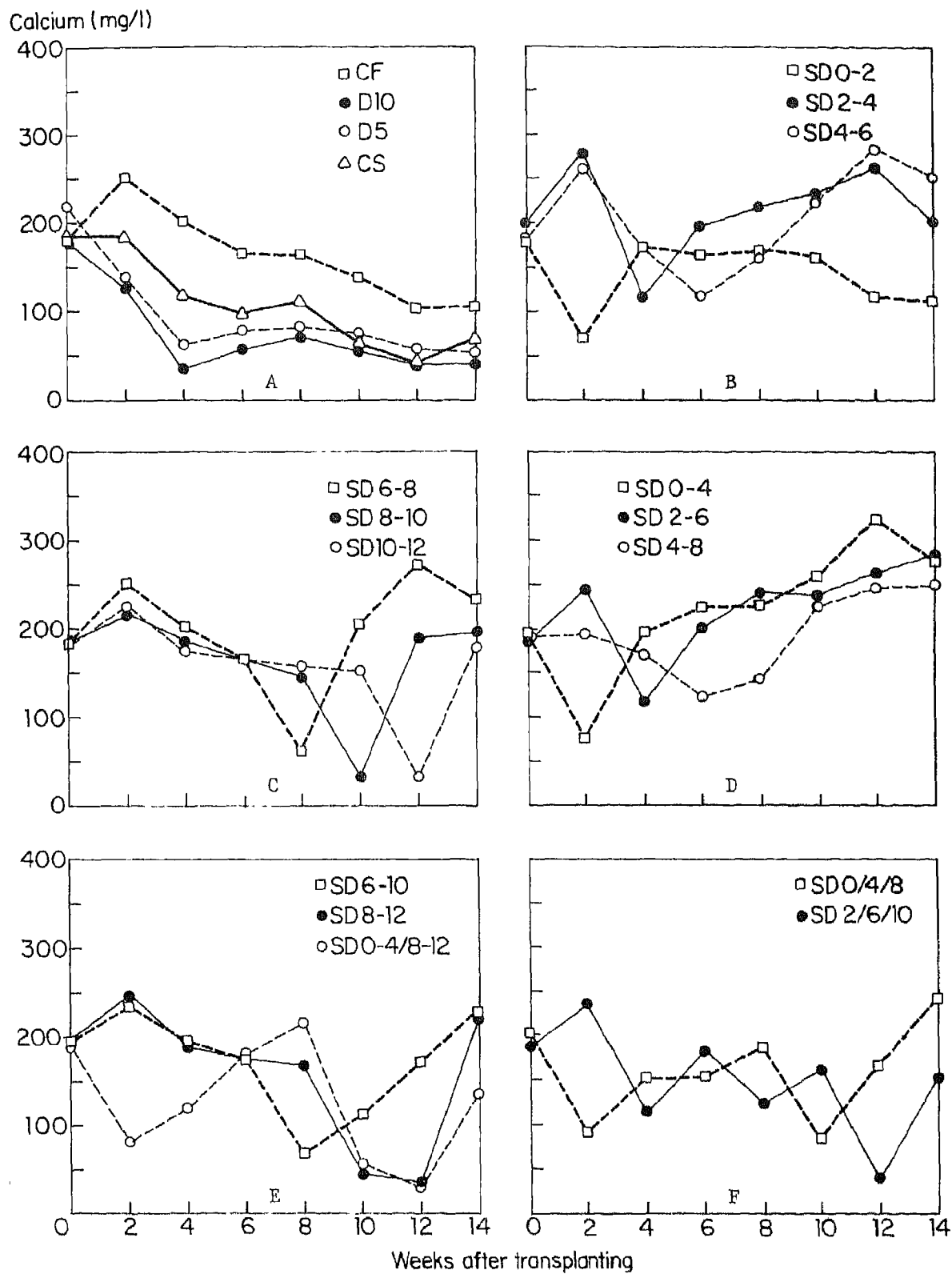


Fig. 10. Influence of eighteen water regimes on kinetics of water-soluble Ca in Maahas-1 soil.

Soil drying for 2 to 4 weeks decreased the Ca^{2+} concentration of the soil solution during the dry period while reflooding the dry soil rapidly increased the soil solution Ca^{2+} to greater concentration than in the continuously flooded water regime (Figs. 10B-F).

The initial increase in soil solution Ca^{2+} on flooding was due to replacement of Ca^{2+} from the soil exchange complex by NH_4^+-N , Fe^{2+} and Mn^{2+} ions released on soil reduction (Islam and Islam, 1973; Kadrekar, 1976; Subramanian and Rajagopal, 1980). Microbial production of a variety of organic metabolites might also be responsible for the release of Ca^{2+} from the exchange sites and its mineral reservoirs (Silverman and Munoz, 1980). The later decrease could be due to readsorption of Ca^{2+} on to the exchange sites when Fe^{2+} and Mn^{2+} were precipitated and plant uptake.

The lower Ca^{2+} concentration in soil solution of drained soil was due to its removal with drainage water.

Magnesium (Mg^{2+})

Magnesium concentration of the soil solution followed the same trend as calcium but the amount of Mg^{2+} was lower than that of Ca^{2+} (Figs. 11A-F).

Iron (Fe^{2+})

Soil solution Fe^{2+} concentration in continuously flooded water regime (CF) reached to a peak value 2 weeks after flooding and decreased to a nearly stable value (Fig. 12A). Drainage (D5 and D10) decreased the Fe^{2+} concentration of soil solution. Saturated water regime (CS) maintained a little lower Fe^{2+} in soil solution compared to the flooded

Magnesium (mg/l)

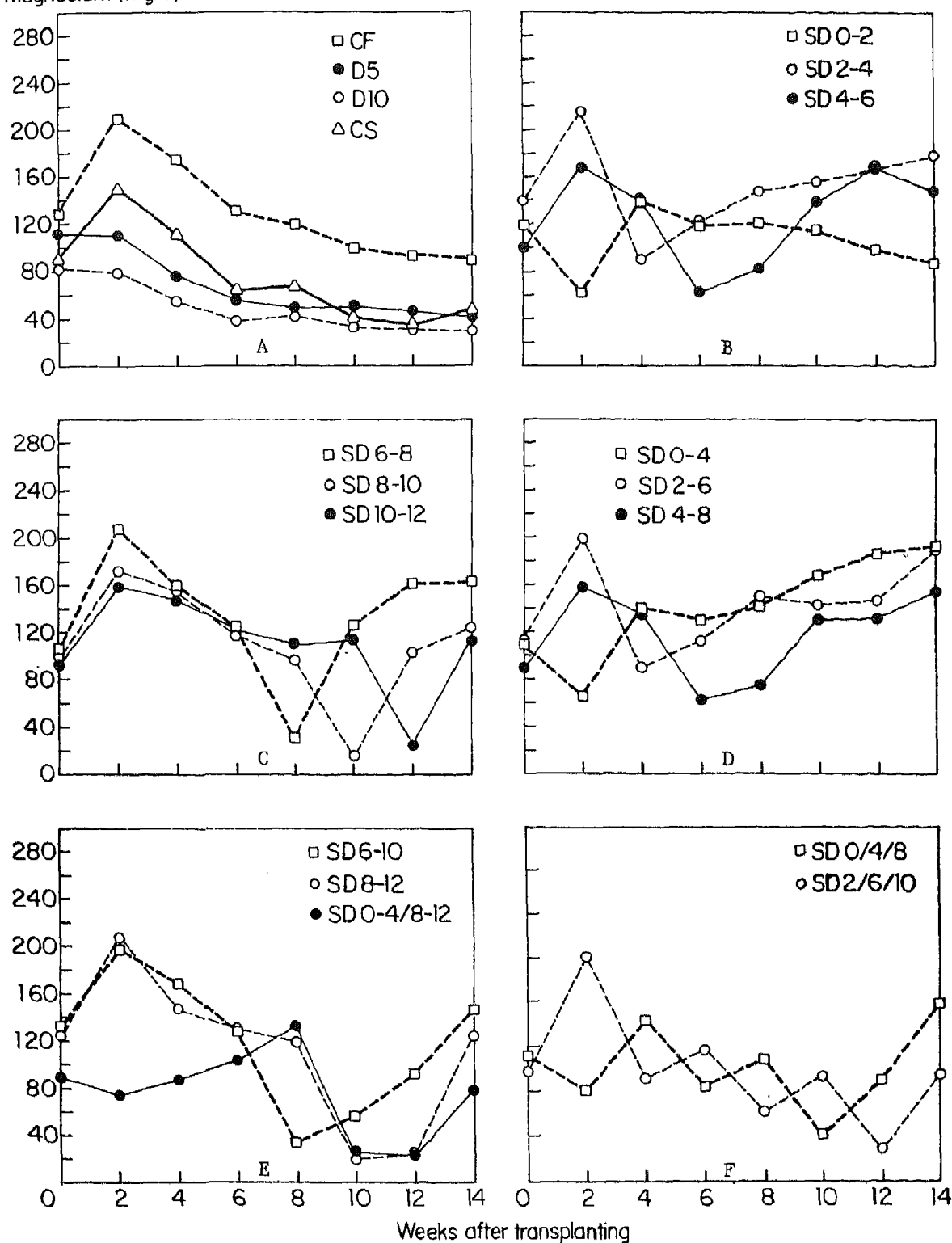


Fig. 11. Influence of eighteen water regimes on kinetics of water-soluble Mg in Maahas-1 soil.

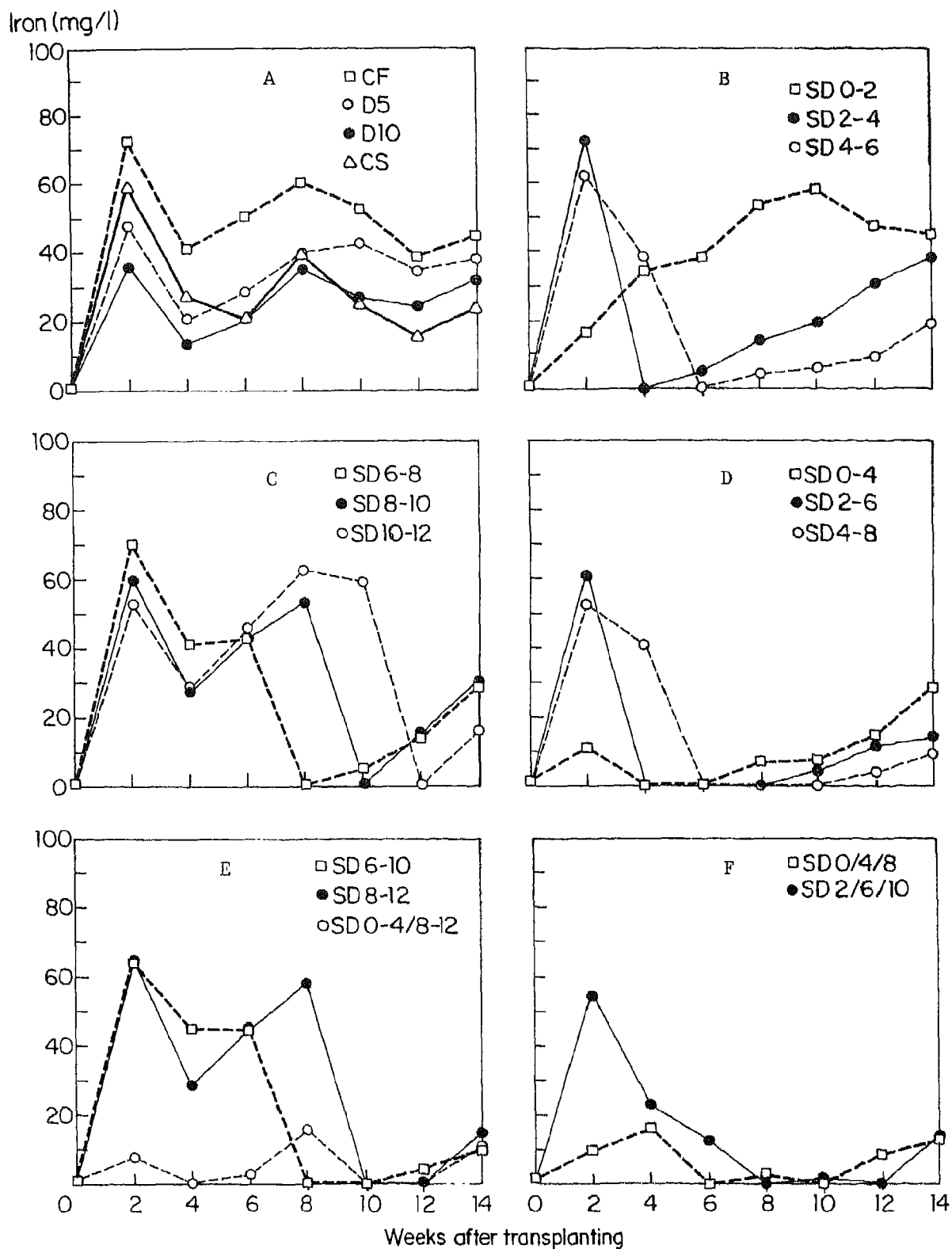


Fig. 12. Influence of eighteen water regimes on kinetics of water-soluble Fe in Maahas-1 soil.

one. Soil drying decreased the soil solution Fe^{2+} concentration to negligible value and on reflooding Fe^{2+} increased but only slowly (Figs. 12B-F).

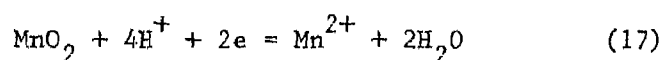
The initial increase in soil solution Fe^{2+} on flooding was due to reduction of Fe(III) to Fe(II) (Gotoh and Patrick, 1974; Ponnamperuma, 1972; 1985, Schwab and Lindsay, 1983) and the subsequent decrease in this soil was probably due to precipitation of FeCO_3 (Schwab and Lindsay, 1983). The decrease in soil solution Fe^{2+} due to soil drying was due to reoxidation of Fe(II) to Fe(III) hydroxide.

Manganese (Mn^{2+})

In continuously flooded water regime (CF) Mn^{2+} concentration of the soil solution increased sharply on flooding and reached a peak value 2 weeks after flooding (Fig. 13A) and decreased to a stable value 8 weeks after flooding. Drained flooded (D5 and D10) water regime followed the same trend but drained soils maintained little higher Mn^{2+} in soil solution from 6 weeks after flooding. Continuously saturated (CS) water regime also followed the same pattern but with higher concentration from 6 weeks after flooding.

Soil drying for 2 to 4 weeks decreased the soil solution Mn^{2+} concentration to very negligible value but reflooding sharply increased it to values as high as 35 ppm (Figs. 13B-F).

The increase in soil solution Mn^{2+} on flooding was due to reduction of Mn(IV) to Mn(II) (Ponnamperuma, 1972; 1985)



Manganese (mg/l)

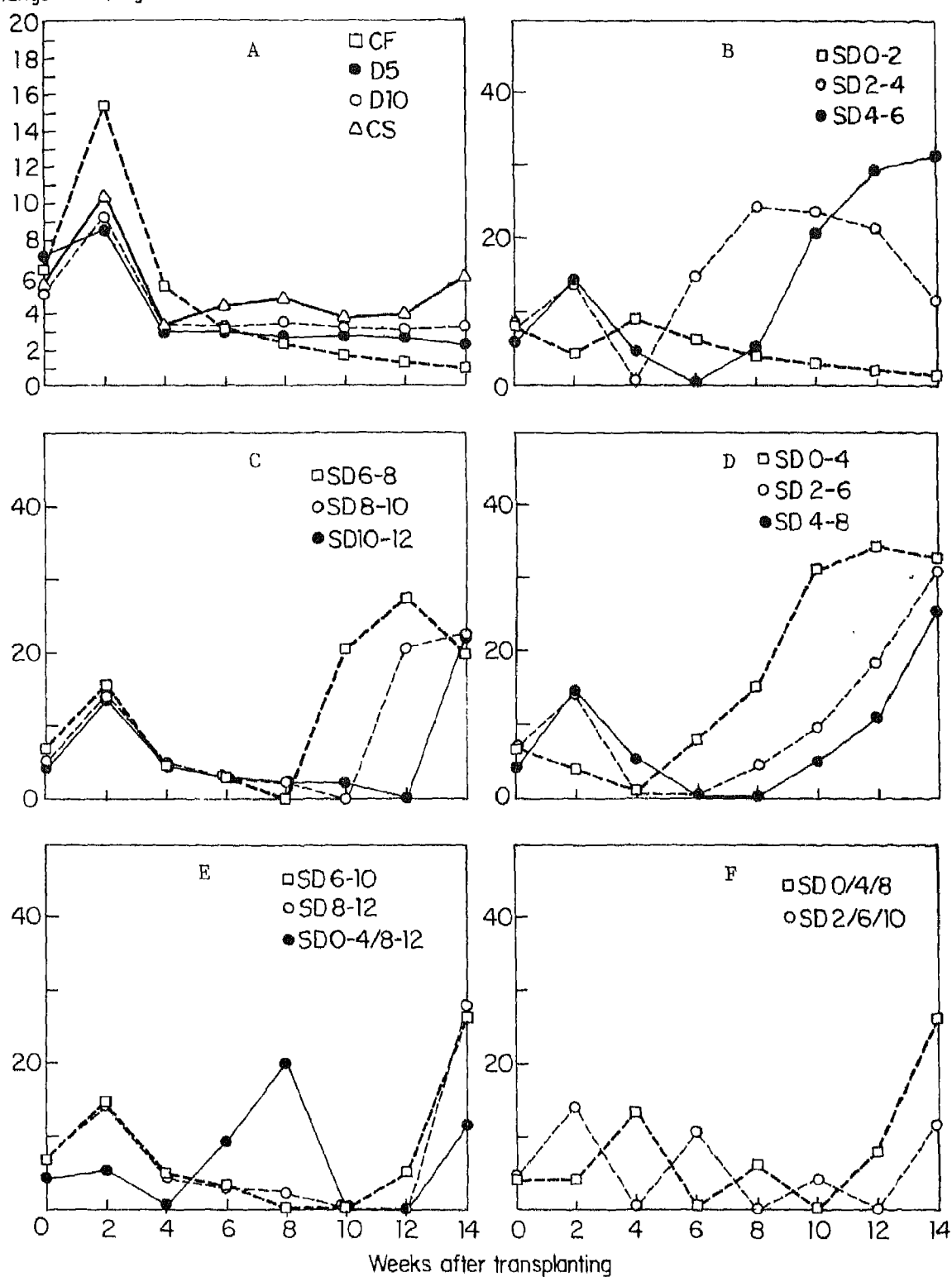


Fig. 13. Influence of eighteen water regimes on kinetics of water-soluble Mn in Maahas-1 soil.

while the decrease thereafter was due to precipitation of Mn as MnCO_3 or Mn oxides (Ponnamperuma, 1972; 1985; Schwab and Lindsay, 1983).

Decrease in soil solution Mn^{2+} on soil drying was due to oxidation of Mn(II) to Mn(IV). The increase in Mn^{2+} concentration in soil solution on reflooding dry soil could be due to reduction of precipitated Mn(IV) on reflooding. Saturated water regime (CS) maintained little higher Mn^{2+} concentration than the CF probably due to its lower CO_2 status which precipitated less Mn as MnCO_3 .

Zinc (Zn^{2+})

In continuously flooded water regime (CF) Zn^{2+} concentration of the soil solution decreased with time (Fig. 14A). However, a small increase in Zn^{2+} concentration started from 10 weeks after transplanting. Soil solution Zn^{2+} concentration fluctuated with soil drying and reflooding -- decreased during the dry periods and increased on reflooding (Figs. 14B-F).

The decrease in soil solution Zn^{2+} with flooding could be due to the formation of sulfides, carbonates and hydroxides and its reaction with soluble silica (Randhawa et al., 1978; Sinha et al., 1975; Sajwan and Lindsay, 1986). Similarly, increase in Zn^{2+} concentration of soil solution after reflooding the dry soil could be due to decrease in CO_2 and soluble silica.

Zinc (mg/L)

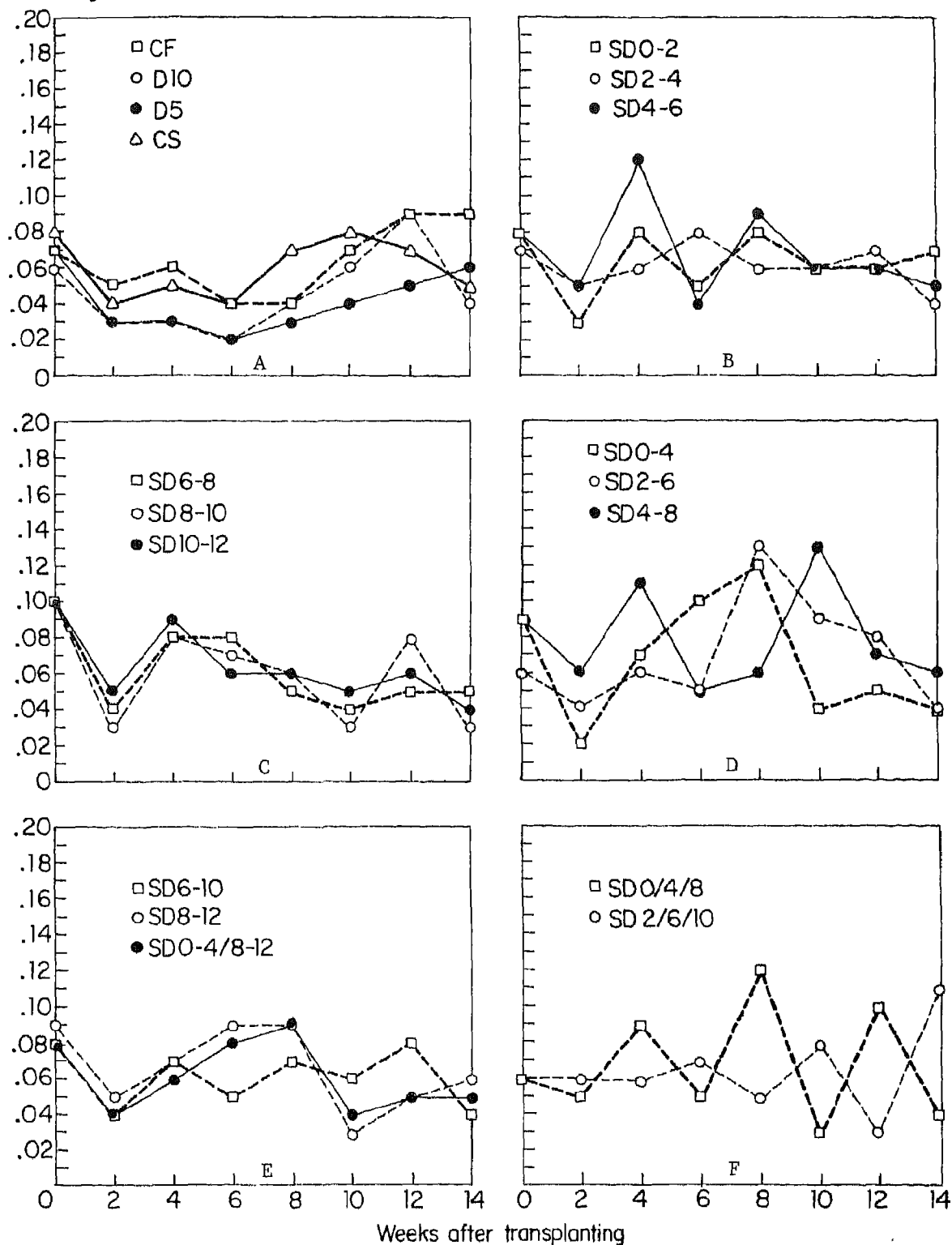


Fig. 14. Influence of eighteen water regimes on kinetics of water-soluble Zn in Maahas-1 soil.

Silicon (Si)

In continuously flooded water regime (CF) the Si concentration of the soil solution increased with time, came to a broad peak between 4 and 8 weeks after transplanting and declined thereafter (Fig. 15A). Saturated water regime (CS) followed the same pattern but with slightly lower values. Drainage of 5-10 mm/day (D5 and D10) did not deviate the trend from non drained flooded water regime (CF). Soil drying for 2 to 4 weeks decreased soil solution Si concentration (Fig. 15B-F) while reflooding increased it.

The increase in soil solution Si was due to release of occluded Si by reduction of iron oxides (Ponnamperuma, 1965; 1972). Similarly, on soil drying the decrease in soil solution Si could be due to the reversal of the situations in flooded conditions.

To summarize, the study of the soil solution kinetics in this soil showed that compared to that under continuously flooded water regime in alternately dried and reflooded water regimes:

- i. availability of nitrogen was lower
- ii. solubility of P decreased due to soil drying and reflooding
did not improve it
- iii. availability of Fe and Si was lower during the dry spells and
this was not improved by reflooding.
- iv. K, Ca, Mg and Zn solubility was lower during the dry spells
but reflooding improved their availability
- v. Mn concentration was almost undetectable during dry spells but
on reflooding there was big flush of Mn.

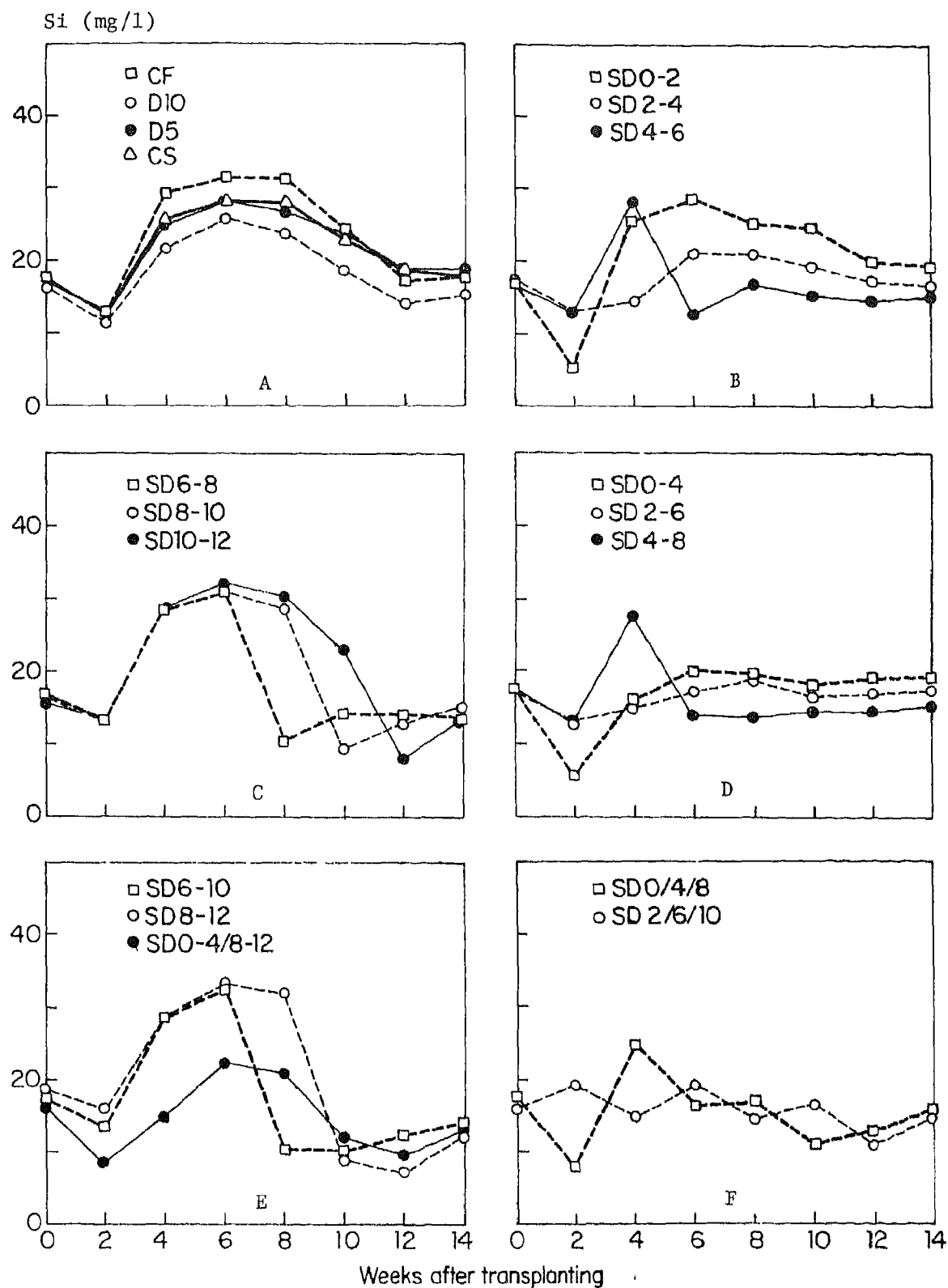


Fig. 15. Influence of eighteen water regimes on kinetics of water-soluble Si in Maahas-1 soil.

The availability of different nutrients were not affected by drainage in flooded soils. Continuously saturated water regime maintained comparable nutritional environment as the continuously flooded water regime.

Mineral Nutrition of Rice

Concentrations of mineral nutrients in 8 week-old rice shoots and mature straw are presented in Tables 3 and 5. As the dry matter yields were highest under continuously flooded (CF) among the different water regime treatments, the nutrient concentrations may not reflect the true picture of mineral nutrition due to the dilution effect. Therefore, total uptake of nutrients by shoots and by grain plus straw at harvest were also computed and are presented in Tables 4 and 6. These results are discussed in the following pages.

Nitrogen

Soil drying and reflooding in the early vegetative growth stages did not affect the N concentration of the shoot (Table 3), but soil drying for 2 to 4 weeks between 4 and 10 weeks after transplanting significantly increased the N concentration of mature straw (Table 5). The lower concentration of N in mature straw was not because of lower N availability in flooded soil but because of dilution of N in higher total dry matter yield. Drainage (D5 and D10) did not affect the N concentration of straw in flooded soil. Rice straw on continuously saturated soil (CS) had N concentration comparable to the flooded water regime.

Table 3. Influence of eighteen water regimes on the mineral nutrient concentration in 8 week-old rice (IR54) shoots in Maahas-1 soil.

Treatments	N	P	K	Ca	Mg	SiO ₂	Fe	Mn	Zn	Cu
	ppm									
	%									
CF	3.40	0.283 A	5.00 FG	0.158 EF	0.281 A-C	11.5 B-E	287	298 DE	24.8 FG	40.8 BC
D10	3.37	0.260 AB	5.00 FG	0.171 R-F	0.269 A-D	12.5 A-C	260	402 DE	25.5 E-G	45.3 BC
D5	3.15	0.269 A	4.91 FG	0.164 D-F	0.261 A-D	12.8 A	237	395 DE	26.7 E-G	41.8 BC
CS	3.19	0.187 C	4.92 FG	0.157 F	0.240 C-E	12.6 AB	230	275 E	32.7 DE	52.0 BC
SD 0-2	3.20	0.225 B	5.04 E-G	0.183 B-F	0.236 DE	11.9 A-D	268	558 C	32.0 D-F	46.3 BC
SD 2-4	2.88	0.133 DE	5.62 A-D	0.169 C-F	0.206 E	9.8 FG	198	770 B	63.3 A	77.0 A
SD 4-6	3.28	0.133 DE	5.50 B-E	0.198 B-D	0.260 A-D	9.1 G	200	447 CD	58.3 A-C	82.2 A
SD 6-8	3.15	0.145 D	5.83 A-C	0.193 B-E	0.277 A-D	9.4 G	228	323 DE	36.3 D	43.2 BC
SD 8-10	2.98	0.255 AB	5.00 FG	0.167 C-F	0.273 A-D	11.4 C-E	245	267 E	23.3 G	43.3 BC
SD 10-12	2.88	0.245 AB	4.79 G	0.171 B-F	0.261 A-D	11.3 DE	203	257 E	26.7 E-G	39.7 C
SD 0-4	3.10	0.163 CD	5.37 C-F	0.187 B-F	0.248 B-D	9.8 FG	218	810 AB	55.2 BC	87.5 A
SD 2-6	2.97	0.139 DE	5.33 D-F	0.202 BC	0.261 A-D	10.1 FG	237	352 DE	60.8 AB	84.0 A
SD 4-8	3.13	0.104 E	5.04 E-G	0.235 A	0.290 AB	9.3 G	215	280 E	55.8 A-C	54.2 B
SD 6-10	3.22	0.153 CD	5.91 AB	0.193 B-E	0.294 A	10.0 FG	250	327 DE	34.8 D	43.3 BC
SD 8-12	3.15	0.281 A	5.29 D-F	0.158 EF	0.290 AB	11.7 A-E	272	292 E	24.2 FG	43.8 BC
SD 0-4/8-12	2.92	0.163 CD	6.00 A	0.176 B-F	0.261 A-D	10.6 EF	240	928 A	56.7 A-C	86.8 A
SD 0/4/8	3.27	0.144 D	5.54 A-D	0.181 E-F	0.256 A-D	10.1 FG	240	393 DE	51.8 C	83.3 A
SD 2/6/10	3.32	0.134 DE	5.37 C-F	0.205 AB	0.290 AB	10.6 EF	217	348 DE	54.8 BC	79.8 A
LSD (0.01)	ns	0.048	0.59	0.040	0.051	1.3	ns	174	9.5	16.3
LSD (0.05)	ns	0.035	0.44	0.030	0.038	1.0	ns	130	7.1	12.1

*In a column, treatment means having common letter are not significantly different by DMRT at alpha 5%.

Table 4. Influence of eighteen water regimes on the total uptake of mineral nutrients by 8-week-old rice (IR54) shoots in Maahas-1 soil.

Treatments	N	P	K	Ca	Mg mg/pot	Fe	Mn	Zn	Cu	SiO ₂ g/pot
CF	967 A-C	81.5 AB	1442 AB	45.3 AB	80.5 AB	8.23 A	8.73 B-D	0.71 BC	1.16 A-E	3.33 B
D10	929 A-C	72.3 BC	1371 AB	47.5 A	74.4 A-C	7.14 AB	11.10 A-C	0.70 BC	1.25 A-D	3.45 B
D5	1104 A	94.2 A	1719 A	57.6 A	91.2 A	8.34 A	13.62 A	0.92 AB	1.46 AB	4.47 A
CS	856 A-C	50.8 DE	1323 AB	42.0 AB	64.5 BC	6.13 A-C	7.28 C-E	0.86 AB	1.37 AB	3.38 B
SD 0-2	819 A-C	57.8 CD	1292 AB	46.8 AB	60.4 BC	6.90 AB	14.24 A	0.82 AB	1.19 A-D	3.05 B-D
SD 2-4	392 D	18.1 F-H	765 CD	23.0 C	28.0 E	2.72 E	10.24 A-C	0.87 AB	1.05 B-E	1.34 F-H
SD 4-6	682 C	27.0 F-H	1120 BC	41.2 AB	53.5 CD	4.09 C-E	8.92 B-D	1.18 A	1.70 A	1.78 E-G
SD 6-8	796 BC	36.7 EF	1472 AB	48.8 A	70.0 A-C	5.75 A-C	8.16 B-D	0.92 AB	1.08 B-E	2.37 C-E
SD 8-10	988 AB	84.6 AB	1657 A	55.4 A	90.4 A	8.19 A	8.91 B-D	0.77 BC	1.44 AB	3.80 AB
SD 10-12	937 A-C	78.8 AB	1546 AB	55.7 A	84.5 AB	6.35 A-C	8.46 B-D	0.87 AB	1.29 A-C	3.67 AB
SD 0-4	314 D	16.5 F-H	544 D	19.0 C	25.3 E	2.21 E	8.11 E-D	0.55 BC	0.89 B-E	0.99 GH
SD 2-6	211 D	9.9 H	383 D	14.3 C	18.4 E	1.68 E	2.35 F	0.43 C	0.60 E	0.71 H
SD 4-8	398 D	13.4 GH	649 D	30.0 BC	37.4 DE	2.72 E	3.65 EF	0.72 BC	0.70 DE	1.19 GH
SD 6-10	706 BC	33.4 E-G	1295 AB	42.3	64.6 BC	5.45 B-D	7.16 C-E	0.76 BC	0.95 B-E	2.19 D-F
SD 8-12	831 A-C	73.9 BC	1418 AB	41.6 AB	76.9 A-C	7.01 AB	7.99 B-D	0.65 BC	1.15 A-E	3.11 BC
SD 0-4/8-12	370 D	20.7 F-H	757 CD	22.3 C	32.9 DE	3.21 DE	11.84 AB	0.71 BC	1.05 B-E	1.37 F-H
SD 0/4/8	396 D	17.4 F-H	674 D	22.0 C	31.1 DE	2.90 E	4.75 D-F	0.63 BC	1.02 B-E	1.22 GH
SD 2/6/10	326 D	13.0 H	518 D	19.9 C	28.0 E	2.02 E	3.32 E-F	0.54 BC	0.76 C-E	1.02 GH
LSD (0.01)	335	23.8	538	20.2	28.9	3.06	4.87	0.44	0.66	1.12
LSD (0.05)	249	17.7	400	15.0	21.5	2.28	3.63	0.33	0.49	0.83

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 5. Influence of eighteen water regimes on the mineral nutrient concentration in rice (IR54) straw at maturity in Maahas-1 soil.

Treatments	N	P	K	Ca %	Mg	SiO ₂	Fe	Mn	Zn ppm	Cu
CF	0.76 C	0.068	4.05	0.237	0.397 A	18.4	287	486 DE	28.5 F	19.2 E
D10	0.80 C	0.084	4.61	0.234	0.356 AB	20.1	260	594 C-E	32.7 EF	20.2 E
D5	0.73 C	0.085	3.92	0.226	0.314 BC	18.1	257	666 CD	40.2 B-F	20.3 E
CS	0.84 BC	0.058	4.26	0.257	0.304 B-D	21.4	230	320 E	37.5 C-F	23.8 C-E
SD 0-2	0.86 BC	0.077	4.15	0.274	0.284 CD	20.5	268	811 A-C	36.3 D-F	21.7 DE
SD 2-4	1.10 A-C	0.074	4.88	0.276	0.278 CD	21.3	198	1013 A	38.2 C-F	23.3 C-E
SD 4-6	1.37 A	0.100	4.55	0.266	0.278 CD	19.3	200	327 A-C	55.3 A-D	27.2 A-E
SD 6-8	1.37 A	0.077	4.54	0.258	0.273 CD	20.4	228	827 A-C	44.3 B-F	24.2 C-E
SD 8-10	0.94 BC	0.054	4.59	0.285	0.263 CD	20.6	215	801 A-C	45.0 B-F	25.3 B-E
SD 10-12	0.75 C	0.077	5.15	0.355	0.263 CD	25.5	203	1054 A	56.7 A-D	31.5 A-C
SD 0-4	0.94 BC	0.070	4.35	0.243	0.253 C-E	19.8	218	976 AB	37.7 C-F	25.5 B-E
SD 2-6	1.00 A-C	0.073	4.83	0.280	0.253 C-E	20.3	237	1013 A	62.0 AB	34.3 AB
SD 4-8	1.24 AB	0.111	4.27	0.260	0.252 C-E	17.3	215	858 A-C	68.2 A	35.3 A
SD 6-10	1.24 AB	0.068	4.27	0.251	0.247 C-E	18.3	250	635 CD	59.3 A-C	26.8 A-E
SD 8-12	1.03 A-C	0.063	4.45	0.304		21.1	272	501 DE	58.0 A-D	26.7 A-E
SD 0-4/8-12	1.04 A-C	0.061	4.50	0.272	0.242 DE	21.5	240	449 DE	52.7 A-E	28.3 A-E
SD 0/4/8	1.13 A-C	0.078	4.25	0.292	0.237 DE	21.0	240	713 R-D	59.0 A-C	30.5 A-D
SD 2/6/10	1.12 A-C	0.078	4.58	0.279	0.185 E	20.7	217	522 DE	70.8 A	35.0 A
LSD (0.01)	0.47	ns	ns	ns	0.081	ns	ns	330	25.3	10.5
LSD (0.05)	0.35	ns	ns	ns	0.061	ns	ns	246	18.9	7.8

*In a column treatment means having common letter are not significantly different by DMRT at alpha 5%.

Table 6. Influence of eighteen water regimes on the total uptake of mineral nutrients by rice (IR54) grain plus straw at harvest in Maahas-1 soil.

Treatments	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu	SiO ₂ g/pot
	mg/pot									
CF	2.34 A	0.28 A	4.49 B	0.25 BC	0.40 B	58.3 A-D	51.8 B-D	5.63 B-E	6.40 BC	21.9 B-D
D10	1.89 A-E	0.28 A	4.34 B	0.22 B-D	0.32 B-D	68.1 A-C	54.2 B-D	5.47 B-E	5.84 B-D	21.1 B-D
D5	2.02 A-D	0.31 A	4.42 B	0.25 B-C	0.38 B	44.4 C-F	75.0 BC	7.24 BC	6.84 B	23.4 BC
CS	2.11 A-C	0.22 BC	4.49 B	0.27 B	0.35 B-C	52.2 B-E	34.3 CD	6.40 B-D	6.31 BC	24.9 B
SD 0-2	2.24 AB	0.30 A	4.20 B	0.27 B	0.41 B	82.3 A	78.0 B	6.03 B-E	6.55 BC	22.0 B-D
SD 2-4	1.88 A-E	0.20 CD	3.47 BC	0.19 B-D	0.24 C-E	28.8 D-G	70.0 BC	4.85 B-E	4.43 C-G	17.2 B-F
SD 4-6	1.68 C-E	0.15 D-G	2.87 B-D	0.16 B-D	0.19 EF	23.9 E-G	50.4 B-D	4.93 B-E	3.95 D-G	13.9 C-F
SD 6-8	2.18 A-C	0.18 C-F	3.64 BC	0.20 B-D	0.25 C-E	56.8 A-D	65.0 B-D	5.50 B-E	4.90 B-G	18.3 B-E
SD 8-10	1.77 B-E	0.17 C-F	3.60 BC	0.21 B-D	0.26 C-E	41.4 C-G	58.7 B-D	5.38 B-E	5.34 B-F	18.2 B-E
SD 10-12	2.34 A	0.27 AB	6.70 A	0.45 A	0.58 A	80.8 AB	136.8 A	10.53 A	9.16 A	36.2 A
SD 0-4	1.00 H	0.12 F-H	2.00 CD	0.11 D	0.12 F	31.7 D-G	43.8 B-D	2.95 E	3.29 FG	10.5 EF
SD 2-6	0.86 H	0.08 H	1.72 D	0.10 D	0.12 F	17.0 FG	35.1 B-D	3.16 DE	2.73 G	8.1 F
SD 4-8	1.00 H	0.10 GH	1.99 CD	0.12 D	0.15 EF	11.9 G	38.4 B-D	4.04 C-E	2.84 G	9.3 EF
SD 6-10	1.57 D-F	0.13 E-H	3.33 B-D	0.19 B-D	0.23 DF	39.3 C-G	50.4 B-D	6.06 B-E	4.26 C-G	15.8 B-F
SD 8-12	2.15 A-C	0.18 C-E	4.39 B	0.28 B	0.39 B	51.5 B-E	47.2 B-D	7.60 B	5.68 B-E	21.7 B-D
SD 0-4/8-12	1.19 F-H	0.11 GH	2.48 CD	0.14 CD	0.19 EF	38.9 C-G	24.8 D	4.28 C-E	3.57 D-G	12.4 D-F
SD 0/4/8	1.51 E-G	0.14 E-G	2.93 B-D	0.20 B-D	0.23 D-F	40.7 C-G	49.4 B-D	5.51 B-E	4.47 C-G	15.5 B-F
SD 2/6/10	1.08 GH	0.11 GH	2.12 CD	0.12 D	0.17 EF	29.3 D-G	23.7 D	4.40 B-E	3.47 E-G	10.4 EF
LSD (0.01)	0.59	0.07	1.91	0.15	0.14	35.2	48.8	3.66	2.72	11.3
LSD (0.05)	0.44	0.05	1.42	0.11	0.11	26.2	36.3	2.73	2.03	8.4

*In a column treatment means having common letter are not significantly different by DMRT at alpha 5%.

Soil drying for 2 to 4 weeks decreased the total N uptake by shoot (Table 4) as well as by straw and grain at harvest (Table 6). Lower N availability in soil has contributed significantly to the lower dry matter production and ultimately the total N uptake at vegetative as well as at reproductive stages.

Phosphorus

While the P concentration of rice shoot decreased due to soil drying and reflooding (Table 3) that of rice straw at maturity was not affected (Table 5). Soil drying and reflooding for 2 to 4 weeks decreased also the total P uptake by rice shoot (Table 4) and by grain plus straw at harvest (Table 6). Drainage in flooded soil did not influence the P nutrition of rice. The same effect of drainage was observed in the soil solution P concentration. The P concentration and P uptake at maturity under continuously saturated condition were significantly lower compared to those in flooded soil. It can be recalled here that the P concentrations in soil solution in continuously saturated (CS) and flooded and dried water regimes were also lower than that in continuously flooded water regime (Fig. 8).

Potassium

Potassium concentration of shoot increased due to soil drying and reflooding (Table 3) while that of straw was not affected (Table 5). This could be explained by the fact that soil solution K^+ concentration also increased due to soil drying and reflooding (Fig. 9). However, total K uptake by rice shoots (Table 4) as well as by grains plus straw

at maturity (Table 6) were significantly lower under alternate dried and reflooded conditions than under continuously flooded condition. This was again due to lower dry matter yield under alternately flooded and dried conditions compared to that under continuously flooded conditions (Table 7).

Calcium and magnesium

Soil drying for 2 to 4 weeks during the first 8 weeks after transplanting increased the Ca concentration of rice shoot while its Mg concentration was not affected (Table 3). While soil drying for 2 or 4 weeks at any stage between 0 and 12 weeks after transplanting decreased the Mg concentration of mature rice straw (Table 5) its Ca concentration was not affected but uptake of both Ca and Mg by rice shoots and by grains plus straw at harvest decreased (Tables 4, 6) due to soil drying and reflooding. This difference in total uptake of Ca and Mg was due to higher dry matter production under flooded condition than in other water regimes (Table 7).

Iron

Total Fe concentration of shoot as well as mature straw were not affected by soil drying and reflooding (Tables 3, 5), but 4 weeks soil drying and reflooding between 2 and 8 weeks after transplanting decreased Fe uptake by rice shoots (Table 4) as well as straw plus grains at maturity (Table 6).

Table 7. Influence of eighteen water regimes on yield of rice (IR54) grown in Maahas-1 soil.

	Dry matter yield of 8-week-old shoots	Grain yield (g/pot)	ΔGY (%)	Straw yield (g/pot)
CF	28.7 A-C	92.1 A	-	94.8 A-D
D10	27.5 A-D	78.3 A-C	-15.0	82.5 B-E
D5	35.0 A	82.9 AB	-10.0	101.2 AB
CS	26.8 A-D	74.3 A-C	-19.3	95.9 A-C
SD 0-2	25.6 B-D	85.2 A	-7.5	88.4 B-D
SD 2-4	13.6 EF	59.3 C-E	-35.6	62.9 E-G
SD 4-6	20.2 DE	40.4 E-H	-56.1	56.2 F-H
SD 6-8	25.3 B-D	52.5 D-F	-43.0	73.2 C-F
SD 8-10	33.2 AB	58.8 C-E	-36.1	70.1 D-F
SD 10-12	32.7 AB	85.4 A	-7.3	115.4 A
SD 0-4	10.1 F	36.4 F-H	-60.5	41.7 GF
SD 2-6	7.1 F	27.4 G-H	-70.2	32.1 H
SD 4-8	12.8 EF	22.3 H	-75.8	44.2 GH
SD 6-10	21.9 CD	36.4 F-H	-60.5	72.6 C-F
SD 8-12	26.8 A-D	62.9 B-D	-31.7	87.2 B-E
SD 0-4/8-12	12.7 EF	34.0 F-H	-63.1	49.7 F-H
SD 0/4/8	12.1 EF	44.9 D-G	-51.2	62.7 E-G
SD 2/6/10	9.7 F	32.0 F-H	-62.2	42.0 GH
LSD (0.01)	9.9	25.5		29.1
LSD (0.05)	7.4	19.0		21.7

$$\Delta \text{GY} \quad (\%) = \frac{[\text{Grain yield in a treatment} - \text{Grain yield in CF}]}{[\text{Grain yield in CF}]} \times 100$$

*In a column, treatment means having common letter are not significantly different by DMRT at alpha 5%.

One interesting point that emerges from the comparison of the Fe^{2+} concentration in soil solution and Fe concentration in plant tissue is that, in spite of the very low soil solution Fe^{2+} concentration under alternately flooded and dried soils (Fig. 12), the plants grown under that condition did not have significantly lower total iron concentration in plant tissues as compared to those under continuously flooded soils. This demonstrates the special capacity of the rice plants for regulating Fe-nutrition.

Manganese

Manganese concentration of shoot and mature rice straw (Tables 3, 5) increased on soil drying and reflooding, but Mn uptake by the crop was not affected (Tables 4 and 6). The concentration of Mn in plant tissues increased under soil drying and reflooding because of increased Mn availability under these conditions as was seen in the Mn^{2+} kinetics of soil solution (Fig. 13). The total Mn uptake did not increase because of corresponding decrease in dry matter yield due to soil drying and reflooding (Table 7).

Zinc and copper

Soil drying and reflooding increased the Zn and Cu concentration of rice shoot (Table 3) and of mature rice straw (Table 5), but the opposite was true in case of uptake of these elements at harvest (Tables 4 and 6).

Silica

Soil drying and reflooding during the vegetative growth stage decreased the SiO_2 concentration (Table 3) of rice plant, while the SiO_2 concentration of mature straw was not affected (Table 5). Soil drying for 2 to 4 weeks and reflooding decreased the total SiO_2 uptake by shoot (Table 4). Four weeks soil drying and reflooding and three cycles of soil drying and reflooding during the vegetative growth stage decreased the SiO_2 uptake by the rice crop at harvest but 2 weeks soil drying had no effect on SiO_2 uptake by rice at harvest (Table 6).

Relationship Between Soil Solution Nutrient Kinetics and Mineral Nutrition of Rice

Comparison of the chemical kinetics of the experimental soil and mineral nutrient concentration and their uptake by rice plants under different water regimes revealed:

- Lower availability of N, P, K, Ca, Mg, Fe, Mn, Zn and Si during the dry spell.
- Lower availability of N, P, Fe and Si after reflooding
- Relatively higher availability of K, Ca, Mg, Zn and Cu after reflooding
- Higher availability of Mn after reflooding.
- Comparable Fe concentration in the tissues of rice grown under alternate flooded and dried conditions and continuously flooded condition, despite the very low concentration of water soluble Fe^{2+} in the soil under drying and reflooding treatments.

Growth and Yield of Rice (IR54)

Plant height

Height of IR54 at different stages under different water regimes are presented in Figures 16A-F. The figures show that although plants were tallest under continuously flooded condition, draining the flooded soil (D5 and D10) or keeping the soil saturated (CS) did not reduce plant height (Fig. 16A). Soil drying for 2 weeks and reflooding between 4 and 8 WAT (SD 4-6 and SD 6-8) resulted in shorter plants (Fig. 16B-C) but at other stages 2 weeks drying did not influence plant height. Soil drying for 4 weeks and reflooding from the day of transplanting to 6 WAT (SD0-4, SD2-6) decreased plant height (Fig. 16D-E) and cycles of soil drying and reflooding produced shorter plants (Fig. 16F).

Tillering

Changes in the number of tillers per hill upto 10 WAT were recorded and are presented in Figure 17A-F. The figures show that the number of tillers per hill under CF, D5, D10 and CS were comparable (Fig. 17A). Two weeks soil drying and reflooding from the day of transplanting to 8 WAT reduced number of tillers per hill (Fig. 17B-C). Four weeks soil drying from the day of transplanting to 6 WAT also decreased number of tillers (Fig. 17D-E). Cycles of soil drying and reflooding drastically reduced number of tillers per hill (Fig. 17E-F).

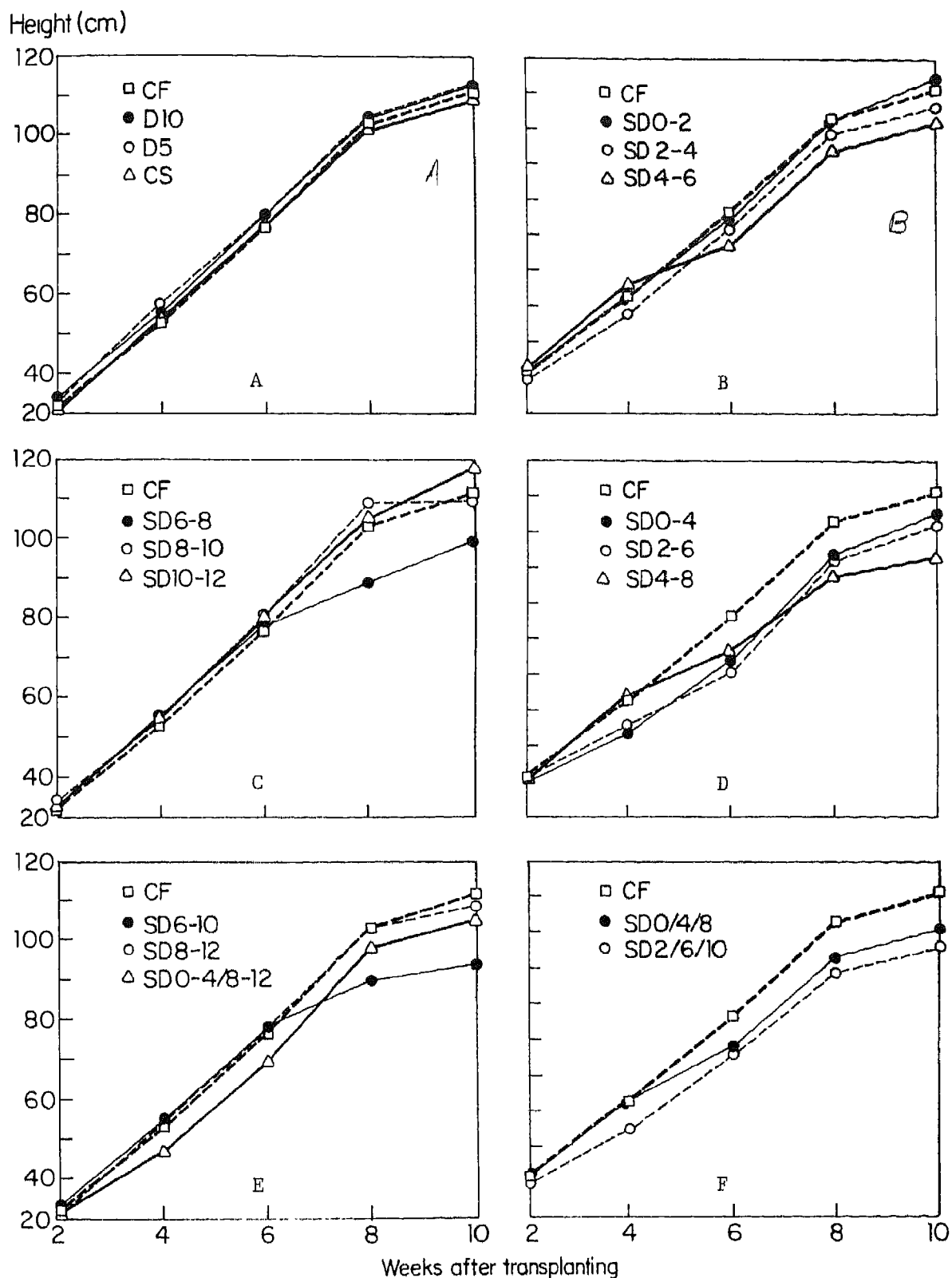


Fig. 16. Influence of eighteen water regimes on height of rice plants at different growth stages in Maahas-1 soil.

Tillers/hill

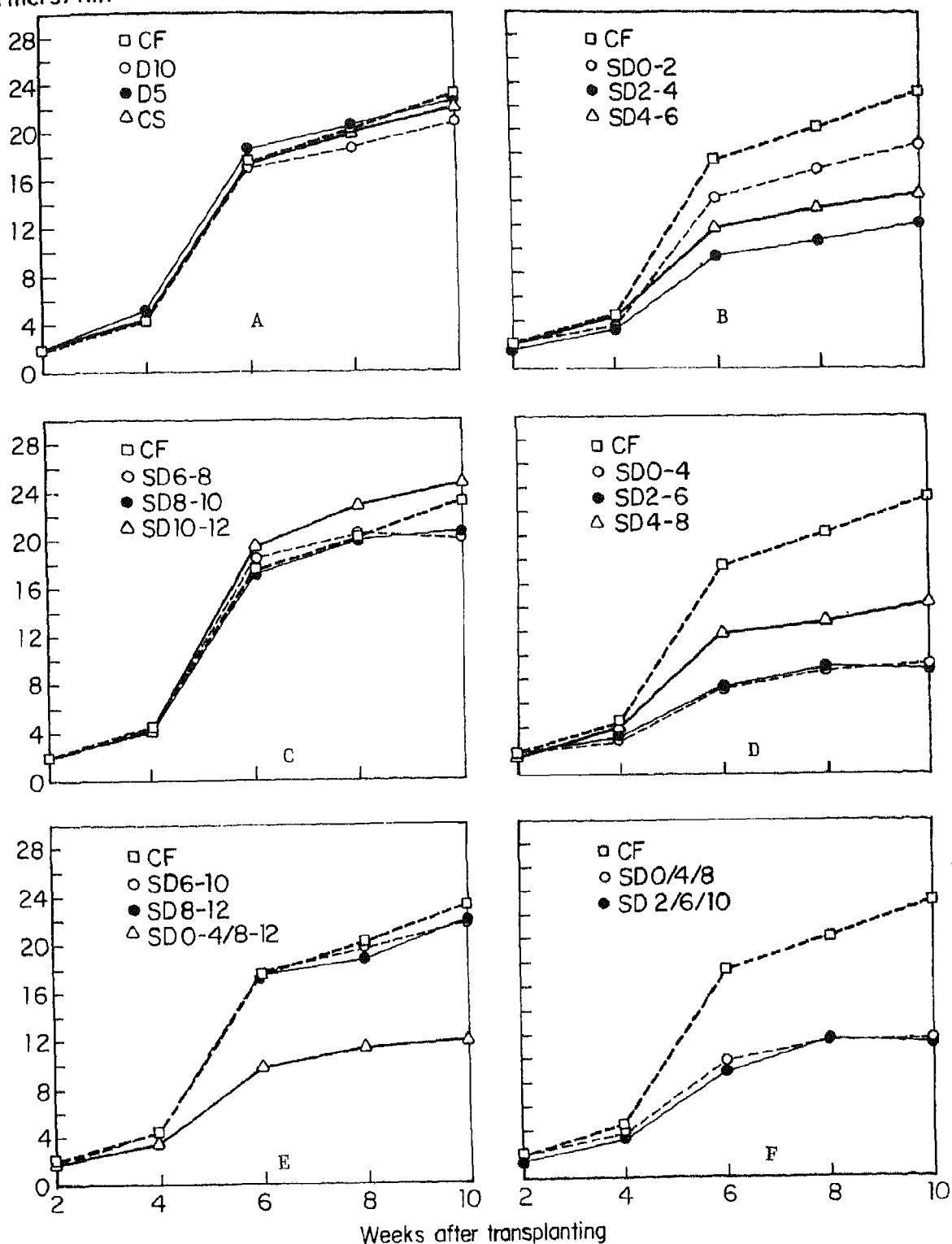


Fig. 17. Influence of eighteen water regimes on tillering of rice at different growth stages in Maahas-1 soil.

Visual symptoms

Best crop growth was observed under continuously flooded water regime (Plates 2,3). However, plant growth under drained flooded soil (D5 and D10) or saturated soil (CS) did not show any visual difference from that under flooded water regime. Soil drying and reflooding caused stunted growth with less number of tillers and plants showed mild nitrogen deficiency symptoms 6 weeks after transplanting (Plates 2,3).

Dry matter yield of 8 week-old shoot

Dry matter yield of 8 week-old rice shoot is presented in Table 7. Highest dry matter yield was obtained under continuously flooded water regime (Table 7). However, dry matter yield in D5, D10, CS and SD 0-2 were not significantly different from that under continuously flooded water regime. Soil drying for 2 to 4 weeks at any other stages significantly decreased dry matter yield of shoot.

Grain yield

Continuously flooded condition without drainage was found to be the best water management practice as this treatment produced the highest rice grain yield (Table 7). Drying the soil for 2 or 4 weeks or 3 cycles of drying and reflooding between 2 and 10 WAT reduced rice grain yield to different extents depending on the time and duration of drying. Drying for 4 weeks and reflooding at 4 WAT resulted in highest (75%) yield loss in this soil. Drainage of 5-10 mm/day in the flooded soil decreased rice grain yield by 10 and 15% respectively, but the difference was not statistically significant. Similarly, saturated

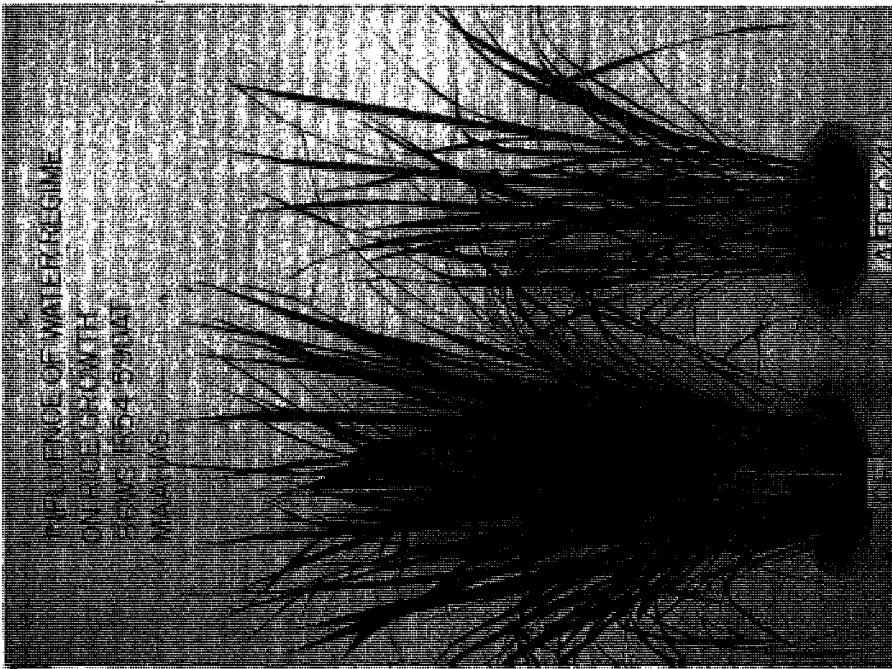


Plate 2. Influence of 4 weeks soil drying on rice (IR54) growth in Maahas-1 soil (AFD 0-4 is SD 0-4) in the text.

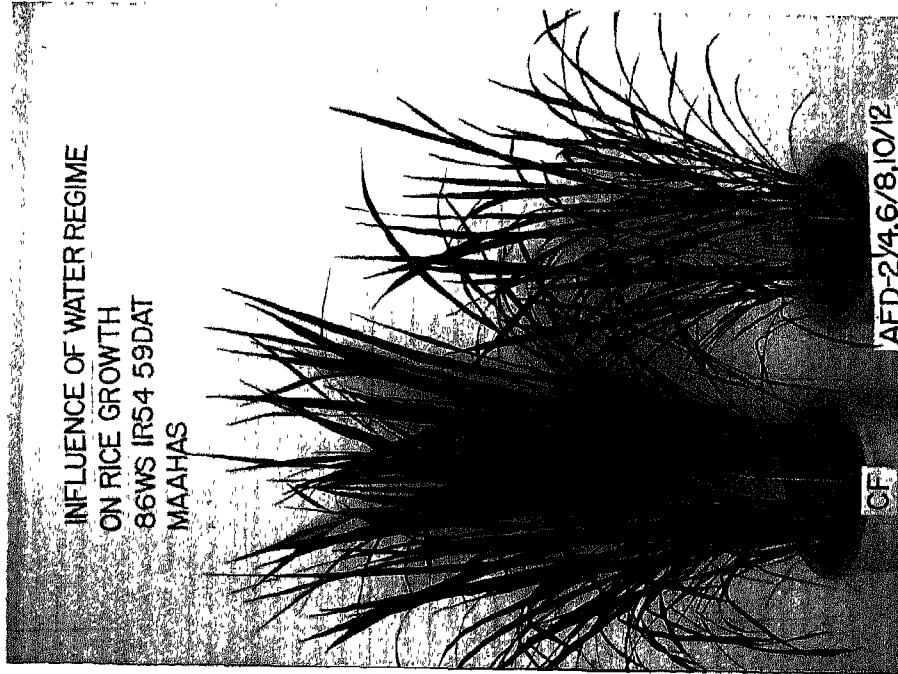


Plate 3. Influence of alternate soil drying and reflooding on rice (IR54) growth in Maahas-1 soil (AFD-2/4, 6/8, 10/12 is SD 2/6/10 in the text).

water regime produced 19% less grain yield compared to continuously flooded water regime. Drying the soil for 2 weeks in the beginning (SD 0-2) or at the later stage (10-12 WAT) decreased rice grain yield by about 7%.

Straw yield

Highest straw yield was obtained in continuously flooded water regime (Table 7). Drainage of 5-10 mm/day of the flooded soil did not decrease the straw yield. Similarly, continuously saturated water regime also produced comparable straw yield. Drying and reflooding for 2 or 4 weeks between 2 and 8 WAT reduced straw yield. Three cycles of drying for 2 weeks and reflooding and 2 cycles of drying for 4 weeks and reflooding also decreased rice straw yield.

Experiment 2

Influence of Nine Water Regimes on the Chemical Kinetics and
Rice Growth in an Acid Luisiana Soil

In Experiment 1, soil drying and reflooding at different rice growing stages was found to affect mineral nutrition of rice and decrease rice grain yield in a near neutral fertile Maahas soil. However, the chemical environment of problem soils differ from neutral fertile soils. Therefore, this experiment was conducted in the greenhouse to study the effect of nine water regimes on the chemical kinetics of an acid, potentially iron toxic Luisiana soil and growth and yield of rice (JR54).

MATERIALS AND METHODS

Soil

An acid Luisiana clay soil (Luisiana-1, Tropudult) was used in this experiment. Some characteristics of the soil are presented in Table 8.

Design

This experiment was laid out in randomized complete block design with three replications.

Treatments

i. Continuously flooded with 3-5 cm standing water	(CF)
ii. Continuously flooded with a drainage of 5 mm/day	(CF D5)
iii. Continuously flooded with a drainage of 10 mm/day	(CF D10)
iv. Continuously saturated	(CS)

- v. Soil drying for 2 weeks imposed 2 WAT and reflooding (SD 2-4)
- vi. Soil drying for 2 weeks each imposed 2 and 6 WAT and
reflooding (SD 2-4/6-8)
- vii. Soil drying for 2 weeks imposed 4 WAT and reflooding (SD 4-6)
- viii. Soil drying for 4 weeks imposed 4 WAT and reflooding (SD 4-8)
- ix. Soil drying for 2 weeks imposed 6 WAT and reflooding (SD 6-8)

Greenhouse procedure

Bulk soil samples were collected from field from the 0-20 cm depth, air-dried, crushed to 0.6 cm clods and mixed thoroughly.

Twelve kg soil was placed in 16-L glazed porcelain pots. In order to bring down the soil solution Fe^{2+} concentration below toxic levels this soil which was high in active iron and organic matter (Table 8) was kept flooded for 2 weeks before transplanting. Basal doses of N, P, and K at the rate of 100, 50 and 75 mg respectively per kg soil were applied to the soil in the form of urea, KH_2PO_4 and KCl on the day of transplanting. The soil solution was recycled three times for uniform mixing of the fertilizer elements with soil. The greenhouse set up and procedures were same as in experiment 1.

As the available Zn content of this soil was not in the deficient range, the seedlings were not given any "root dip" in 2% ZnO suspension.

Soil solution was collected from each pot at 0, 2, 4, 6, 8 and 10 weeks after transplanting of rice. Two plants were harvested at 8 WAT and the remaining two were grown to maturity and grain and straw yields recorded.

Table 8. Some characteristics of the soil (Luisiana-I)
soil used in experiment 2

pH (1:1)	4.8
Organic C (%)	2.20
Total N (%)	0.24
Total S (%)	0.07
Available	
N (mg/kg)	283.7
P (Olsen) (mg/kg)	2.1
S (mg/kg)	39.4
Zn (mg/kg)	2.64
Cu (mg/kg)	3.60
Exchangeable	
K (me/100 g)	0.38
Ca (me/100 g)	12.5
Mg (me/100 g)	6.2
Active	
Fe (%)	6.71
Mn (%)	0.04
Water soluble Si (mg/kg)	100.1
CEC (me/100 g)	41.4
Mechanical analysis	
Clay (%)	63
Silt (%)	35
Sand (%)	2
Textural class	Clay

Growth observation and yield data

The following growth parameters were determined:

- i. Plant height and tiller number at different stages
- ii. Dry matter yield of shoot at 8 WAT
- iii. Grain and straw yield

Analytical Procedures

1. Soil

The initial soil sample was analyzed for pH, organic C, total N and S; available N, P, S, Zn and Cu; water soluble Si; active Fe and Mn; exchangeable K, Ca and Mg; and particle size distribution following the methods described under experiment 1.

2. Soil solution

The pH, Eh, EC, NH_4^+ -N, P, K^+ , Ca^{2+} , Mg^{2+} , Fe^{2+} , Mn^{2+} , Zn^{2+} and Si(OH)_4 content of the soil solution samples were analyzed following the methods described in experiment 1. In this experiment the soil solution samples were also analyzed for oxidizable matter, and HCO_3^- as follows:

- a. Oxidizable matter was determined by treatment with KMnO_4 under standard conditions (Ponnamperuma, 1955).
- b. HCO_3^- was determined by titrating with H_2SO_4 and NaOH (DiLallo and Albertson method 1961; IRRI, 1969).

The partial pressure of CO_2 ($^p\text{CO}_2$) was computed from HCO_3^- , pH and EC values using the relation,

$$P_{CO_2} = (H^+)(HCO_3^-) \times 10^{7.85}$$

where P_{CO_2} is the partial pressure of CO_2 in atmosphere, (H^+) is the activity of H^+ ions derived from pH, and (HCO_3^-) is the activity of bicarbonate. The activity coefficient of bicarbonate was determined using ionic strength derived from EC, in Debye-Huckel equation (Ponnamperuma et al., 1966).

3. Plant samples

Shoot, straw and grain samples were analyzed for total N, P, K, Ca, Mg, Fe, Mn, Zn, Cu and crude silica by the methods described in experiment 1.

Calculations

Total uptake of nutrients by shoot and grain plus straw at harvest were calculated using formulae described in experiment 1. All the statistical analyses were performed using an IBM PC XT microcomputer with the help of standard statistical programmes.

RESULTS AND DISCUSSION

Chemical Kinetics of Soil Solution

On the sampling dates soil solutions were collected from the three replications of each treatment and analyzed. The results presented graphically in the following pages are the mean of the three replications.

pH

As the soil was flooded for 2 weeks before transplanting, the soil solution pH on the day of transplanting had already risen to about 6.7 (Fig. 18). The pH increased to around 6.8 within the next 4 weeks and remained stable at that value. Continuously saturated water regime (CS) maintained comparatively lower pH compared to continuously flooded water regime (CS). This was due to difficulty in maintaining saturation at the later growth stages when water demand was high.

Soil drying for 2 or 4 weeks depressed the pH and reflooding started to raise it again but not to the level of that in the flooded water regime (Fig. 18B,C). The increase in pH on flooding is due to reduction of Fe(III) to Fe(II) with release of OH^- (Ponnamperuma, 1972; 1985) while the decrease in pH on soil drying could have been due to oxidation of Fe(II) to Fe(III) and oxidation of NH_4^+-N to NO_3^--N . The slowness in the increase in pH on reflooding the soil after drying may be due to depletion of the most readily oxidizable organic matter.

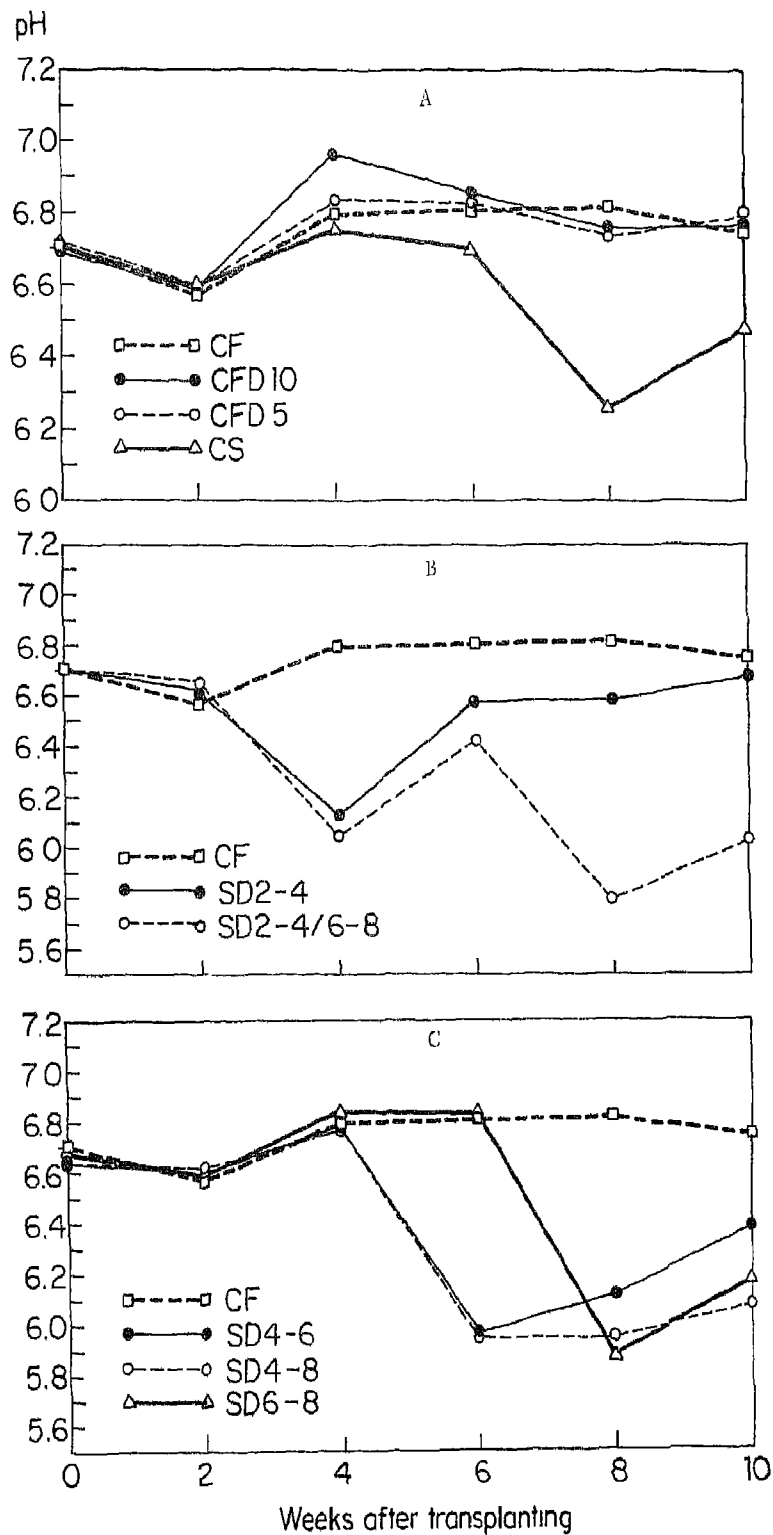


Fig. 18. Influence of nine water regimes on kinetics of solution pH in Louisiana-1 soil.

Eh

Soil solution Eh decreased to 0 mV within the 2 week preflooding period and it continued to drop for another two weeks and a stable value of nearly -100 mV was maintained in the treatments CF, CF D5 and CF D10 thereafter (Fig. 19A). Continuously saturated water regime (CS) maintained a little higher soil solution Eh at 4 and 8 WAT compared to that in flooded water regime (Fig. 19A). This again was due to difficulty in maintaining saturation at these stages when water demand of plant was very high.

Drying the soil for 2 or 4 weeks oxidized the soil as was evident from higher and positive Eh values of soil solution during the dry periods (Fig. 19B-C). Reflooding caused reduction of the soil but the Eh did not drop to the level of flooded water regime. This could be due to the formation of NO_3^- and Mn(IV) during soil drying which prevented the reduction of soil.

The soil Eh measured in situ, like in experiment 1, also indicated soil reduction due to flooding and oxidation on soil drying (Fig. 20A-C). However, the soil Eh values were much lower than soil solution Eh under flooded condition while the opposite was true under soil drying conditions.

Under continuously flooded condition (CF) both the soil and soil solution Eh in Luisiana-1 soil were lower compared to those in Maahas-1 soil used in experiment 1. This was due to a comparatively higher organic matter content in Luisiana-1 soil.

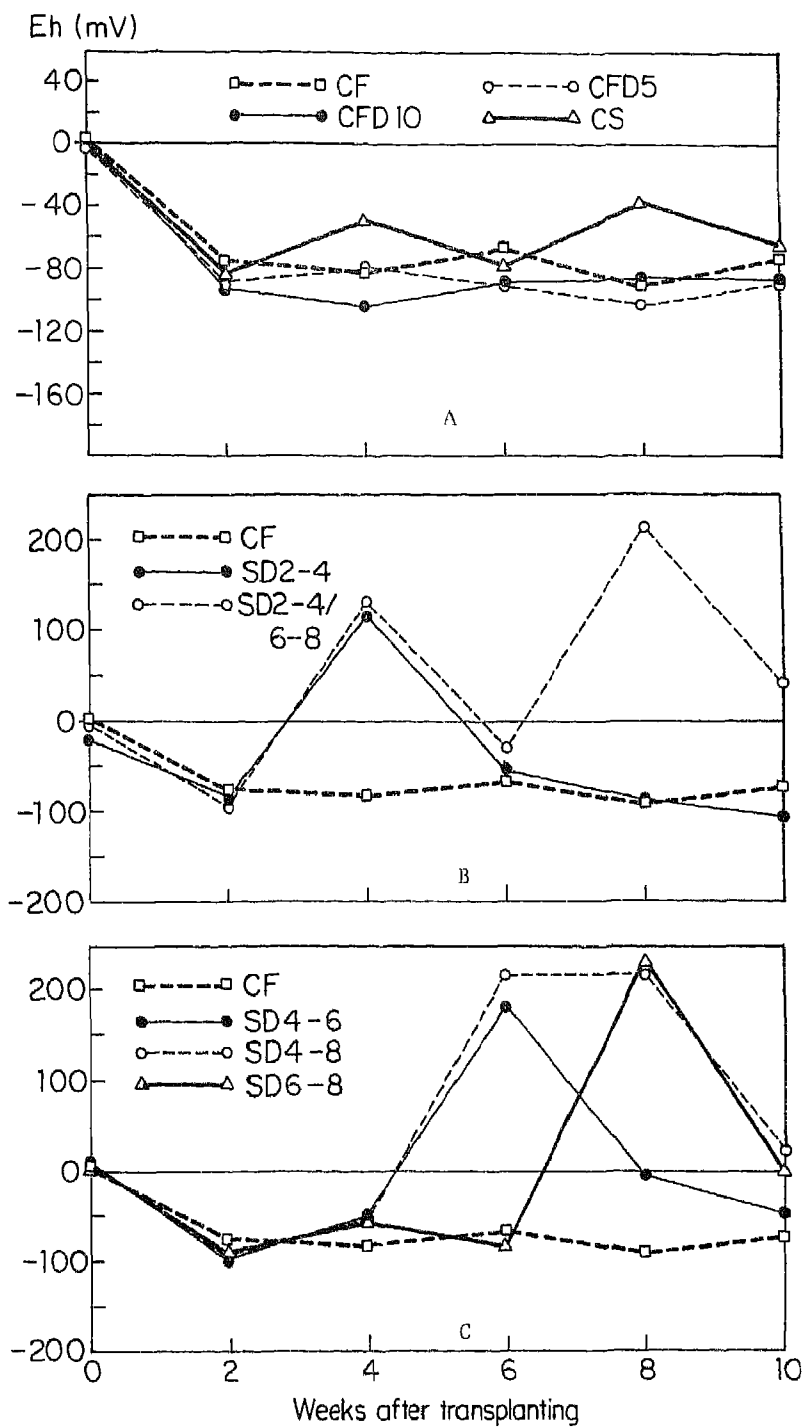


Fig. 19. Influence of nine water regimes on kinetics of solution Eh in Louisiana-1 soil.

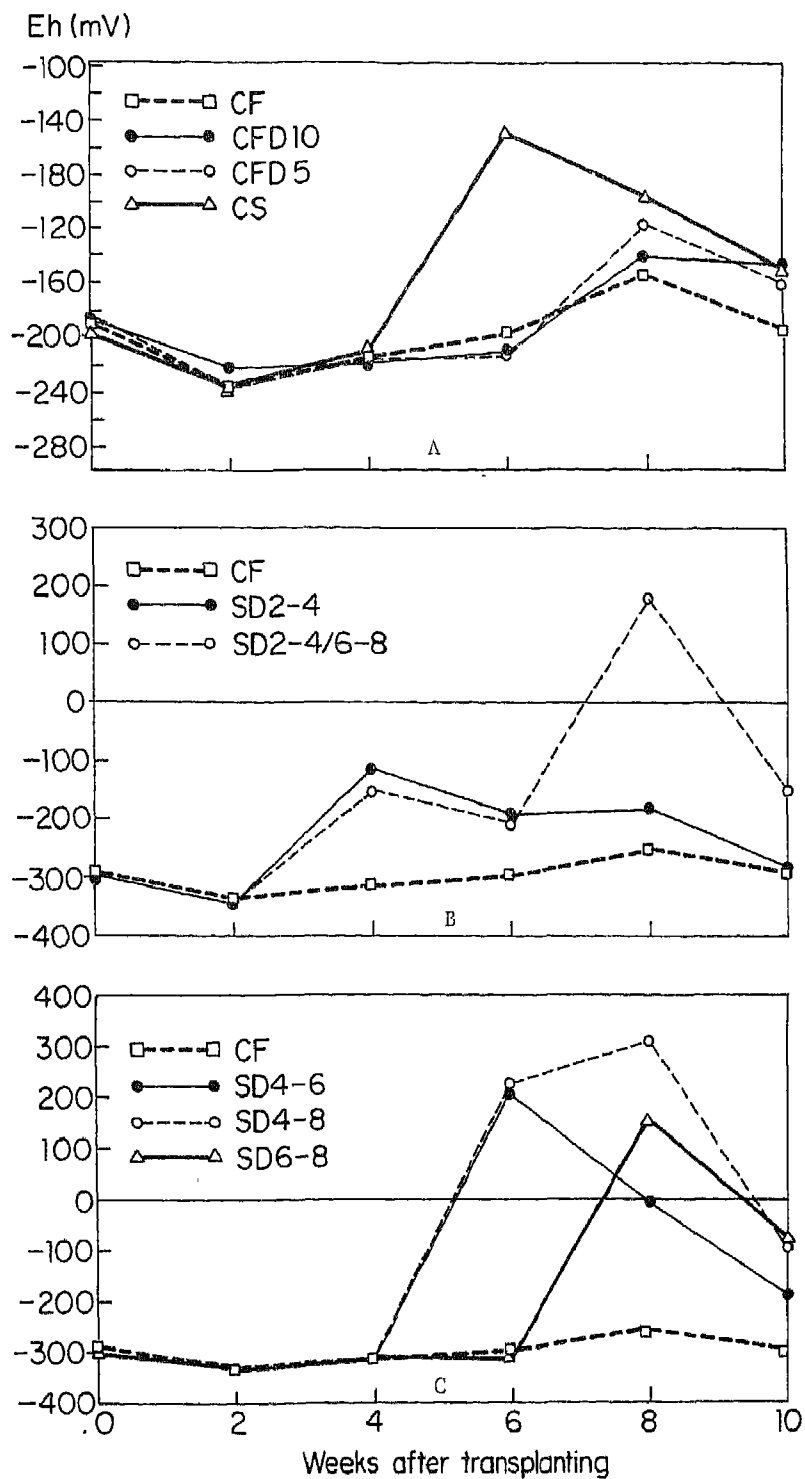


Fig. 20. Influence of nine water regimes on kinetics of Eh in Luisiana-1 soil.

EC

Two weeks of preflooding brought the EC to its peak value on the day of transplanting and started decreasing gradually with time to a stable value of around 1.3 dS/m within 4 weeks (Fig. 21A). Saturated water regime (CS) followed the same trend as the flooded water regime but maintained lower EC after 4 WAT (Fig. 21A). Drainage of 5-10 mm/day (CFD5 and CFD10) decreased the EC of flooded soil by removing ions with drainage water (Fig. 21A).

Soil drying for 2 to 4 weeks depressed the soil solution EC but reflooding caused an increase to that of continuous flooded water regime or even higher (Fig. 21B-C).

Much of the variation in EC can be explained by the concentration of Fe^{2+} , and HCO_3^- . The Fe^{2+} plots (Fig. 30) and bicarbonate plots (Fig. 23) are parallel to the EC plots. Iron (Fe^{2+}) is the predominant cation while HCO_3^- is the predominant anion in this soil.

Oxidizable matter

Oxidizable matter in soil solution includes those substances that reduce KMnO_4 under mild conditions. Since water soluble Fe^{2+} accounts for less than 25% of the reducing capacity, the bulk of the reducing substances must be organic (Ponnamperuma, 1972). Presence of traces of aldehydes, ketones, alcohols, reducing sugars, aliphatic hydroxy and unsaturated-acids and mercaptans and organic sulfides in flooded soils have been reported (IRRI, 1965). Two phenolic substances -- ferulic acid and sinapic acids have also been detected in flooded

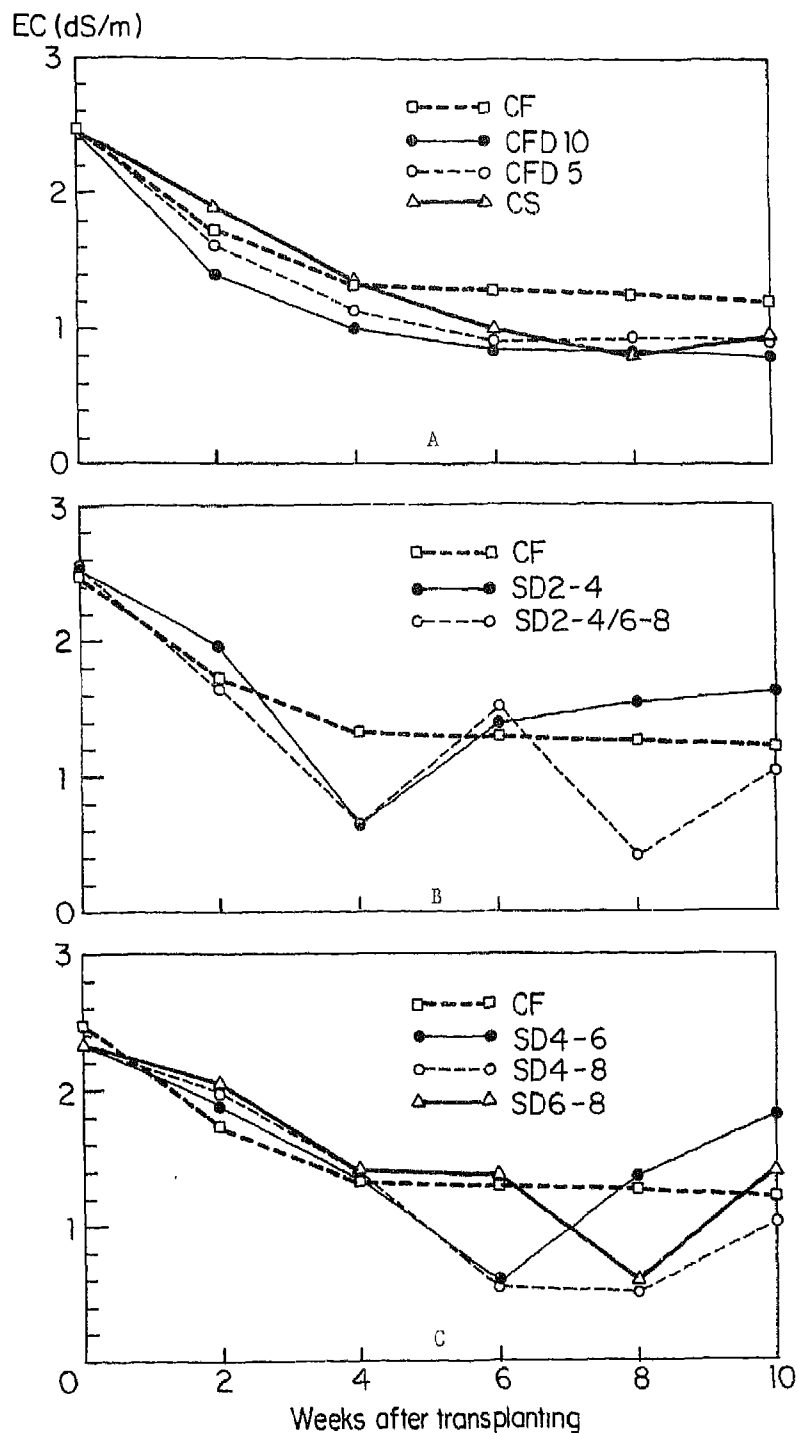


Fig. 21. Influence of nine water regimes on kinetics of solution electrical conductivity in Louisiana-1 soil.

soils (IRRI, 1970) but the nature of the bulk of the reducing substances is unknown. Although it is not an absolute measure of the concentration of reduced products, it can provide a simple and satisfactory index of the extent of reduction in a given soil (Ponnamperuma, 1972).

Because of two weeks preflooding, the oxidizable matter concentration of the soil solution was already at its peak value on the day of transplanting of rice (Fig. 22A-C). It started to decrease gradually to a stable value (around 16 me/l), 6 weeks after transplanting (Fig. 22A). Saturated water regime (CS) maintained lower concentration of oxidizable matter in soil solution and drainage of 5-10 mm/day (CFD5, CFD10) decreased it in flooded soil (Fig. 22A).

Soil drying for 2 weeks drastically decreased the oxidizable matter concentration of soil solution and reflooding started to increase it again (Fig. 22B-C).

The increase in oxidizable matter was due to increase in Fe^{2+} (Fig. 30) on soil reduction and formation of reducing organic substances while the later decrease was caused by precipitation of Fe^{2+} and loss of organic reducing substances in the formation of CO_2 and CH_4 . Decrease in oxidizable matter on soil drying was caused by their oxidation.

Bicarbonate (HCO_3^-)

Bicarbonate concentration of soil solution was also at its peak value on the day of transplanting and started decreasing with time (Fig. 23A). Saturated (CS) and drained flooded soils (CFD5, CFD10) had lower bicarbonate in soil solution (Fig. 23A).

Oxidisable matter (me/l)

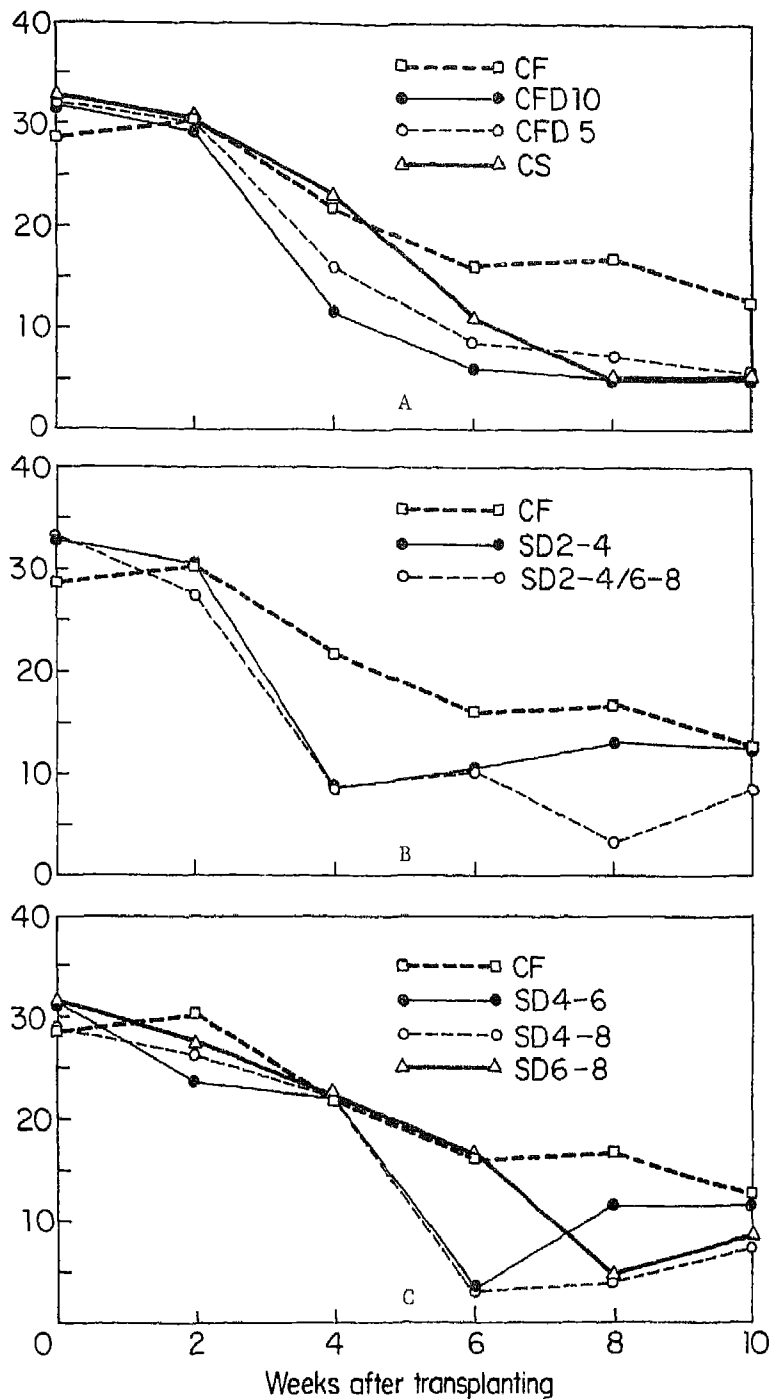


Fig. 22. Influence of nine water regimes on kinetics of water-soluble oxidizable matter in Louisiana-1 soil.

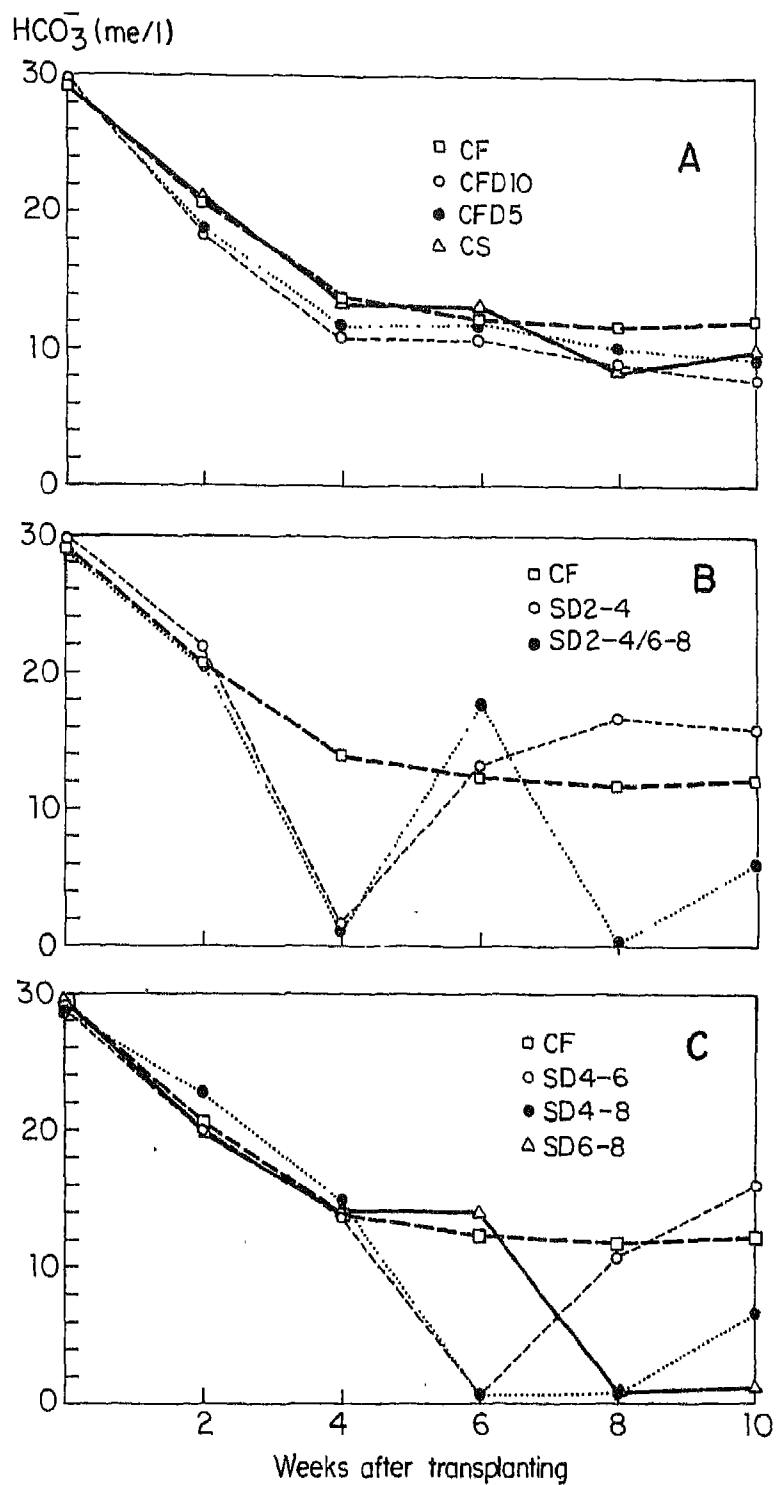


Fig. 23. Influence of nine water regimes on kinetics of water soluble bicarbonate in Luisiana-1 soil.

Soil drying for 2 or 4 weeks decreased the soil solution HCO_3^- concentration to a very negligible value and reflooding started to raise it again (Fig. 23B-C).

P^{CO_2}

The P^{CO_2} of the soil solution was already on its peak value after 2 weeks preflooding period. Thereafter, it started decreasing and within next 4 weeks time reached a fairly stable value of around 0.1 atmosphere in continuously flooded water regime (CF) (Fig. 24A). Drained flooded soil (CFD5, CFD10) maintained relatively lower P^{CO_2} in soil solution compared to that in continuously flooded soil (CF). Continuously saturated (CS) water regime maintained relatively higher P^{CO_2} in soil solution compared to that in continuously flooded water regime.

Soil drying for 2 to 4 weeks decreased the soil solution P^{CO_2} to very low value. Reflooding the dry soil increased the P^{CO_2} and within 2 weeks it bypassed its level in continuously flooded soil (Fig. 24B-C).

The decrease in P^{CO_2} after the peak has been explained to the escape and leaching of CO_2 , its removal as insoluble carbonates, and its reduction to CH_4 (Ponnamperuma, 1972).

NH_4^+-N

On the day of transplanting N as urea was applied to the soil at the rate of 100 mg/kg soil. As urea hydrolysis takes a few days the NH_4^+-N concentration of the soil solution on the day of transplanting represents the available NH_4^+-N of the soil 2 weeks

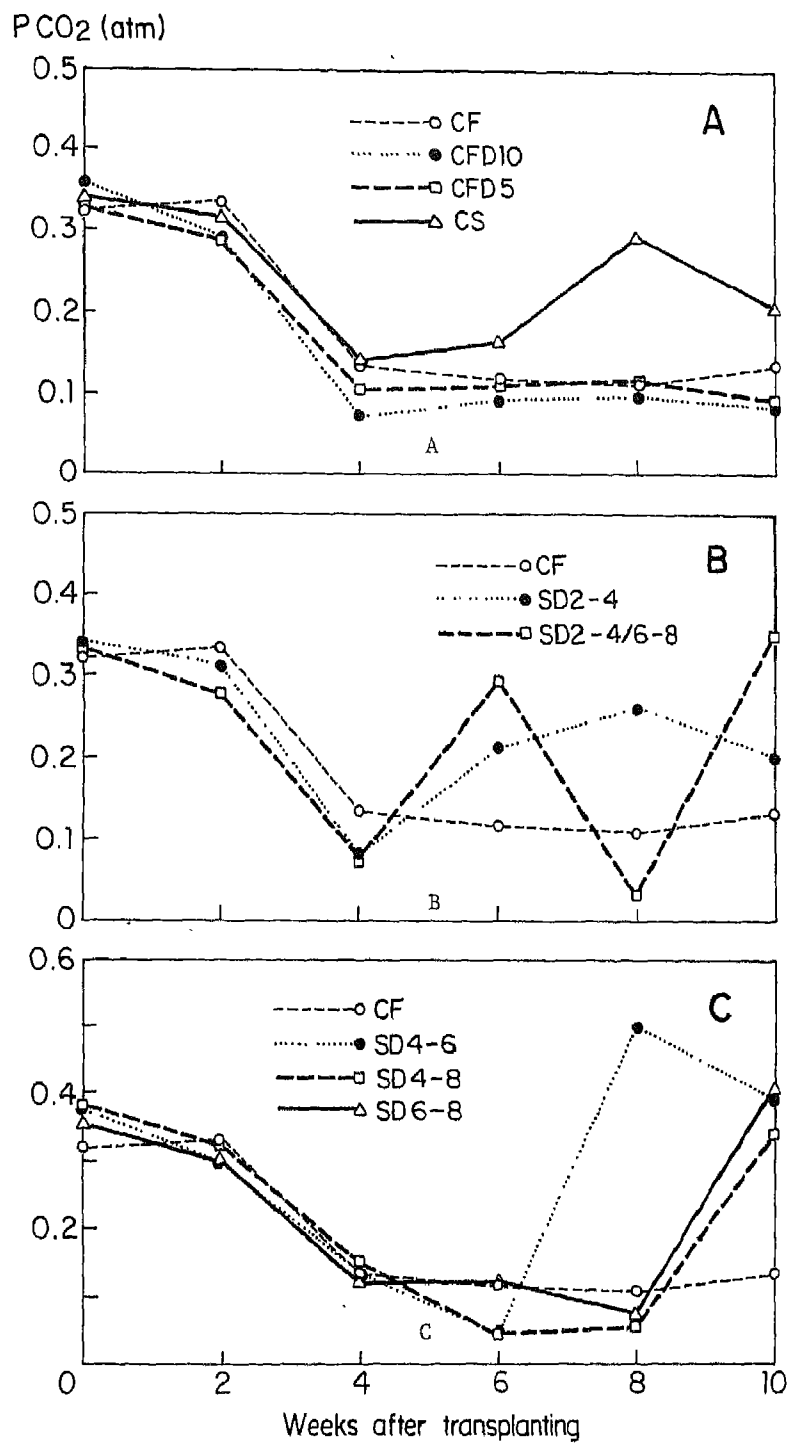


Fig. 24. Influence of nine water regimes on kinetics of solution $p\text{CO}_2$ in Louisiana-1 soil.

after flooding. This amount decreased gradually with time and reached a value of 40 ppm 10 weeks after transplanting (Fig. 25A). Saturated (CS) and drained flooded soils (CFD5, CFD10) maintained lower $\text{NH}_4^+\text{-N}$ in soil solution. Soil drying for 2 to 4 weeks decreased the $\text{NH}_4^+\text{-N}$ concentration of the soil solution but not below 20 ppm (Fig. 25B-C). Reflooding increased the $\text{NH}_4^+\text{-N}$ concentration beyond the level of that in continuously flooded soil at comparable time indicating accelerated mineralization of organic nitrogen due to alternate wetting and drying (Birch, 1960; Reddy and Patrick, 1975; Shiga and Ventura, 1976).

In flooded water regime (CF) the decrease in $\text{NH}_4^+\text{-N}$ concentration of soil solution was due to its adsorption on the exchange complex, plant uptake and loss of N by different mechanisms. The decrease in $\text{NH}_4^+\text{-N}$ concentration of soil solution during dry period was due to nitrification of $\text{NH}_4^+\text{-N}$ and it is possible that the nitrates were lost on reflooding. This amounts to a significant loss of nitrogen but drying and reflooding accelerated organic nitrogen mineralization and consequently nitrogen loss after drying and reflooding might not be a problem for rice growth in this soil.

Phosphorus (P)

This soil was originally low in available P and a basal dose of 50 mg P/kg soil as KH_2PO_4 was applied on the day of transplanting. The sharp decrease in phosphorus concentration of the soil solution during first 2 weeks after transplanting (Fig. 26A) indicates high P fixing capacity of the soil. This coincided with the decrease in water soluble

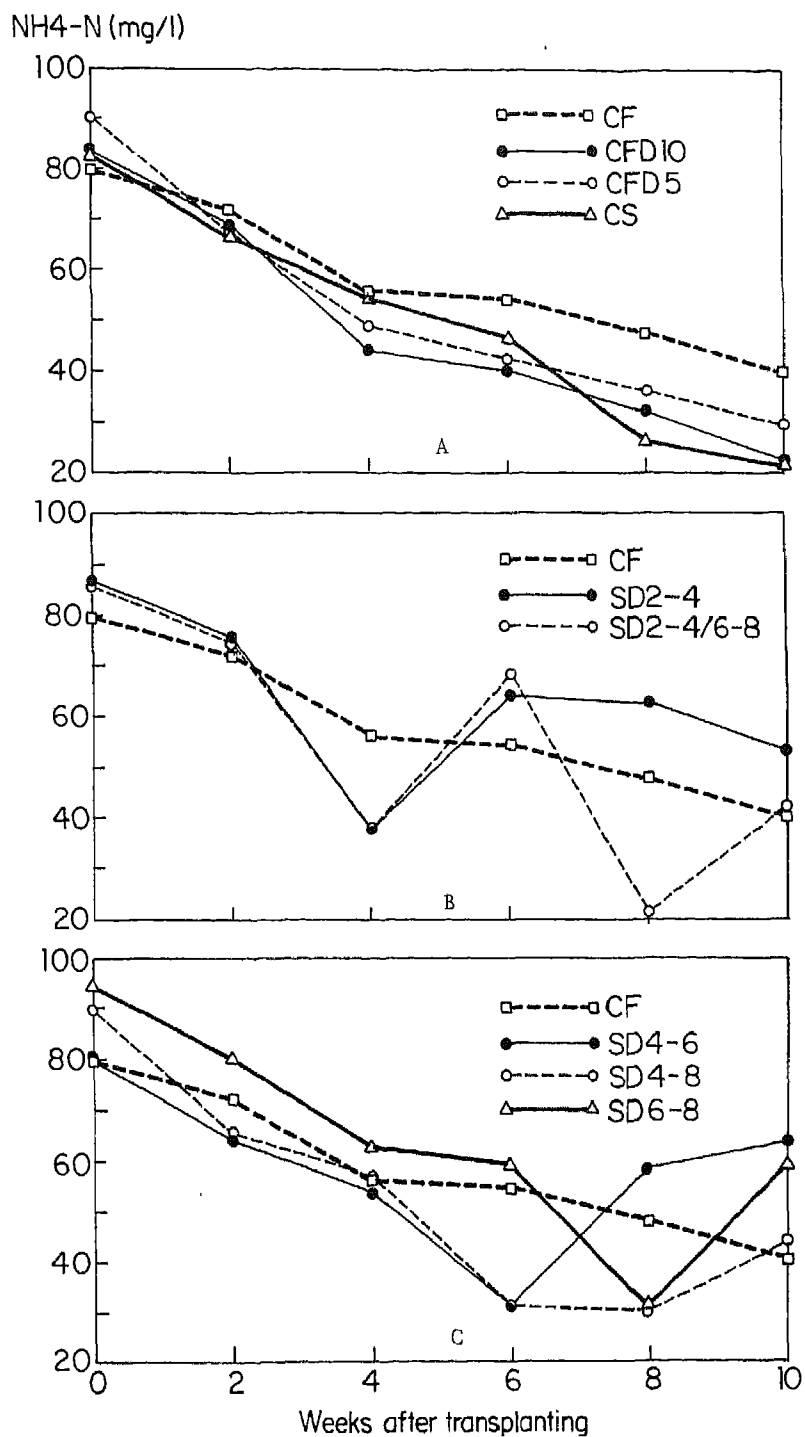


Fig. 25. Influence of nine water regimes on kinetics of water-soluble NH₄⁺-N in Louisiana-1 soil.

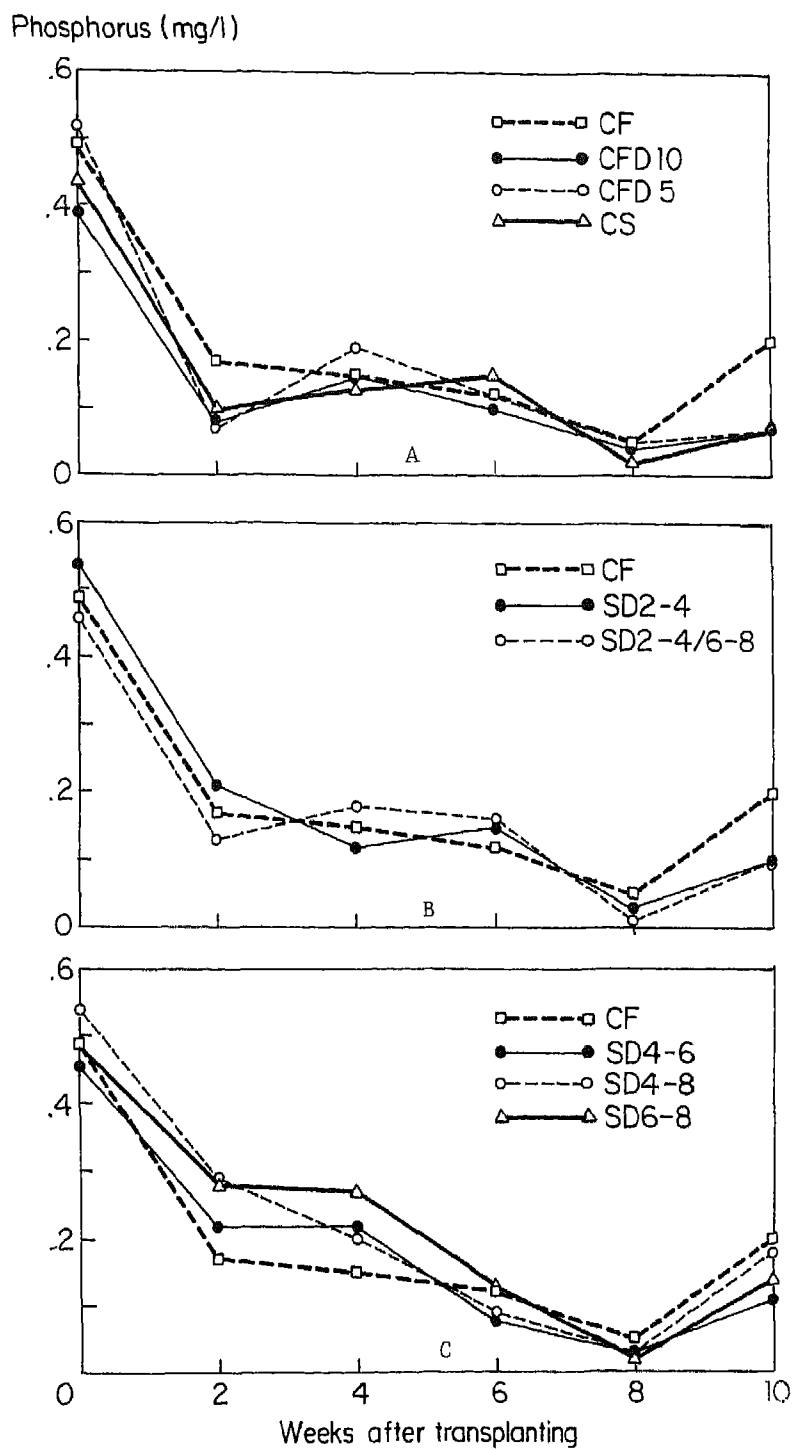


Fig. 26. Influence of nine water regimes on kinetics of water-soluble P in Luisiana-1 soil.

Fe^{2+} concentration of the soil. Soluble phosphates were probably adsorbed on the precipitated iron hydroxides and Fe-carbonates. However, at all times continuously flooded water regime (CF) maintained phosphorus in soil solution at the level between 0.1 and 0.2 ppm. Because of its very low P concentration in soil solution, the influence of soil drying at different growth stages (Fig. 26B-C) was not clearly reflected in its kinetics studies.

Potassium (K^+)

The soil was treated with potassium @75 mg K/kg soil as KH_2PO_4 and KCl on the day of transplanting. In the flooded (CF), flooded with drainage (CF D5, CF D10) and saturated (CS) water regimes soil solution K^+ decreased with time and came to a stable value four weeks after transplanting (Fig. 27A). Saturated (CS) and drained flooded water regime (CFD5, CFD10) maintained comparatively lower K^+ in soil solution.

Soil drying for any period of time depressed the soil solution K^+ concentration during the dry periods but on reflooding it increased again. But unlike in Maahas-1 soil (experiment 1) reflooding did not raise the soil solution K^+ level beyond that in continuously flooded water regime, probably because of its lower exchangeable K content (0.38 me/100 g soil as compared to 2.3 me/100 g in Maahas-1 soil) and difference in their mineralogy.

The initial drop in soil solution K^+ was due to plant uptake and adsorption of K^+ on to the exchange complex when HCO_3^- and Fe^{2+} concentrations decreased. Some K^+ might also have been fixed by soil

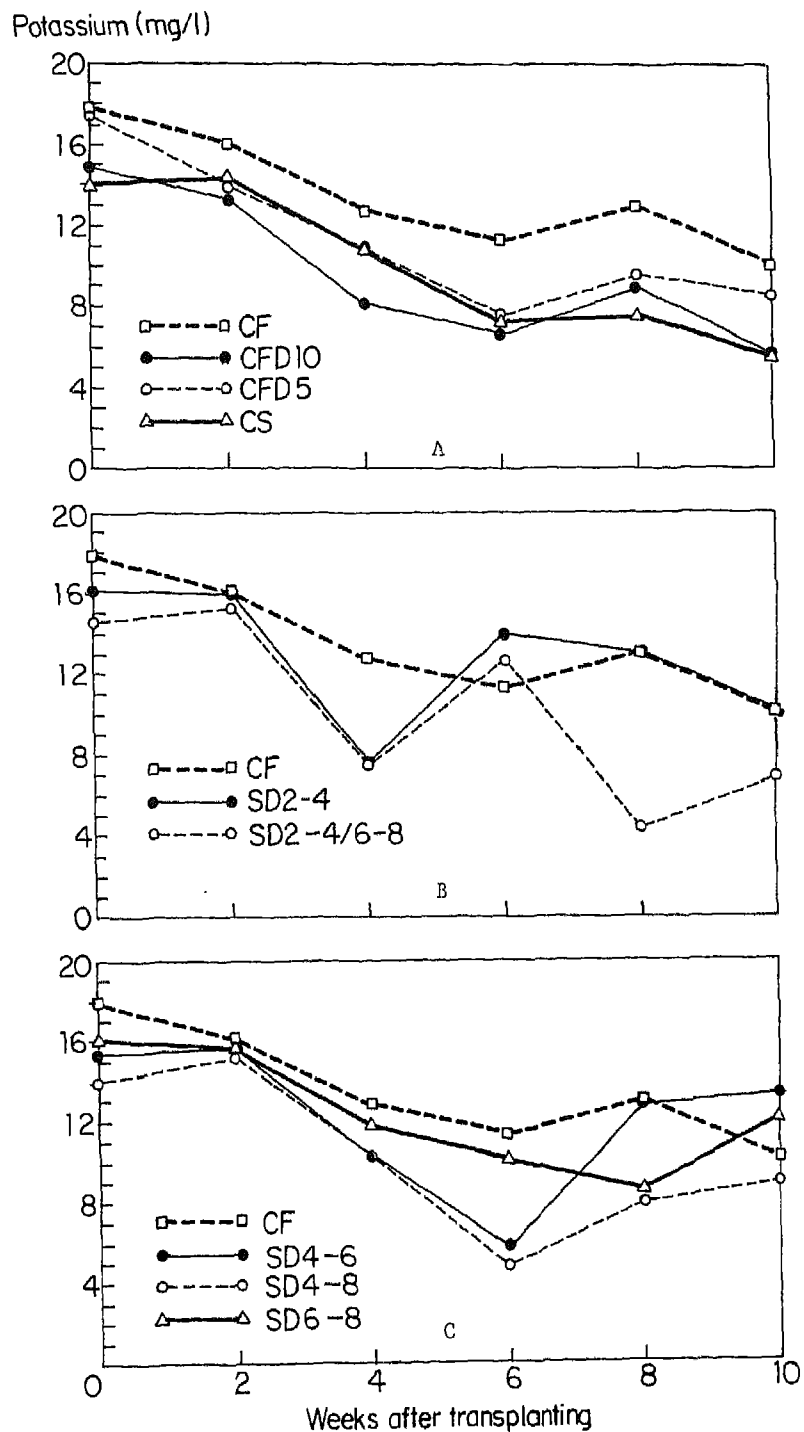


Fig. 27. Influence of nine water regimes on kinetics of water-soluble K in Louisiana-1 soil.

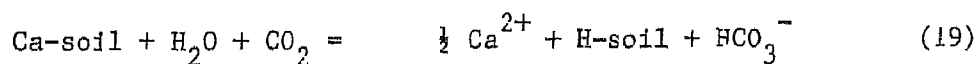
clays. The decrease in K^+ concentration of soil solution during drying was due to its movement to the exchange sites when the Fe^{2+} and Mn^{2+} of soil solution precipitated.

Calcium (Ca^{2+})

From a concentration of about 240 ppm two weeks after flooding, the soil solution Ca^{2+} decreased steadily during the first 4 weeks after transplanting and then gradually reached a concentration of around 50 ppm, 10 weeks after transplanting (Fig. 28A). The soil solution Ca^{2+} concentration in saturated CS) and drained flooded water regimes (CF D5, CF D10), followed the trend in flooded water regime (CF) but maintained a slightly lower concentration (Fig. 28A).

Soil drying for any period of time decreased the soil solution Ca^{2+} during the dry period while reflooding started to increase it again (Fig. 28B-C).

Calcium plots ran parallel to Fe^{2+} and HCO_3^- plots (Figs. 30 and 23). Whenever there was a drop in Fe^{2+} and HCO_3^- , Ca^{2+} also decreased. This indicates that when there was oxidation of Fe^{2+} , the Fe^{2+} on the exchange sites were replaced by Ca^{2+} . On reflooding the precipitated $Fe(III)$ were reduced again resulting in the displacement of Ca^{2+} from the exchange sites. The influence of HCO_3^- on Ca^{2+} concentration in soil solution is explained by equation (19) (Bloom and Inskeep, 1986).



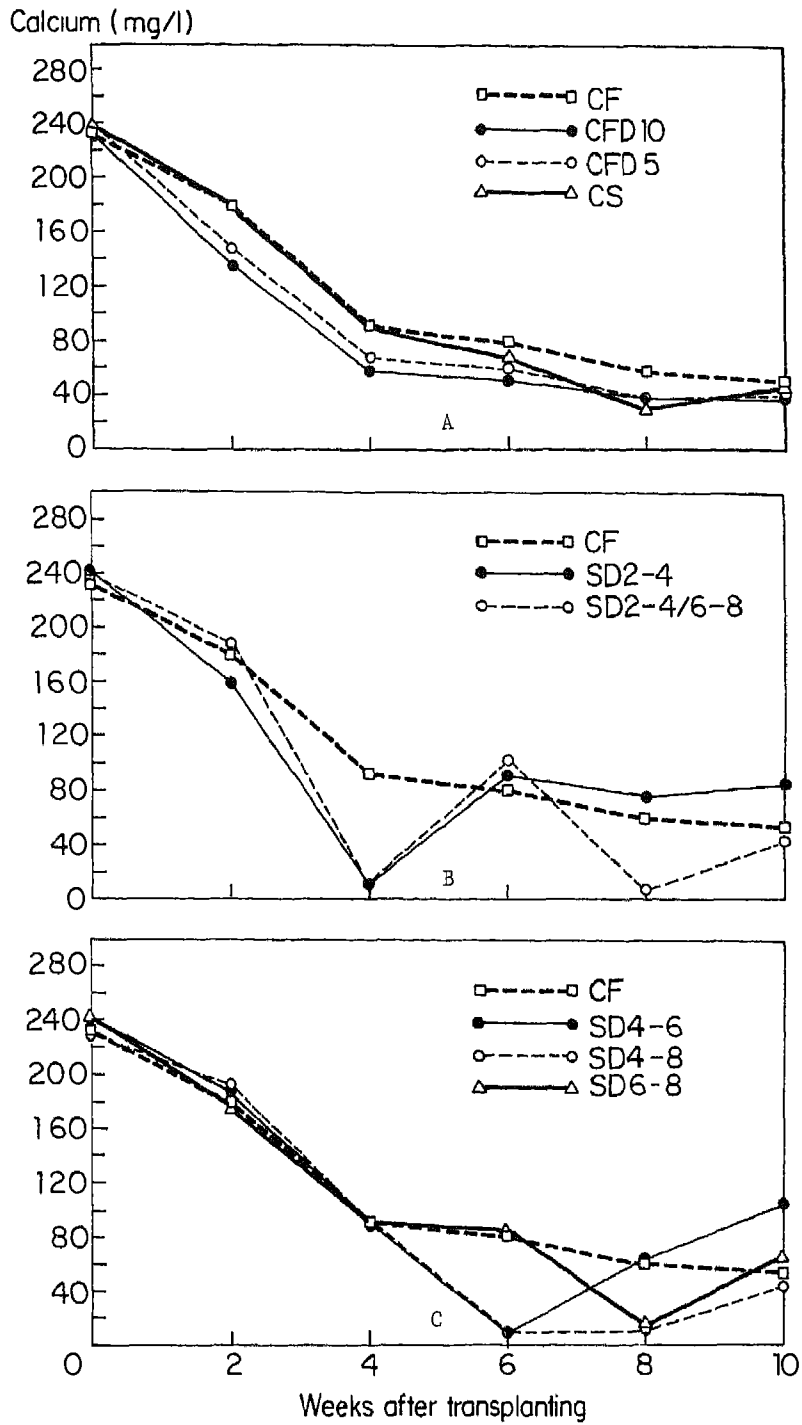


Fig. 28. Influence of nine water regimes on kinetics of water-soluble Ca in Luisiana-1 soil.

Magnesium (Mg^{2+})

Soil solution Mg^{2+} followed the same trend as that of Ca^{2+} (Fig. 29A-C) but the corresponding concentrations of Mg^{2+} were lower than Ca^{2+} .

Iron (Fe^{2+})

Since the soil was subjected to 2 weeks flooding before transplanting of rice, the soil solution Fe^{2+} concentration was already at the maximum of 220 ppm on the day of transplanting (Fig. 30). In continuously flooded water regime (CF) Fe^{2+} concentration decreased to around 80 ppm 6 weeks after transplanting and stayed at that level (Fig. 30A). Drainage of 5 to 10 mm/day in flooded soil (CF D5, CF D10) and turning the flooded soil to saturated condition (CS) decreased the soil solution Fe^{2+} concentration to a lower value within two weeks and thereafter these treatments maintained comparable Fe^{2+} concentration (Fig. 30A). As rice plants are more susceptible to high Fe^{2+} concentration during the early stages (Tadano, 1974), making the soil saturated would have important implications for rice growth. The improved rice growth in drained flooded and saturated water regimes as will be discussed later could probably be explained by these changes.

Soil drying for any period of time decreased soil solution Fe^{2+} concentration to almost 0 during the dry periods but reflooding tended to increase it again to the level of that in flooded water regime (Figs. 30B-C).

Magnesium (mg/l)

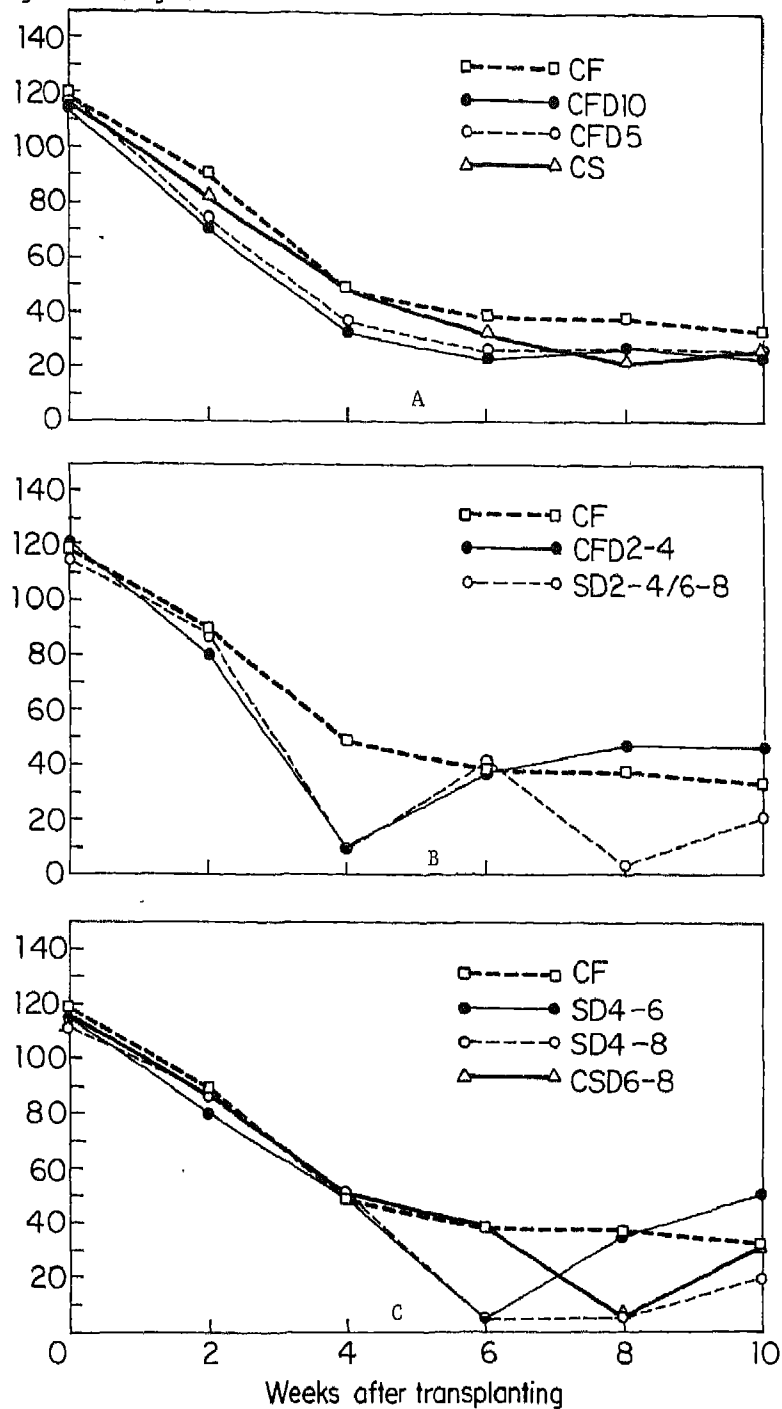


Fig. 29. Influence of nine water regimes on kinetics of water-soluble Mg in Luisiana-1 soil.

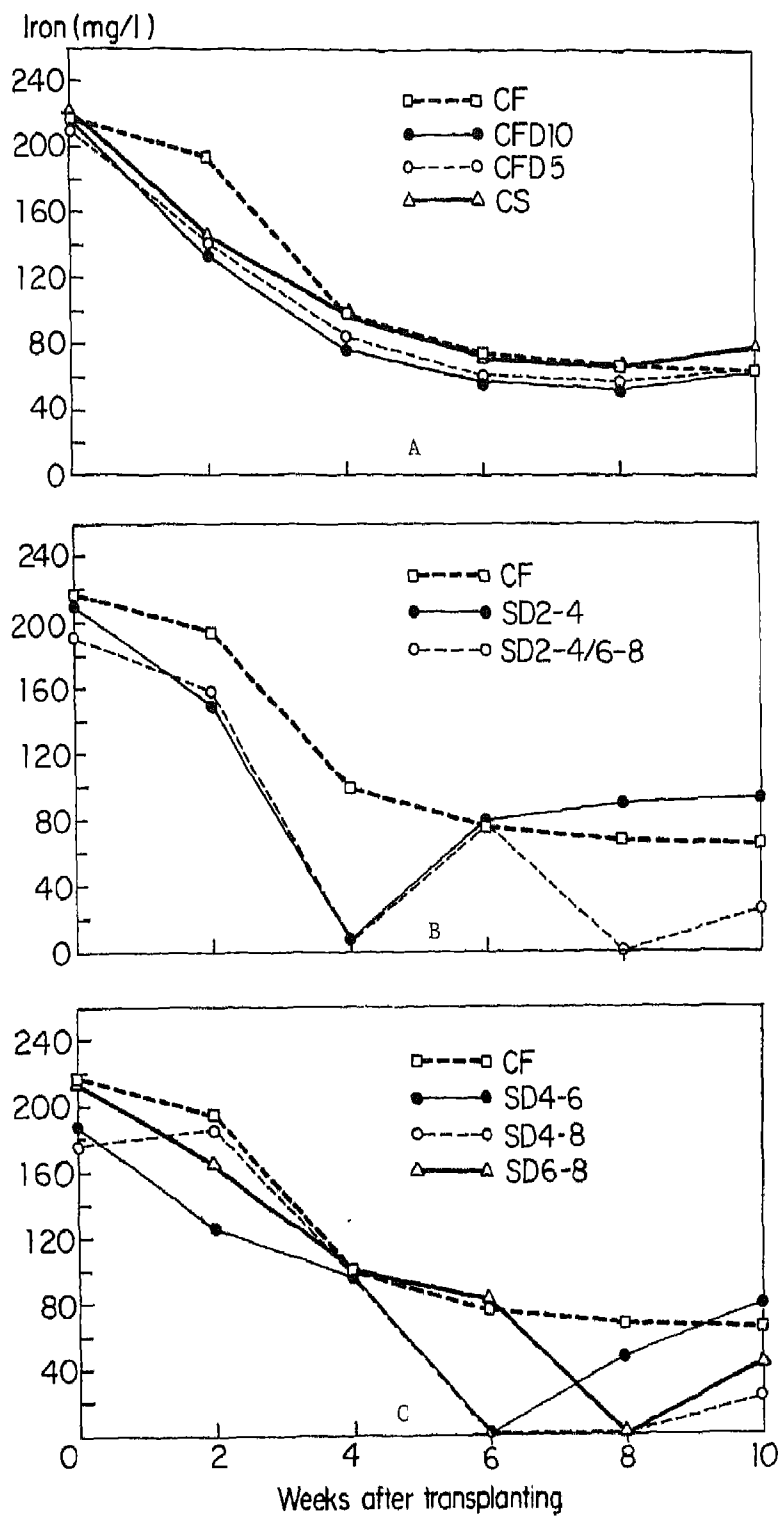


Fig. 30. Influence of nine water regimes on kinetics of water-soluble Fe in Luisiana-1 soil.

Manganese (Mn^{2+})

Manganese concentration of the soil solution decreased first sharply and then gradually in the CF, CF D5, CF D10 and CS treatments and maintained the level at around 1 ppm, 6 weeks after transplanting (Fig. 31A). Since this soil had very low active Mn content (0.04%) and low pH, the oxidation of Mn was very slow during soil drying. Thus soil drying and reflooding showed only small effects on soil solution Mn^{2+} concentration (Fig. 31B-C).

Zinc (Zn^{2+})

Zinc concentration of the soil solution in CF increased during the first 2 weeks after transplanting and decreased to a stable value of around 0.06 ppm thereafter (Fig. 32A). Saturated water regime (CS) maintained Zn^{2+} concentration comparable to flooded water regime (CF) but drainage of 5-10 mm/day in flooded soil (CF D5, CF D10) decreased the soil solution Zn^{2+} concentration.

Zinc concentration in soil solution fluctuated with soil drying and reflooding -- it decreased during the dry periods and increased on reflooding (Fig. 32B-C).

The decrease in soil solution Zn^{2+} concentration in continuously flooded water regime (CF) was probably due to formation of insoluble sulfides, carbonates and hydroxides and its reaction with soluble silica. The increase in Zn^{2+} concentration on soil drying was probably due to corresponding decrease in soil pH, because the solubility of Zn increases 100 fold for each unit decrease in pH (Norwell and Lindsay, 1969).

Manganese (mg/l)

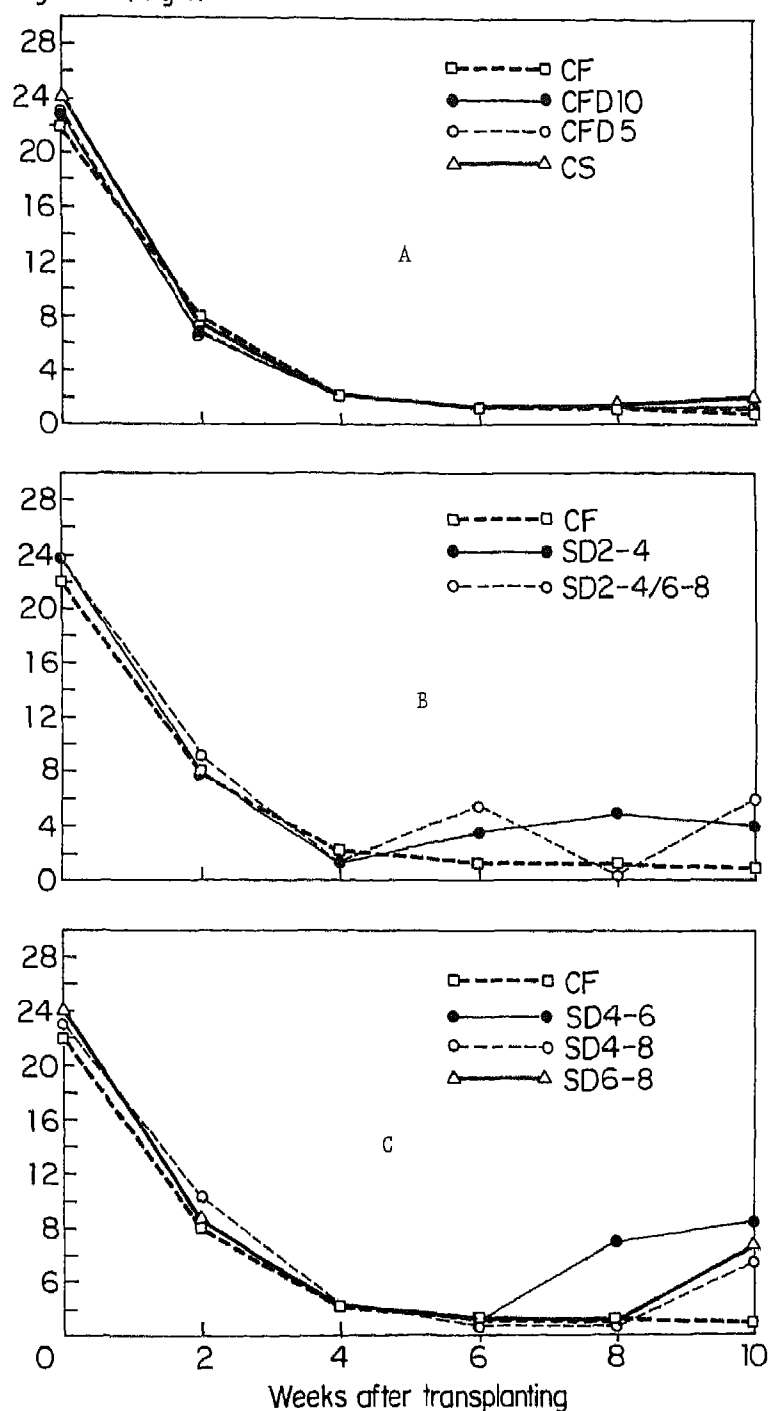


Fig. 31. Influence of nine water regimes on kinetics of water-soluble Mn in Luisiana-1 soil.

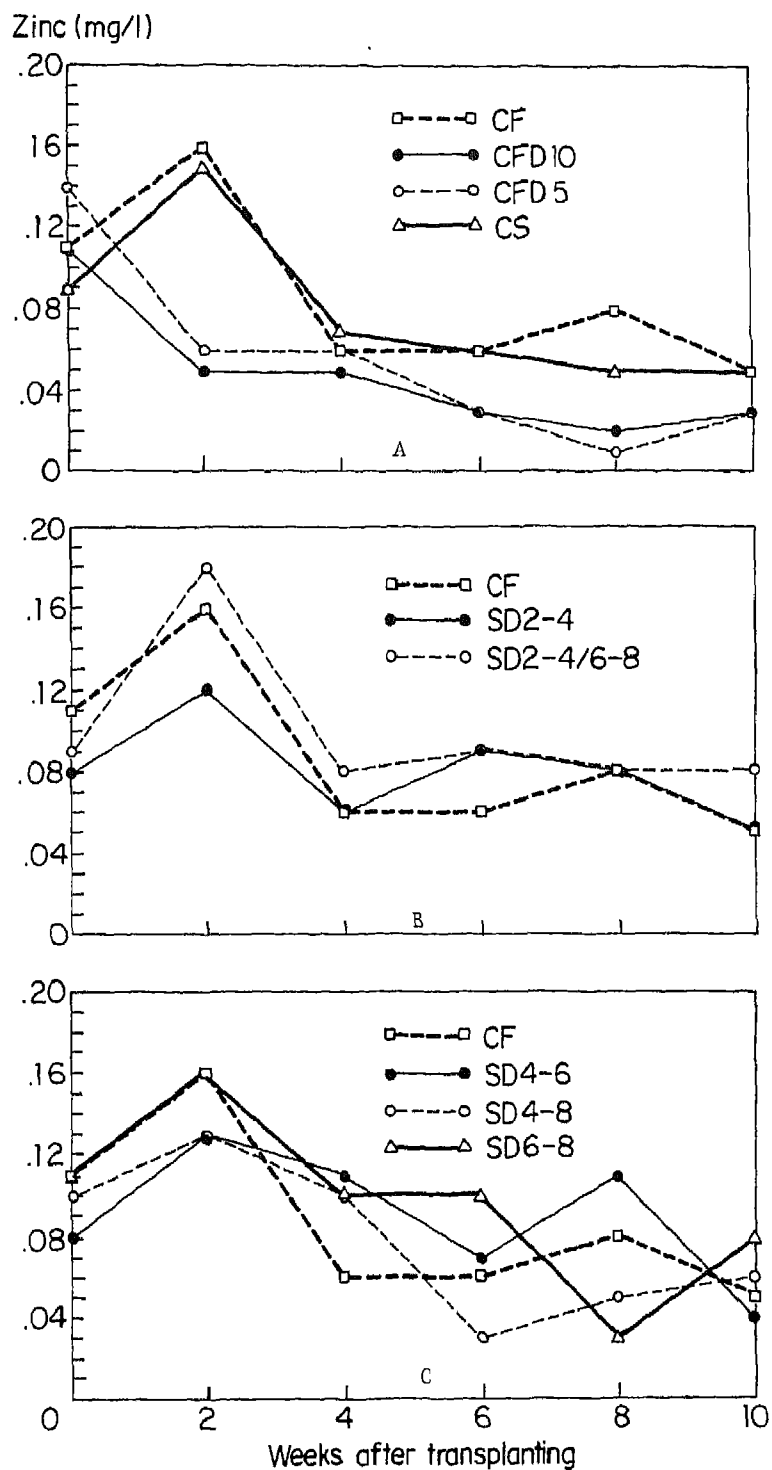


Fig. 32. Influence of nine water regimes on kinetics of water-soluble Zn in Luisiana-1 soil.

Silicon (Si)

Since the soil was flooded for 2 weeks before transplanting, soil solution Si concentration was at its peak value which decreased with time after transplanting (Fig. 33A). Saturated water regime (CS) maintained soil solution Si comparable to the flooded water regime (CF) while drainage of 5 to 10 mm/day (CF D5, CF D10) slightly decreased it.

Soil drying for any period decreased soil solution Si but reflooding raised it beyond the concentration in flooded water regime (Fig. 33B-C). The decrease in soil solution Si in continuously flooded (CF) water regime was probably due to increase in pH on flooding. Similarly, decrease in pH due to soil drying could have resulted in solubilization of Si on reflooding.

To summarize, the study of the chemical kinetics of soil solution in this soil showed that:

- i. Under continuously flooded condition this soil was strongly reduced and consequently water soluble oxidizable matter was high. Soil drying for 2 to 4 weeks oxidized the soil and decreased the oxidizable matter concentration in soil solution.
- ii. Soil drying and reflooding decreased the availability of N but the water soluble NH_4^+ -N did not decrease below 20 ppm.
- iii. Soil drying and reflooding did not decrease P solubility.
- iv. Availability of K^+ , Ca^{2+} and Mg^{2+} were lower during the dry spells but on reflooding they increased.
- v. Water soluble Fe^{2+} concentration was high under continuously flooded water regime. Soil drying and reflooding decreased it.

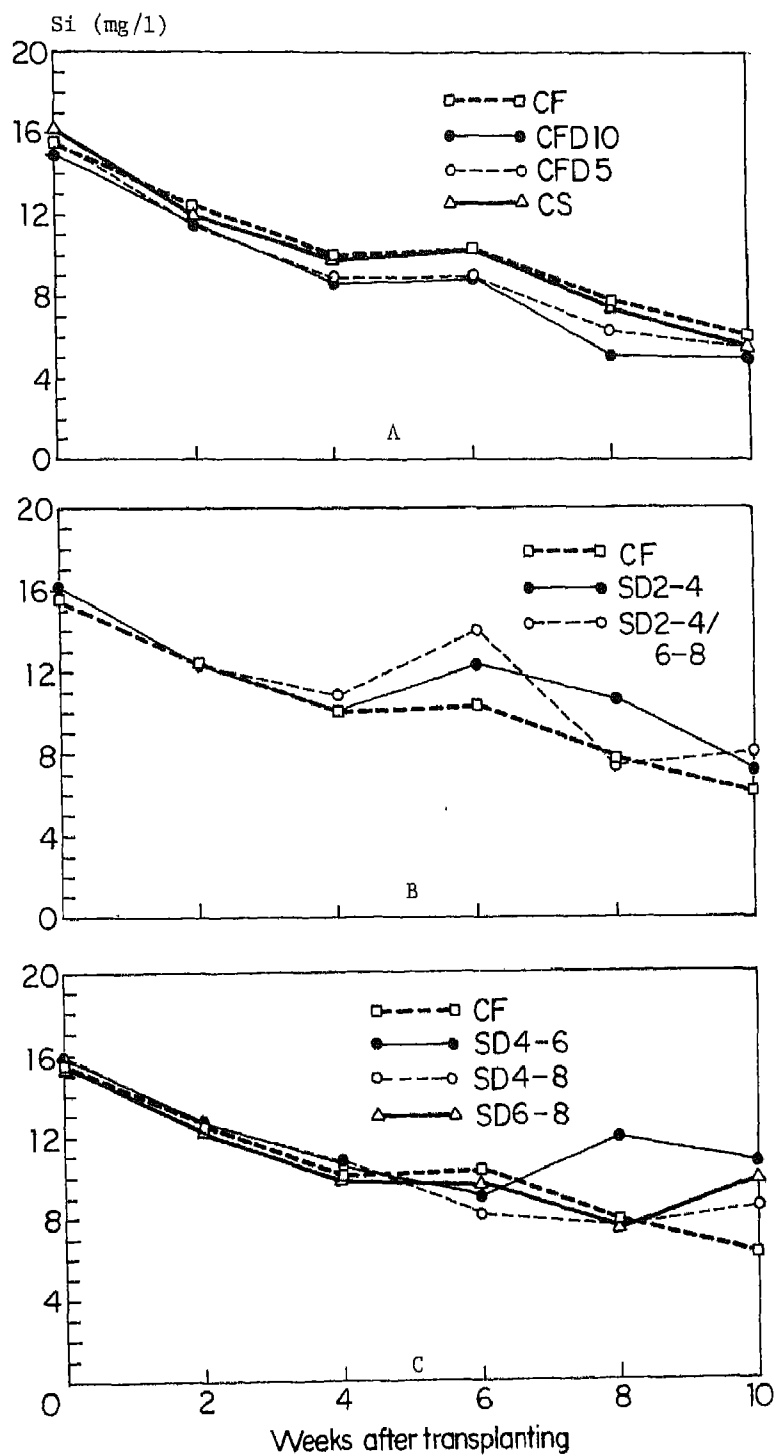


Fig. 33. Influence of nine water regimes on kinetics of water-soluble Si in Louisiana-1 soil.

- vi. Soil drying and reflooding did not show significant effect on Mn^{2+} solubility.
- vii. Availabilities of Zn^{2+} and Si were lower during the dry periods but on reflooding their availabilities increased to higher level than in continuously flooded water regime.

Mineral Nutrition of Rice

Concentration of mineral nutrients in 8 week-old rice shoots and mature straw are presented in Tables 9 and 10. As the dry matter production were lowest under continuously flooded (CF) among the different water regime treatments, the nutrient concentration may not reflect the true picture of mineral nutrition. Therefore, the total uptake of nutrients by shoots and grain plus straw at harvest were also computed and presented in Tables 11 and 12. The results are discussed in the following pages.

Nitrogen

Draining the soil or drying for 2 or 4 weeks and reflooding did not affect the nitrogen concentration of rice shoot (Table 9) and mature rice straw (Table 10). As was seen from the kinetics of NH_4^+-N , (Fig. 25) at no stage drying could decrease it below 20 ppm in soil solution. Thus, N might not have been limiting to rice growth in this soil.

One interesting feature of rice growth in Luisiana-1 soil was high N concentration in straw. At maturity when the grains were ripe and about to shatter, the straw was still very green. This explains why the N concentration of straw was more than 2%.

Table 9. Influence of nine water regimes on the mineral nutrient concentration in eight week-old rice (IR54) shoots in Louisiana-1 soil.

Treatments	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu	SiO ₂ (%)
			%					ppm		
CF	3.60	0.242 A	3.87 B	0.194 A-C	0.283 B-D	442	322 E	42.7 CD	26.0 C	11.1 C
CFD 10	3.54	0.220 AB	3.33 CD	0.212 A	0.309 AB	387	375 E	40.8 CD	25.5 C	11.1 C
CFD 5	3.49	0.231 A	3.71 B	0.212 A	0.292 BC	318	313 E	38.8 D	26.0 C	11.2 BC
CS	3.46	0.153 DE	3.13 D	0.179 E	0.337 A	255	1537 C	54.8 AB	48.2 B	11.1 C
SD 2-4	3.57	0.169 C-E	3.52 BC	0.204 AB	0.300 B	342	677 D	42.2 CD	47.7 B	9.9 D
SD 2-4/6-8	3.37	0.139 E	4.96 A	0.184 BC	0.221 F	293	2078 A	56.5 AB	53.5 B	10.4 D
SD 4-6	3.41	0.202 A-C	4.87 A	0.189 BC	0.250 D-F	295	1432 C	49.3 BC	63.0 A	11.8 AB
SD 4-8	3.40	0.185 B-D	5.00 A	0.188 BC	0.246 EF	375	1912 B	64.3 A	65.8 A	11.4 BC
SD 6-8	3.19	0.177 B-E	4.92 A	0.196 A-C	0.258 C-E	303	2037 A	62.5 A	48.5 B	12.2 A
LSD (0.05)	ns	0.042	0.30	0.020	0.034	131	125	9.2	6.6	0.6
LSD (0.01)	ns	0.057	0.49	0.028	0.047	181	172	12.7	9.1	0.8

*In a column treatment means having common letter are not significantly different by DMRT at alpha 5%.

Table 10. Influence of nine water regimes on the mineral nutrient concentration in rice (IR54) straw at maturity in Louisiana-1 soil.

Treatment	N	P	K	Ca %	Mg	Fe	Mn	Zn ppm	Cu	SiO ₂ %
CF	2.45	0.110 AB	1.67 A	0.208	0.374	335 BC	642 DE	52.2 C	15.5 D	18.0
CFD 10	2.20	0.118 A	1.79 A	0.240	0.420	462 A	770 C-E	65.0 BC	17.3 CD	15.9
CFD 5	2.40	0.122 A	1.71 A	0.212	0.408	378 B	605 E	63.7 BC	15.2 D	16.4
CS	2.18	0.080 C	1.13 B	0.207	0.412	293 C	1320 A	96.0 A	29.2 A	17.1
SD 2-4	2.53	0.101 A-C	1.24 B	0.263	0.445	362 B	843 B-E	57.7 BC	19.7 CD	18.5
SD 2-4/6-8	2.64	0.094 BC	1.28 B	0.226	0.404	337 BC	1082 AB	72.8 B	32.3 A	15.7
SD 4-6	2.61	0.094 BC	1.67 A	0.228	0.449	333 BC	917 B-D	60.0 BC	22.2 BC	17.2
SD 4-8	2.63	0.106 AB	1.50 AB	0.193	0.358	377 B	953 BC	61.3 BC	31.2 A	15.1
SD 6-8	2.70	0.108 AB	1.79 A	0.216	0.412	332 BC	1118 AB	64.3 BC	26.8 AB	17.0
LSD (0.05)	ns	0.021	0.34	ns	ns	48	281	14.7	5.4	ns
LSD (0.01)	ns	0.028	0.47	ns	ns	66	387	20.3	7.4	ns

*In a column treatment means having common letter are not significantly different by DMRT at alpha 5%.

The total N uptake by shoot was lowest under continuously flooded water regime (CF) (Table 11). Drainage of 10 mm/day (CF D10) and soil drying for 2 weeks in the beginning (SD 2-4; SD 2-4/6-8) increased N uptake by rice but drying for 2 or 4 weeks after 4 WAT (SD 4-6; SD 4-8 and SD 6-8) did not increase N uptake by shoot at 8 WAT stage (Table 11).

The total N uptake by rice at harvest did not increase by draining the flooded soil (CF D5, CF D10). Compared to continuously flooded water regime (CF) keeping the soil saturated (CS) or drying and reflooding it (SD 2-4; SD 2-4/6-8; SD 4-6; SD 4-8; SD 6-8) significantly increased total N uptake at harvest (Table 12). This was obviously because of higher total dry matter yield under conditions of less abundant water availability (Table 13).

Phosphorus

Phosphorus concentration of the rice shoot and mature straw were highest under continuously flooded condition (CF) (Tables 9, 10). Under saturated water regime (CS), rice shoot as well as mature straw had lower phosphorus concentration compared to that under flooded condition. Soil drying and reflooding decreased P concentration of rice shoot while that of mature straw was not affected.

Phosphorus uptake by rice shoot was highest under continuously saturated water regime (CS) (Table 11). Drainage of 10 mm/day (CF D10) significantly increased P uptake by rice shoots compared to that under continuously flooded (CF) water regime. However, soil drying for 2 or 4 weeks at the vegetative growth stage did not help improve P uptake by

Table 11. Influence of nine water regimes on the total uptake of mineral nutrients by eight week-old rice (IR54) shoots in Louisiana-1 soil.

Treatment	N	P	K	Ca	Mg mg/pot	Fe	Mn	Zn	Cu	SiO ₂ g/pot
CF	290.0 D	20.3 CD	310.0 E	15.9 D	23.3 D	3.4 C	2.6 E	0.34 E	0.21 D	0.90 D
CFD 10	520.0 B	33.0 B	496.7 CD	31.4 B	45.7 BC	5.6 AB	5.6 E	0.60 B-D	0.38 CD	1.66 B
CFD 5	370.0 CD	24.0 B-D	386.7 DE	22.2 CD	30.7 CD	34.2 C	3.3 E	0.41 DE	0.27 D	1.18 CD
CS	990.0 A	44.0 A	886.7 A	51.2 A	97.2 A	7.3 A	44.1 A	1.57 A	1.37 A	3.17 A
SD 2-4	606.7 B	28.7 BC	603.3 BC	34.7 B	51.2 B	5.7 AB	11.6 D	0.73 BC	0.82 B	1.68 B
SD 2-4/6-8	486.7 BC	19.7 CD	720.0 B	26.7 BC	32.1 CD	4.2 BC	29.9 B	0.82 B	0.77 B	1.50 BC
SD 4-6	313.3 D	18.7 CD	453.3 C-F	17.5 CD	23.1 D	2.7 C	13.2 D	0.46 DE	0.58 BC	1.08 CD
SD 4-8	350.0 CD	19.0 CD	513.3 CD	19.3 CD	25.3 D	3.9 C	19.6 C	0.66 B-D	0.67 B	1.17 CD
SD 6-8	263.3 D	14.7 D	406.7 DE	16.3 D	21.5 D	2.5 C	16.9 CD	0.52 C-E	0.40 CD	1.01 D
LSD (0.05)	134.9	9.5	162.0	8.7	16.1	1.6	5.4	0.23	0.22	0.43
LSD (0.01)	185.9	13.0	223.2	12.0	22.2	2.2	7.4	0.32	0.31	0.60

*In a column treatment means having common letter are not significantly different by DMRT at alpha 5%.

Table 12. Influence of nine water regimes on the total uptake of mineral nutrients by rice (IR54) grains plus straw at harvest in Louisiana-1 soil.

Treatment	N	P	K	g/pot		Fe	Mn	mg/pot	
				Ca	Mg			Zn	Cu
CF	2.21 D	0.15	1.20	0.14	0.28	22.8	41.4 D	4.8 C	2.4 C
CFD 10	2.23 D	0.18	1.46	0.18	0.36	41.0	56.7 CD	6.4 BC	3.1 C
CFD 5	2.14 D	0.19	1.51	0.17	0.36	38.3	45.9 D	6.6 BC	3.2 C
CS	2.92 BC	0.16	1.35	0.21	0.46	40.4	133.4 A	11.3 A	5.1 AB
SD 2-4	3.52 A	0.20	1.37	0.22	0.44	36.9	71.6 B-D	7.0 B	4.1 B
SD 2-4/6-8	3.52 A	0.19	1.42	0.21	0.42	37.6	97.6 B	8.5 B	5.3 A
SD 4-6	2.81 C	0.18	1.62	0.18	0.42	33.8	72.1 B-D	6.9 BC	4.2 B
SD 4-8	3.37 AB	0.21	1.67	0.18	0.38	37.7	83.0 BC	7.5 B	5.5 A
SD 6-8	2.94 BC	0.17	1.54	0.17	0.36	38.6	82.2 BC	6.8 BC	4.2 B
LSD (0.05)	0.51	ns	ns	ns	ns	ns	28.4	2.0	0.9
LSD (0.01)	0.70	ns	ns	ns	ns	ns	39.1	2.8	1.2

*In a column treatment means having common letter are not significantly different by DMRT at alpha 5%.

Table 13. Influence of nine water regimes on the dry weight of eight week old shoot, grain yield and straw yield of rice (IR54) grown in Luisiana-1 soil.

Treatment	Shoot dry weight	Grain yield g/pot	Straw yield	ΔGY (%)
CF	8.1 D	29.1 D	59.8 C	-
CFD 10	14.8 B	39.1 C	68.2 BC	+34.4
CFD 5	10.5 CD	38.0 C	72.1 BC	+30.6
CS	28.6 A	39.3 C	95.9 A	+35.0
SD 2-4	17.1 B	48.6 A	78.6 AB	+67.0
SD 2-4/6-8	14.5 BC	46.9 AB	84.8 AB	+61.2
SD 4-6	9.2 D	51.6 A	72.2 BC	+77.3
SD 4-8	10.3 CD	47.3 AB	79.6 AB	+62.5
SD 6-8	8.3 D	41.3 BC	67.9 BC	+41.9
LSD (0.05)	4.0	6.2	16.7	
LSD (0.01)	5.6	8.5	23.0	

$$\Delta GY = \frac{(\text{Grain yield in a treatment} - \text{Grain Yield in CF})}{(\text{Grain Yield in CF})} \times 100$$

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

rice shoots in this soil. Water regime seemed not to have affected total P uptake by rice at harvest in this soil (Table 12).

Potassium

In general, soil drying and reflooding increased the K concentration of 8 week-old rice shoot while maintaining soil under continuous saturation (CS) decreased it (Table 9). Soil drying for 2 or 4 weeks at 4 WAT onwards did not decrease the K concentration of rice straw but soil drying for 2 weeks at the initial stage (2-4 WAT) and two cycles of soil drying of 2 weeks and reflooding (2-4 and 6-8 WAT) decreased the K concentration of rice straw (Table 10). Reducing the available water from flooding to saturation also decreased the K concentration of rice straw. Total K uptake by rice shoots was lowest under continuously flooded water regime (CF) while drainage (CF D10), maintaining the soil at saturation (CS), and drying and reflooding the soil increased it (Table 11). However, the total uptake of K by rice at harvest was not affected by water regimes (Table 12).

Calcium and magnesium

Reducing the available water from flooding to saturation decreased the Ca concentration of rice shoot but it increased its Mg concentration (Table 9). Soil drying for 2 or 4 weeks and reflooding did not affect the Ca concentration of rice shoot. Two cycles of soil drying for 2 weeks each and reflooding (SD 2-4/6-8) and 4 weeks of soil drying and reflooding (SD4-8) decreased the Mg concentration of rice shoot. But neither the Ca and Mg concentration of straw (Table 10) nor their uptake by rice at harvest (Table 12) was affected by water regimes.

Total uptake of both Ca and Mg by rice shoots were lowest under continuously flooded water regime while these were highest under continuous saturation (CS) (Table 11). Drainage of 10 mm/day (CF D10) and drying the soil for 2 weeks and reflooding at early stage (SD 2-4) increased uptake of both Ca and Mg by shoots.

Iron

Despite the very low concentration of Fe^{2+} in soil solution during during drying and after reflooding (Fig. 30) the Fe concentration of rice shoot and straw under alternate flooded and dried conditions were not significantly lower than that under flooded condition (Tables 9, 10).

Because of low dry matter production, total Fe uptake by shoot was lowest under continuously flooded water regime (CF) (Table 11). Drainage of 10 mm/day (CF D10), maintaining the soil at saturation (CS) and drying the soil for 2 weeks and reflooding in the beginning (SD 2-4) increased total Fe uptake by shoot. However, total Fe uptake by the crop at harvest was not affected by water regime.

Manganese

Although the change in soil solution Mn^{2+} concentration due to soil drying and reflooding was not reflected in the kinetics data (Fig. 31), the concentration of this nutrient element in shoot (Table 9) and mature straw (Table 10) and its uptake by rice shoot (Table 11) and at harvest (Table 12) increased by alternate drying and reflooding the soil.

Zinc and copper

Soil drying and reflooding increased the Zn and Cu concentration of both, shoot and mature straw and their uptake by rice shoot as well as at harvest (Tables 9,10,11,12). The concentration of both these nutrient elements as well as their uptake were lowest under continuously flooded condition (CF), and drainage of 5-10 mm/day (CF D5, CF D10) did not improve it. But decreasing water in the soil from flooded condition (CF) to saturated condition (CS) increased the concentration of these elements in shoot and mature straw and their uptake by shoot and at harvest.

Silica

Decreasing the available water from flooded (CF) to saturated (CF) condition did not affect the SiO_2 concentration of rice shoot and mature straw (Tables 9,10). Soil drying for 2 or 4 weeks, from 4 WAT increased the SiO_2 concentration of rice shoot but not of straw. However, 2 soil drying cycles of 2 weeks each and reflooding (SD 2-4/6-8), decreased the SiO_2 concentration of rice shoot but its concentration in straw at harvest was not affected.

Total uptake of SiO_2 by rice shoot was lowest under continuously flooded condition and drainage (CF D10) or maintaining the soil at saturation (CS), or soil drying for 2 weeks and reflooding in the beginning (SD2-4) increased it (Table 11). Soil drying for 2 or 4 weeks from 4 WAT, did not increase the SiO_2 uptake by shoots.

Relationship Between Soil Solution Chemical Kinetics and Mineral Nutrition of Rice

The results of this experiment seem to indicate that there are factors other than the concentration of mineral nutrients in soil solution governing mineral nutrition and growth of rice plants.

Soil solution kinetics data showed lower concentration of NH_4^+ -N, K^+ , Ca^{2+} , Mg^{2+} and Fe^{2+} in soil solution under alternately dried and reflooded water regimes compared to that under continuously flooded water regime. But in the case of total plant uptake of these nutrients, the opposite was true.

Although the kinetics of P and Mn^{2+} in soil solution were not affected by water regime, total plant uptake of these nutrients were higher under flooded drained (CF D5, CF D10), saturated (CS) and alternately dried and reflooded water regimes than under continuously flooded water regime (CF).

It is possible that, in this soil high reducing conditions under continuously flooded water regime could be a reason for the observed differences between soil solution kinetics and nutrient uptake by plants. It is worth mentioning that in experiment 1 where a near neutral fertile soil (Maahas-1) was used, the mineral nutrition of plants followed closely the soil solution nutrient kinetics.

Growth and Yield of Rice (IR54)

Plant height

Plants were shortest under continuously flooded water regime while they were tallest under continuously saturated water regime (Fig. 34A). Drainage of 10 mm/day (CF D10) increased the plant height but 5 mm/day

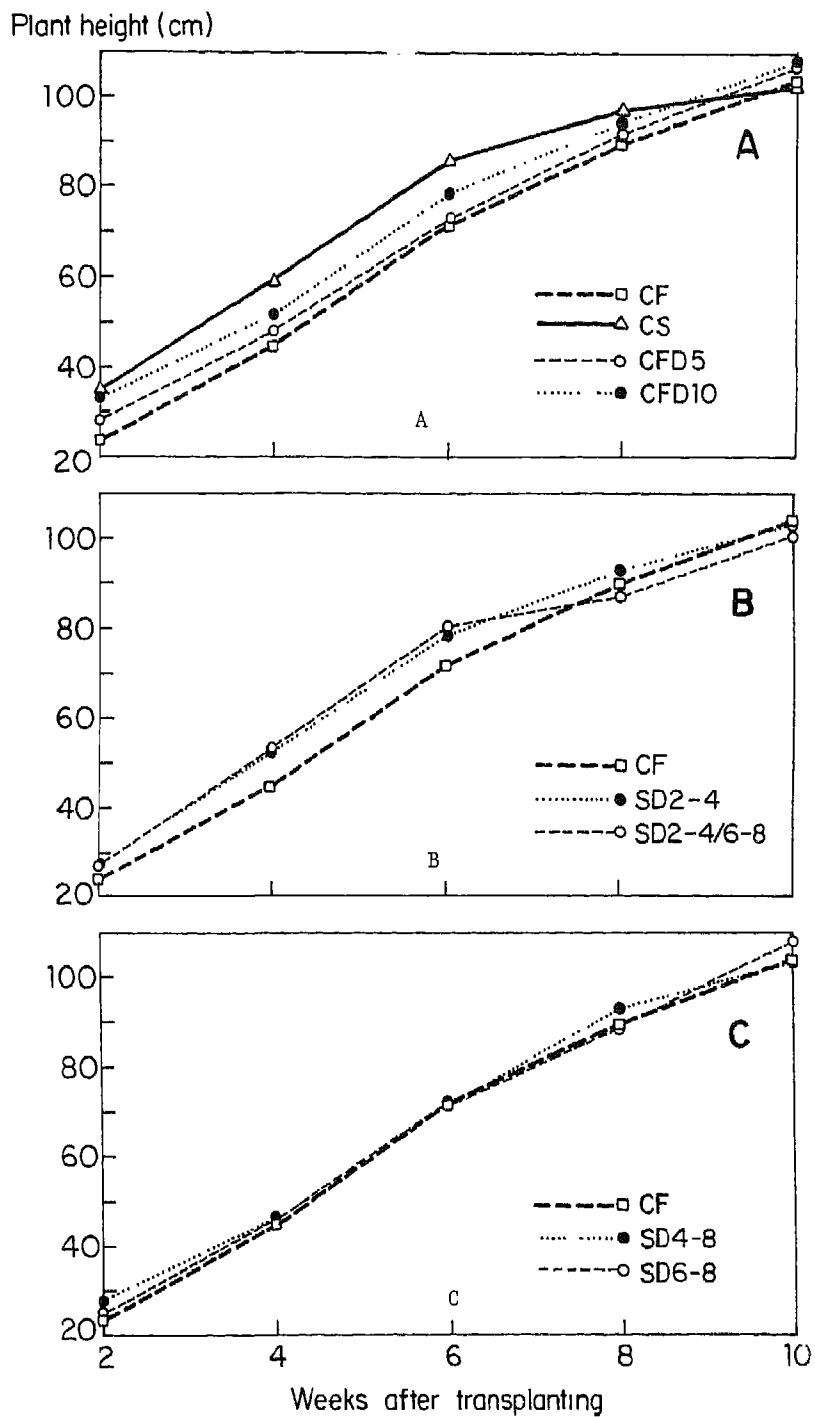


Fig. 34. Influence of nine water regimes on height of rice plants at different growth stages in Luisiana-1 soil.

drainage had no effect on plant height. Soil drying, in general, had little effect on plant height (Fig. 34B-C).

Tiller number

Changes in the number of tillers per hill upto 10 WAT are presented in Figure 35. Tillers per hill were lowest under continuously flooded water regime (CF) while it was highest under continuous saturation regime (CS) (Fig. 35A). Drainage of 5-10 mm/day improved the tillering of the plant only slightly. Soil drying for 2 weeks at the early stage (SD2-4; SD2-4/6-8) increased the number of tillers markedly (Fig. 35B) but soil drying and reflooding at later stages (SD 4-6; SD 4-8; SD 6-8) did not increase the number of tillers very much (Fig. 35C).

Visual symptoms

At the vegetative growth stage (5 WAT) plant growth was poorest under continuously flooded condition (CF) and best under continuously saturated (CS) condition. Drainage of 5-10 mm/day (CF D5, CF D10) and soil drying for 2 weeks (SD 2-4) improved plant growth (Plate 4). The poor plant growth under continuously flooded condition (CF) could be attributed to highly reduced condition that existed in this soil as indicated by low Eh, high oxidizable matter, high $^P\text{CO}_2$ and high Fe^{2+} in soil solution. Although the tissue Fe-concentration at 8 WAT was very high (442 ppm) under continuously flooded water regime, the plants did not show clear symptoms of Fe toxicity. Soil drying for 2 to 4 weeks and reflooding during active tillering stage improved plant growth as was evident from the higher number of tillers (discussed earlier).

Tillers/hill

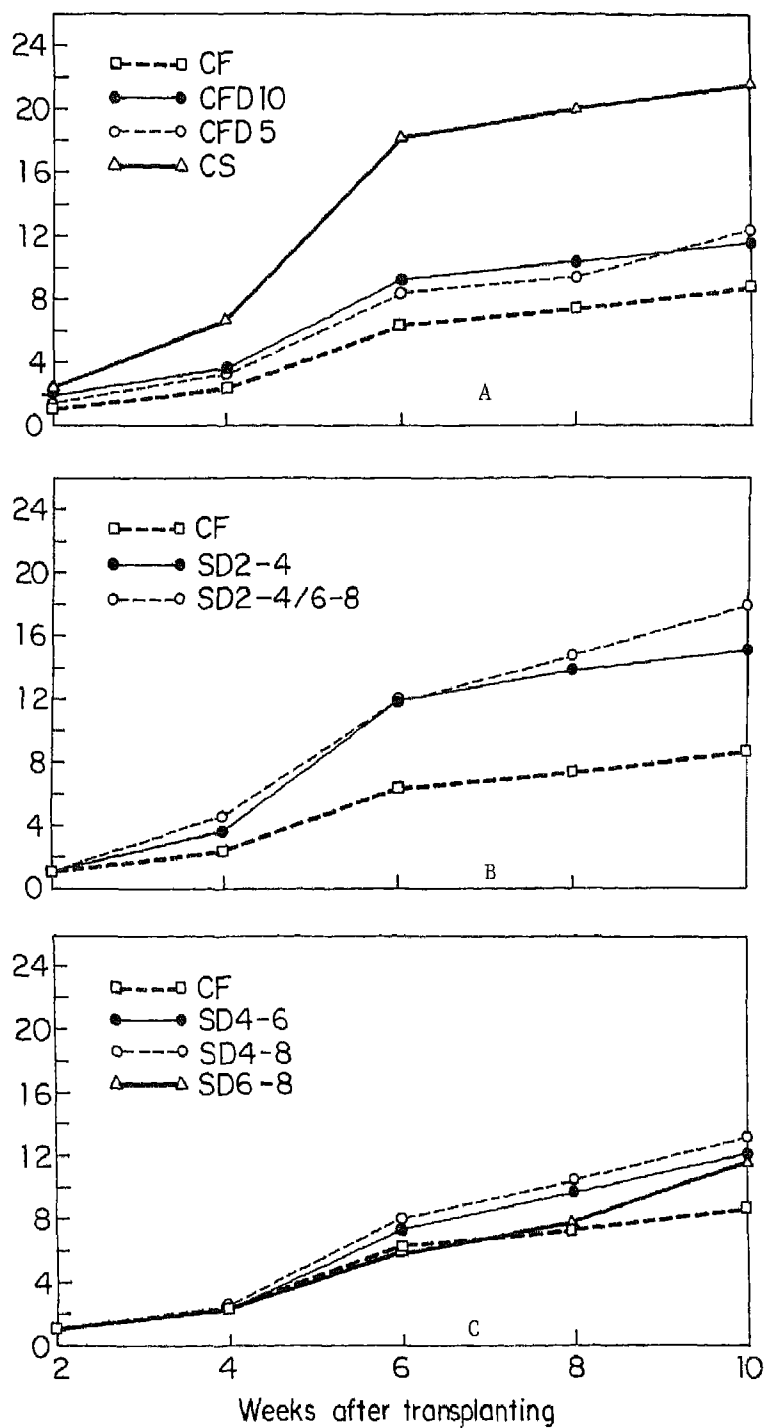


Fig. 35. Influence of nine water regimes on tillering of rice at different growth stages in Louisiana-1 soil.

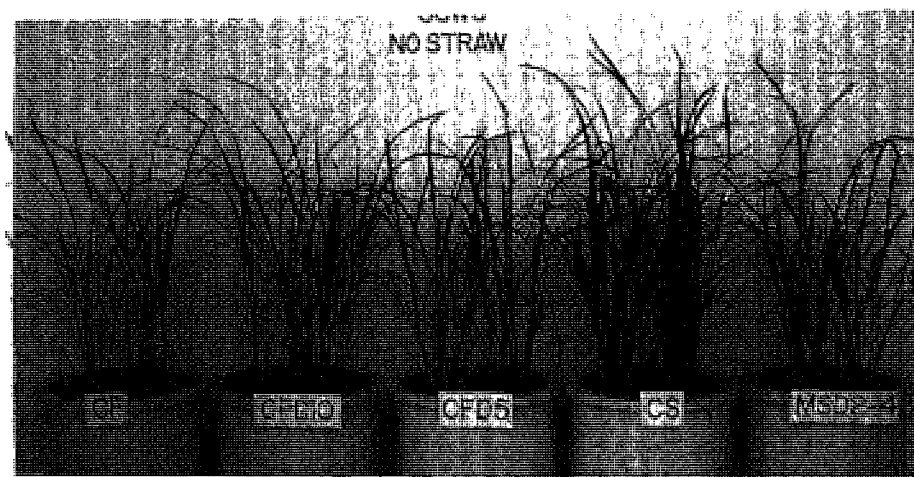


Plate 4. Influence of water regime on rice (IR54) growth in Luisiana-1 soil (MSD 2-4 is SD 2-4 in the text).

Dry weight of 8 weeks old shoot

Continuously saturated water regime (CS) produced highest dry matter of 28.6 g/pot at 8 WAT stage while continuous flooding (CF) produced the lowest (Table 13). Drainage of 5-10 mm/day (CF D5, CF D10) increased the dry matter yield. Soil drying for 2 weeks, and two soil drying cycles of 2 weeks each, increased the dry matter yield significantly at this stage.

Grain yield

Continuously flooded water regime produced the lowest grain yield of 29.1 g/pot (Table 13). Unlike in the neutral fertile Maahas soil, drainage of 5-10 mm/day (CF D5, CF D10) increased the rice grain yield by 30 to 36%. Saturated condition (CS) produced 35% more grains compared to flooded condition (CF) in this soil. Soil drying and reflooding treatments increased markedly grain yield to different extents depending on the time and duration of drying. Soil drying for 2 weeks imposed at 4 WAT and reflooding (SD 4-6) produced the highest grain yield which was 77.3% more than that in the continuously flooded water regime.

Straw yield

Lowest straw yield of 59.8 g/pot was obtained in continuously flooded (CF) water regime while continuously saturated water regime (CS) produced the highest straw yield of 95.9 g/pot (Table 13). Drainage did not increase the straw yield significantly. Although in all the drying and reflooding treatments, increase in straw yield over continuously

flooded water regime was observed, the difference in straw yield was not statistically significant when 2 weeks of soil drying treatment was imposed 4 and 6 weeks after transplanting of rice.

Experiment 3

Influence of Four Water Regimes on the Chemical
Kinetics and Rice Growth in Three Soils

In experiment 1, soil drying and reflooding at different rice growth stages was found to adversely affect the mineral nutrition of rice and decreased rice grain yield on a near neutral fertile Maahas soil but in experiment 2 in a potentially iron toxic soil (Luisiana-1), soil drying and reflooding at different rice growing stages was found to influence mineral nutrition of rice favorably and increased rice grain yield. Rice yields are poor in zinc and/or sulfur deficient soils and soil drying might help to improve rice growth in these soils. Therefore, in this experiment two soils deficient in both Zn and S (Maahas-2 and San Manuel) were used. One acid Luisiana soil with lower active iron content than the one used in experiment 2 was also included.

MATERIALS AND METHODS

Design

The experiment was laid out in a 4 x 3 factorial randomized complete block design with three replications.

Factors and levels

A. Soils:

- i. Maahas-2 (Tropudalf)
- ii. Luisiana-2 (Tropudult)
- iii. San Manuel (Eutropept)

Some characteristics of these soils are presented in Table 14.

B. Water regimes:

- i. Continuously flooded (CF)
- ii. Soil drying for 2 weeks imposed 6 weeks after transplanting (WAT) and reflooding (SD 6-8)
- iii. Soil drying and reflooding for 2 weeks imposed 4 and 8 WAT (SD 4-6/8-10)
- iv. Soil drying and reflooding for 2 weeks imposed 2 and 6 WAT (SD 2-4/6-8).

Greenhouse procedure

Bulk samples of the three soils were collected from the field from 0-20 cm depth, air-dried, crushed to 0.6 cm clods and mixed thoroughly.

Ten kg portion of the soils were mixed with N, P and K at the rate of 100, 25 and 75 mg/kg soil respectively and placed carefully in 16 L glazed porcelain pots. Urea, KH_2PO_4 and KCl were used as source of N, P and K. No zinc and sulfur were applied to the soils. A tensiometer was placed at 10 cm depth in each pot for in situ measurement of soil moisture tension. As the Luisiana-2 soil had less active Fe compared to Luisiana-1, it was not kept preflooded before transplanting of rice.

Soil solution was collected from each pot at 0, 2, 4, 6, 8 and 10 weeks after transplanting of rice following the methods described in experiment 1.

Two plants were harvested from each pot at 6 WAT and the remaining two plants were grown to maturity, and grain and straw yields were recorded. All other greenhouse procedures were same as in the earlier experiments.

Table 14. Some characteristics of the soils used in experiment 3.

	Maahas-2	Luisiana-2	San Manuel
pH (1:1)	6.6	4.5	7.5
Organic carbon (%)	1.65	2.47	0.90
Total N (%)	0.14	0.24	0.08
Total S (%)	0.10	0.08	0.05
Available			
N (mg/kg)	55.7	150.2	30.1
P (Olsen) (mg/kg)	30.9	2.9	7.9
S (mg/kg)	4.1	67.6	2.3
Zn (mg/kg)	0.36	3.32	0.12
Cu (mg/kg)	0.06	5.80	0.08
Exchangeable			
K (me/100 g)	1.80	0.25	0.30
Ca (me/100 g)	17.75	13.20	37.97
Mg (me/100 g)	12.60	6.10	6.93
Active			
Fe (%)	2.9	4.6	1.3
Mn (%)	0.19	0.03	0.06
Water soluble Si (mg/kg)	219.0	110.6	82.7
CEC (me/100 g)	47.0	44.6	45.5
Mechanical analysis			
Clay (%)	29	71	31
Silt (%)	50	26	51
Sand (%)	21	3	16
Textural class	Silty clay loam	Clay	Clay

Growth observation and yield data

Growth and yield of rice in the pots were observed by determining:

- i. plant height and tiller number at different growth stages
- ii. dry matter yield of shoot at 6 WAT
- iii. grain yield
- iv. straw yield

Analytical Procedures

1. Soil

The initial soil samples were analyzed for pH, organic carbon, total N and S; available N, P, S, Zn and Cu; water soluble Si; active Fe and Mn; exchangeable K, Ca and Mg; and particle size distribution following the methods described in experiment 1.

2. Soil solution

The pH, Eh, EC, and NH_4^+ -N, P, K^+ , Ca^{2+} , Mg^{2+} , Fe^{2+} , Mn^{2+} , Zn^{2+} , Si(OH)_4 , and HCO_3^- concentration of the soil solution samples were analyzed following the methods described in experiments 1 and 2. A portion of the soil solution from each pot was flocculated by adding a few drops of 10% AlCl_3 and 25% NaOH. The SO_4^{2-} -S concentration of these flocculated soil solution samples were determined following turbidimetric method standardized by PCARRD (1980). The $^{\text{P}}\text{CO}_2$ in soil solution was calculated following the method described in experiment 2.

3. Plant samples

Shoot and straw samples were analyzed for total P, K, Ca, Mg, Fe, Mn, Zn, Cu and crude silica following the methods described in experiment 1. Total S and N were determined in the shoot, straw and grain samples. Total S was determined by digesting plant samples with NaOBr (Tabatabai and Chae, 1982) and SO_4 -S estimated following methylene blue method (Johnson and Nishita, 1952). Due to lack of enough grain samples in Maahas-2 soil, the grains could not be analyzed for other nutrients.

Calculations

Total uptake of nutrients by shoot and grain plus straw at harvest were calculated using formulae described in experiment 1. All the statistical analyses were performed using an IBM PC XT microcomputer with the help of standard statistical programmes.

RESULTS AND DISCUSSION

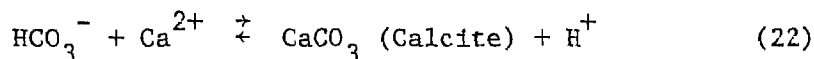
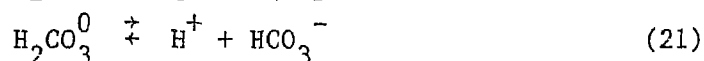
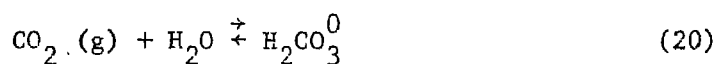
Chemical Kinetics of Soil Solution

On the sampling dates soil solutions were collected from all three replications of each treatment and analyzed. The results presented graphically in the following pages are the mean of three replications.

pH

Regardless of their original pH values all the three soils reached soil solution pH of 6.9 within 6 weeks after flooding and remained at that level until dried (Fig. 36). pH changes reversed during drying periods which again started approaching neutrality on reflooding.

The pH increase in the near neutral Maahas-2 (Fig. 36A) and acid Louisiana-2 (Fig. 36B) soil were due to the release OH^- ions when $\text{Fe}(\text{OH})_3$ and similar compound were reduced to $\text{Fe}(\text{OH})_2$ or $\text{Fe}_3(\text{OH})_8$ (Ponnamperuma, 1972). The pH decrease on flooding calcareous San Manuel clay loam soil (Fig. 36C) can be explained as follows:



The H^+ liberated due to the above reactions decrease the pH of calcareous soil on flooding.

The increase in pH of calcareous San Manuel soil on drying could be because the $\text{CaCO}_3\text{-H}_2\text{O-CO}_2$ system stopped operating during the dry periods.

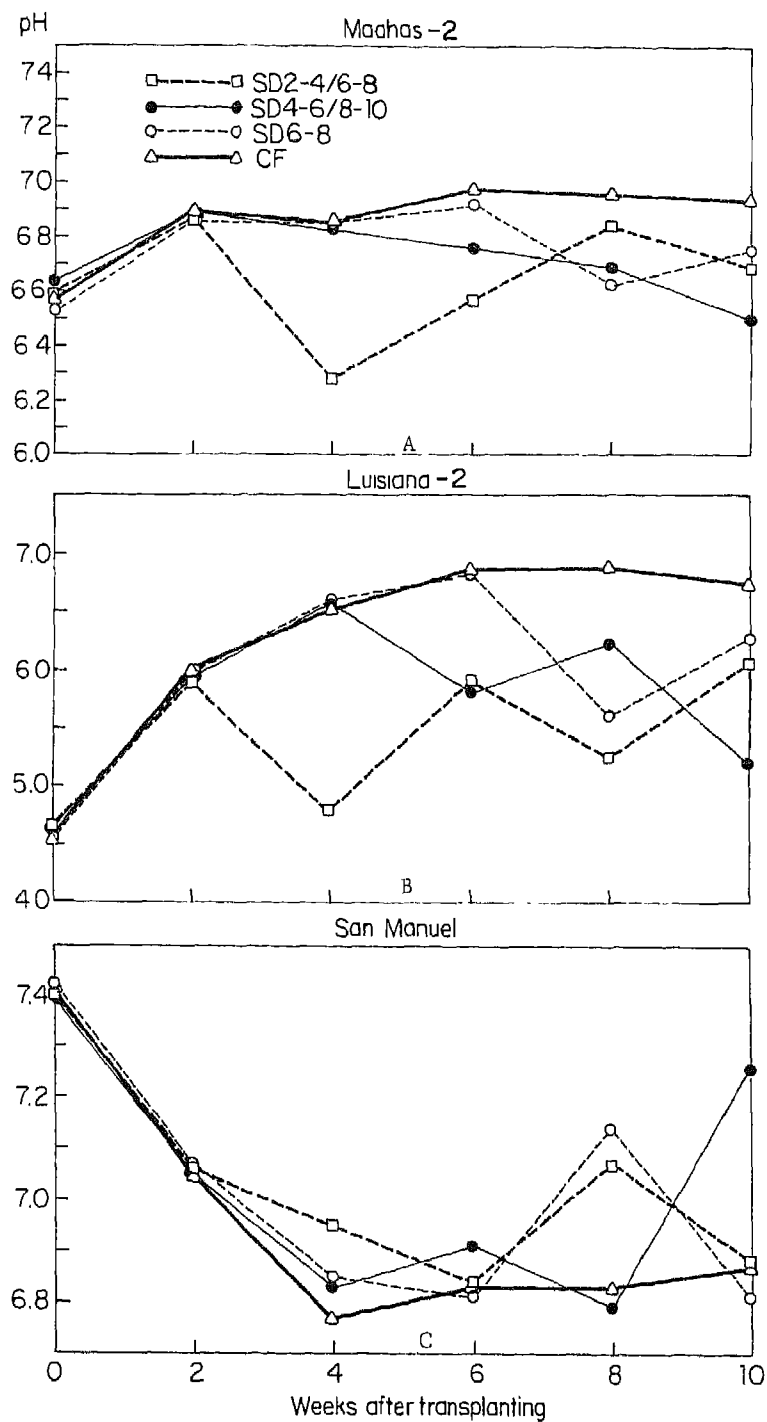


Fig. 36. Influence of four water regimes on kinetics of solution pH in three soils.

Eh

Soil solution Eh decreased sharply on flooding and attained a minimum value within 6 weeks after flooding (Fig. 37). The extent of reduction was a function of organic matter content of the soil. Luisiana-2 (Fig. 37B) having very high organic matter (4.26%) attained an Eh value of -81 mV while Maahas-2 (Fig. 37A) and San Manuel (Fig. 37C) soils attained an Eh value of around +100 mV.

Soil drying increased the soil solution Eh in all the soils. Reflooding decreased Eh again but the Eh of reflooded soil solution were higher as compared to those in the continuously flooded soils as was observed in the earlier 2 experiments.

Electrical conductivity (EC)

Flooding caused an initial increase in EC followed by a decreasing trend (Fig. 38). The major components of initial increase of the soil solution EC in Luisiana-2 soil (Fig. 38B) was the water soluble Fe^{2+} and HCO_3^- which increased sharply on flooding while in San Manuel soil (Fig. 38C) it was the water soluble Ca^{2+} . In flooded San Manuel soil EC increased up to 6 weeks after transplanting while in Maahas-2 (Fig. 38A) it continued up to 9 WAT. These increases also corresponded to the increase in water soluble Ca^{2+} , Mg^{2+} , Fe^{2+} and Mn^{2+} in these two soils. In the Luisiana-2 soil the EC started decreasing 4 WAT which corresponded to the decrease in water soluble Fe^{2+} and Mn^{2+} .

Soil drying caused sharp decrease in soil solution EC in all the three soils. This decrease was due to decrease in Fe^{2+} , Mn^{2+} , Ca^{2+} , Mg^{2+} and CO_2 due to drying.

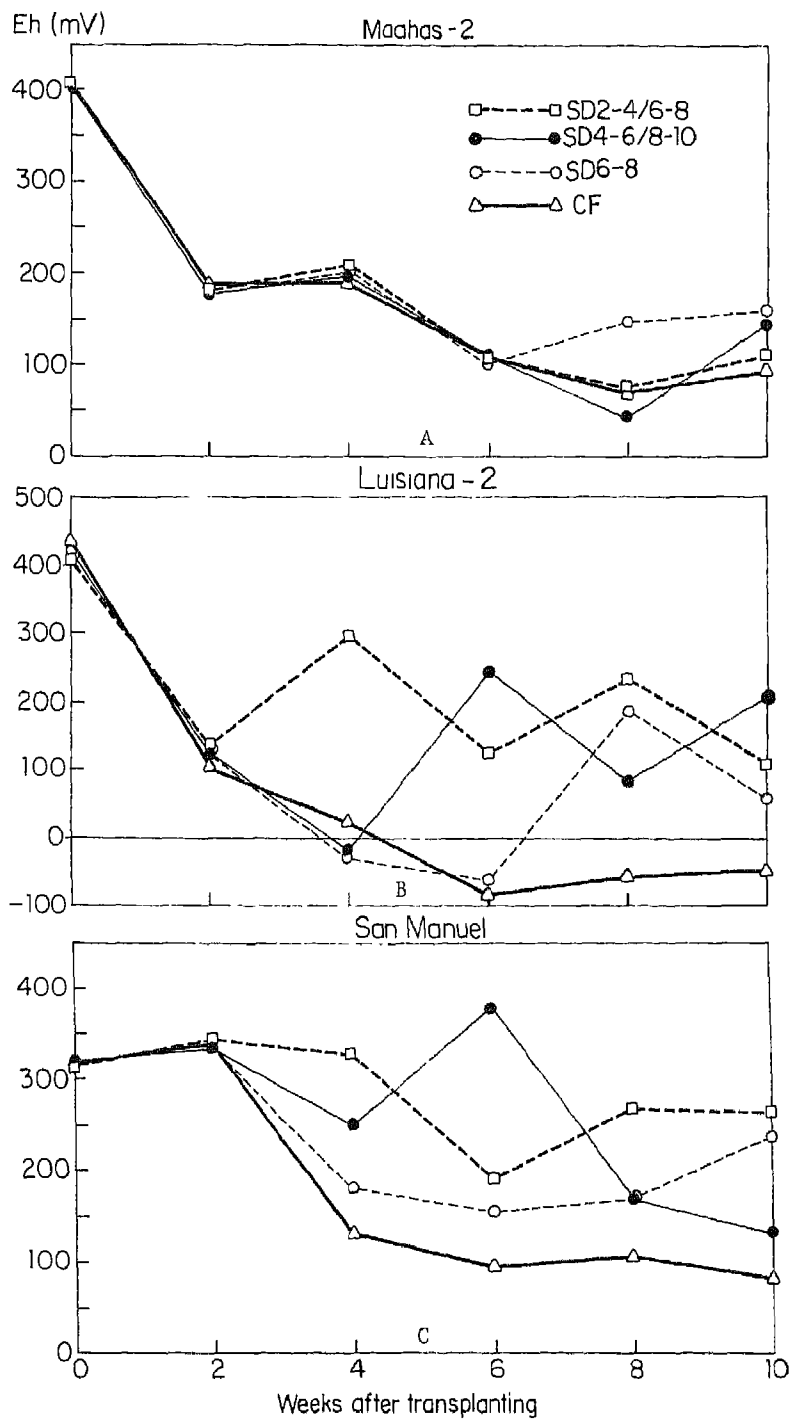


Fig. 37. Influence of four water regimes on kinetics of solution Eh in three soils.

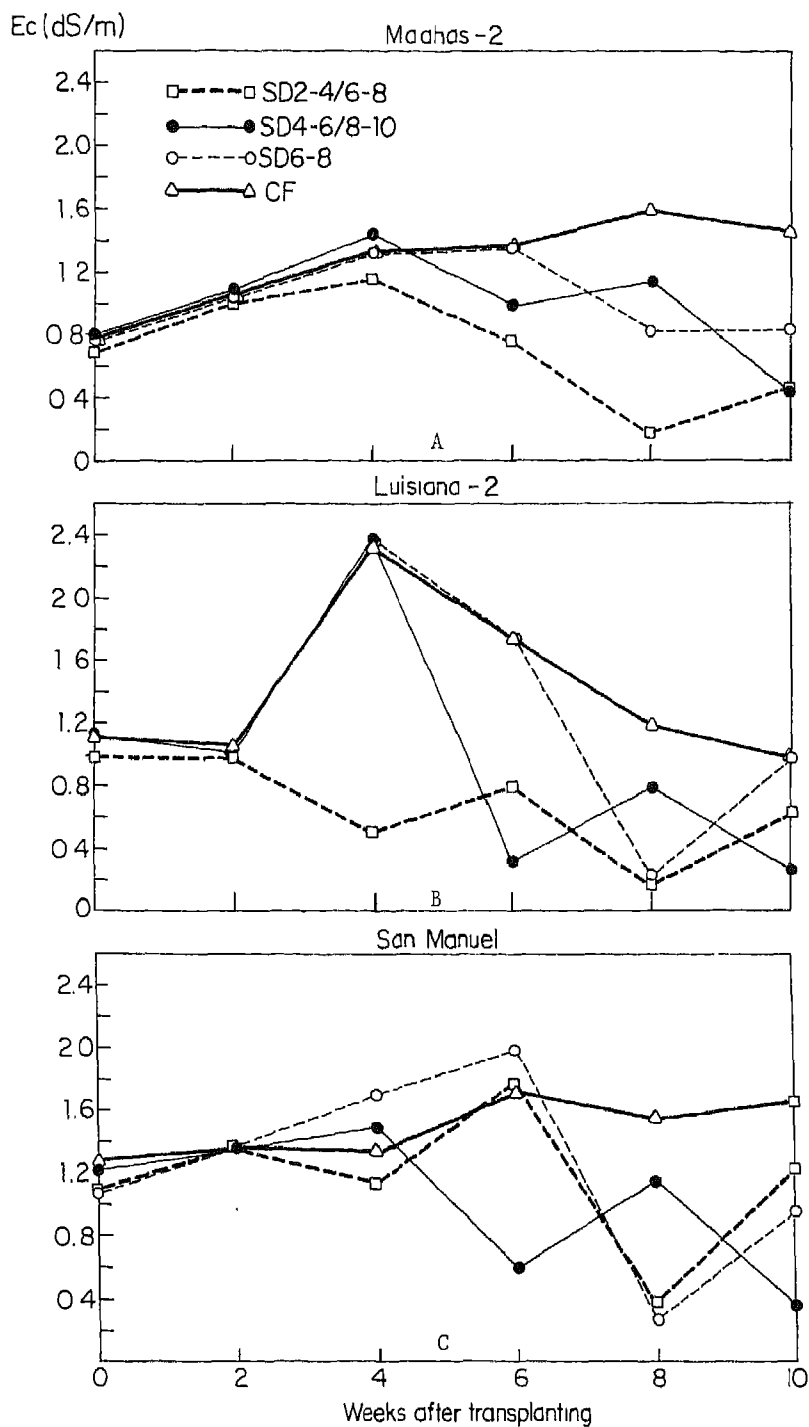


Fig. 38. Influence of four water regimes on kinetics of solution electrical conductivity in three soils.

Bicarbonate (HCO_3^-)

The peak value of bicarbonate in soil solution was obtained between 4-8 WAT depending on the type of soil (Fig. 39). Highest and earliest peak was obtained in Luisiana-2 soil (Fig. 39B) which also had highest organic matter content among the three soils used in the experiment and the lowest Eh. The later decline in soil solution HCO_3^- concentration was due to the loss of CO_2 , precipitation of Fe^{2+} and Mn^{2+} as carbonates (Ponnamperuma, 1985; Schwab and Lindsay, 1983) and in San Manuel soil probably due to formation of CaCO_3 .

Soil drying decreased the HCO_3^- concentration of soil solution. This could be due to loss of CO_2 on drying when CO_2 readily diffused out of the soil.

$^{\text{P}}\text{CO}_2$

In all the three soils, $^{\text{P}}\text{CO}_2$ in soil solution increased after flooding (Fig. 40). While in Maahas-2 (Fig. 40A) and San Manuel (Fig. 40C) soils $^{\text{P}}\text{CO}_2$ maintained this increasing trend upto 8 WAT that in Luisiana-2 soil (Fig. 40B) declined after attaining a peak at 4 WAT. The $^{\text{P}}\text{CO}_2$ plots in Luisiana-2 soil ran parallel to that of Ca^{2+} , Fe^{2+} and Mn^{2+} (Figs. 44,47,48). This suggests that carbonates of Ca^{2+} , Fe^{2+} and Mn^{2+} were formed at this stage in the soil.

Soil drying drastically reduced the $^{\text{P}}\text{CO}_2$ in soil solution in all the three soils. On reflooding the dry soil $^{\text{P}}\text{CO}_2$ started to increase again. In Maahas-2 and San Manuel soil $^{\text{P}}\text{CO}_2$ of reflooded soil did not reach the level of continuously flooded soil but in Luisiana-2 soil $^{\text{P}}\text{CO}_2$ by passed that under continuously flooded water

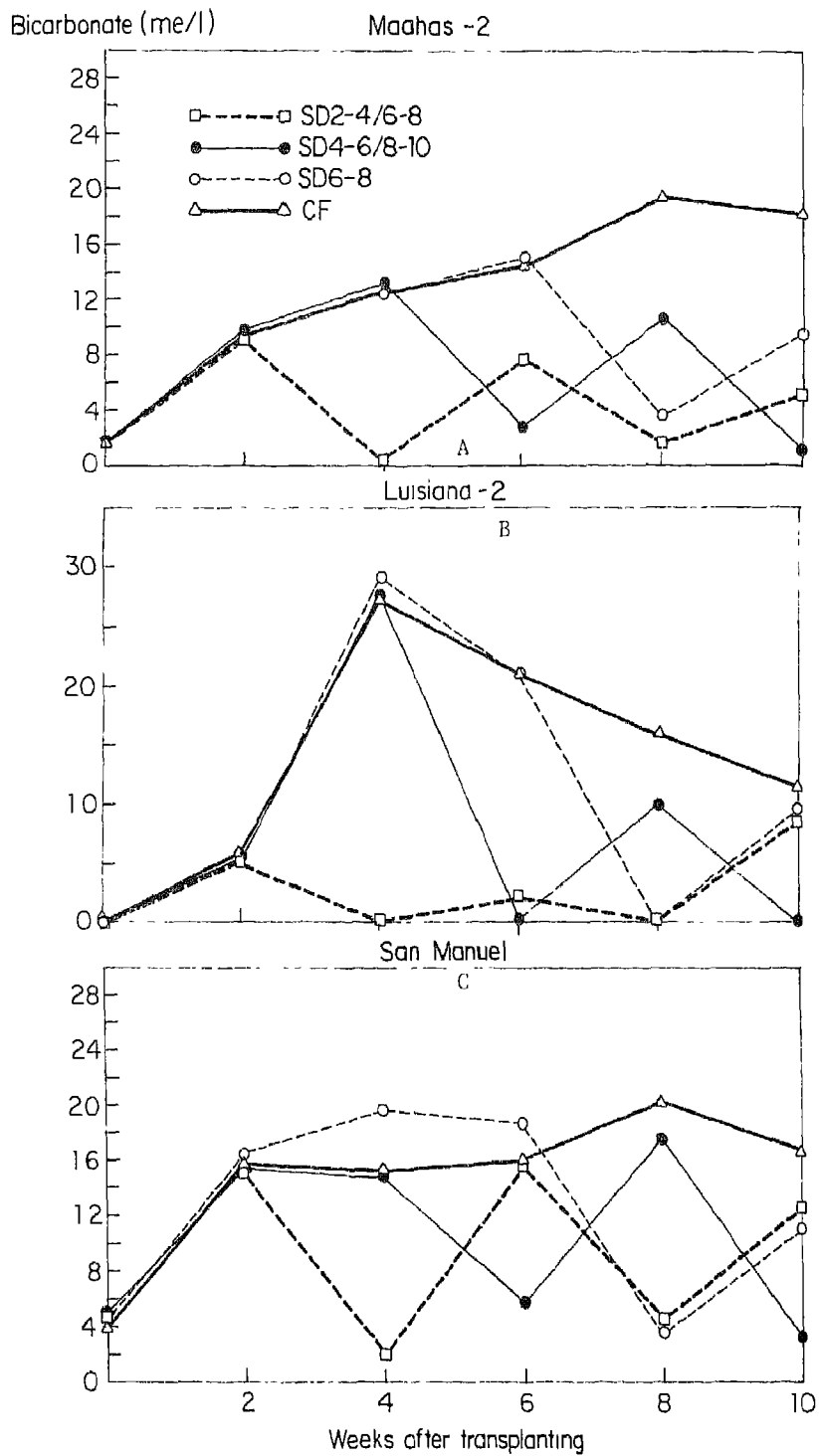


Fig. 39. Influence of four water regimes on kinetics of water-soluble bicarbonate in three soils.

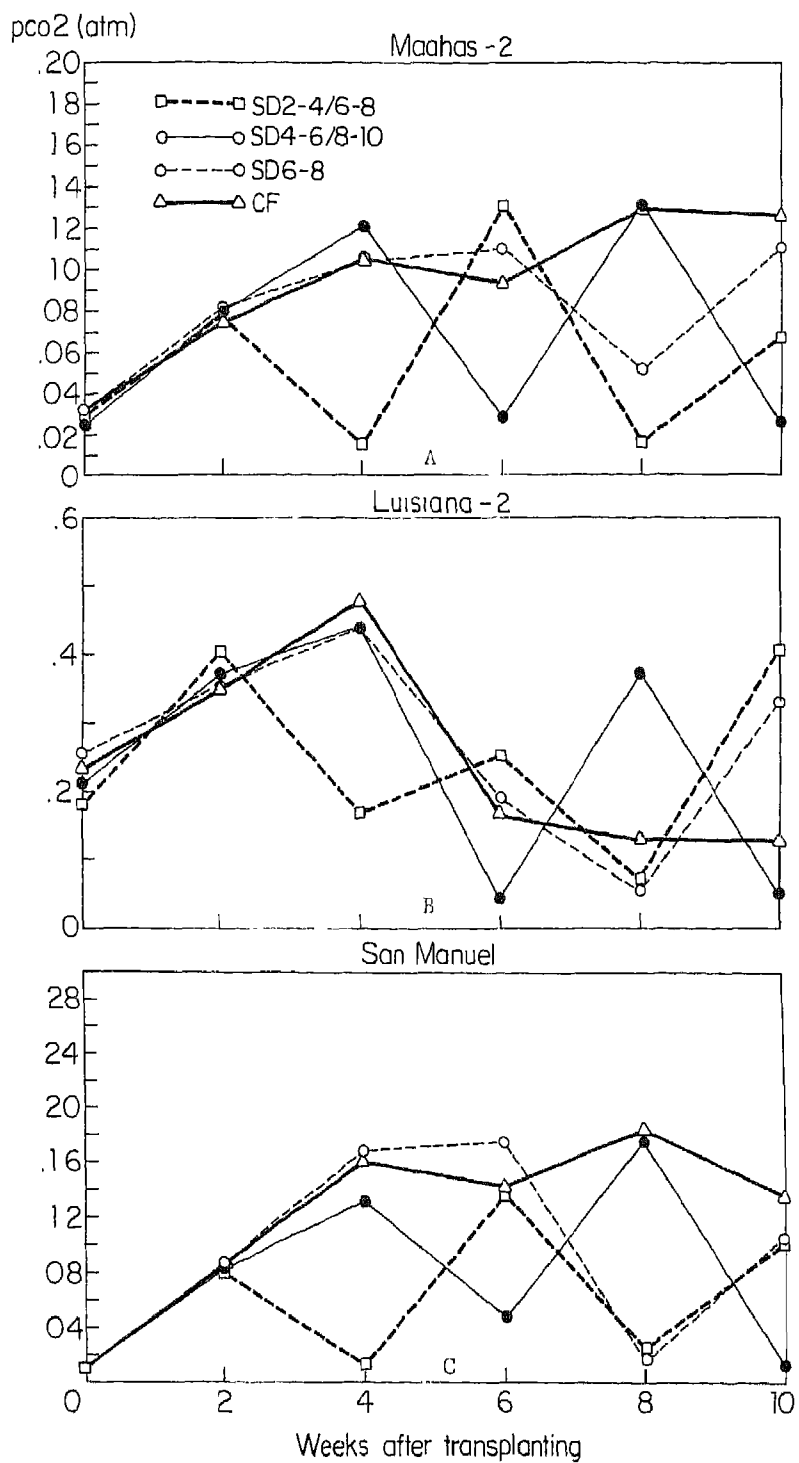
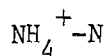


Fig. 40. Influence of four water regimes on kinetics of solution p_{CO_2} in three soils.

regime. This suggests accelerated decomposition of organic matter due to soil drying and reflooding luisiana-2 soil. The $^P\text{CO}_2$ in the Maahas-2 and San Manuel soils did not increase much on reflooding probably due to depletion of most active organic matter in these soils.



All the soils were treated with 100 mg N (as urea) per kg soil on the day of transplanting. On the 2 WAT the NH_4^+-N concentration of the soil solution decreased because of its movement on to the exchange sites of the soils. A portion of NH_4^+-N might also have been lost by NH_3 volatilization. The Luisiana-2 soil (Fig. 41B) showed a rapid increase in NH_4^+-N concentration during the next two weeks probably because of the replacement of NH_4^+-N held on the exchange complex, by Fe^{2+} during that time. Some amount of NH_4^+-N might also have been produced due to mineralization of organic matter. Like in the other two soils, the NH_4^+-N concentration of Luisiana-2 soil also decreased with time. This was because of plant uptake.

Unlike in San Manuel and Luisiana-2 soil (Fig. 41B), the soil solution NH_4^+-N in Maahas-2 (Fig. 41A) soil did not decrease very much with time because of very poor plant growth and so very low N uptake in continuously flooded water regime (Fig. 41B).

In all the soils, drying decreased the NH_4^+-N concentration due to its nitrification. The NO_3^- formed on drying was perhaps lost by denitrification when the dry soils were reflooded.

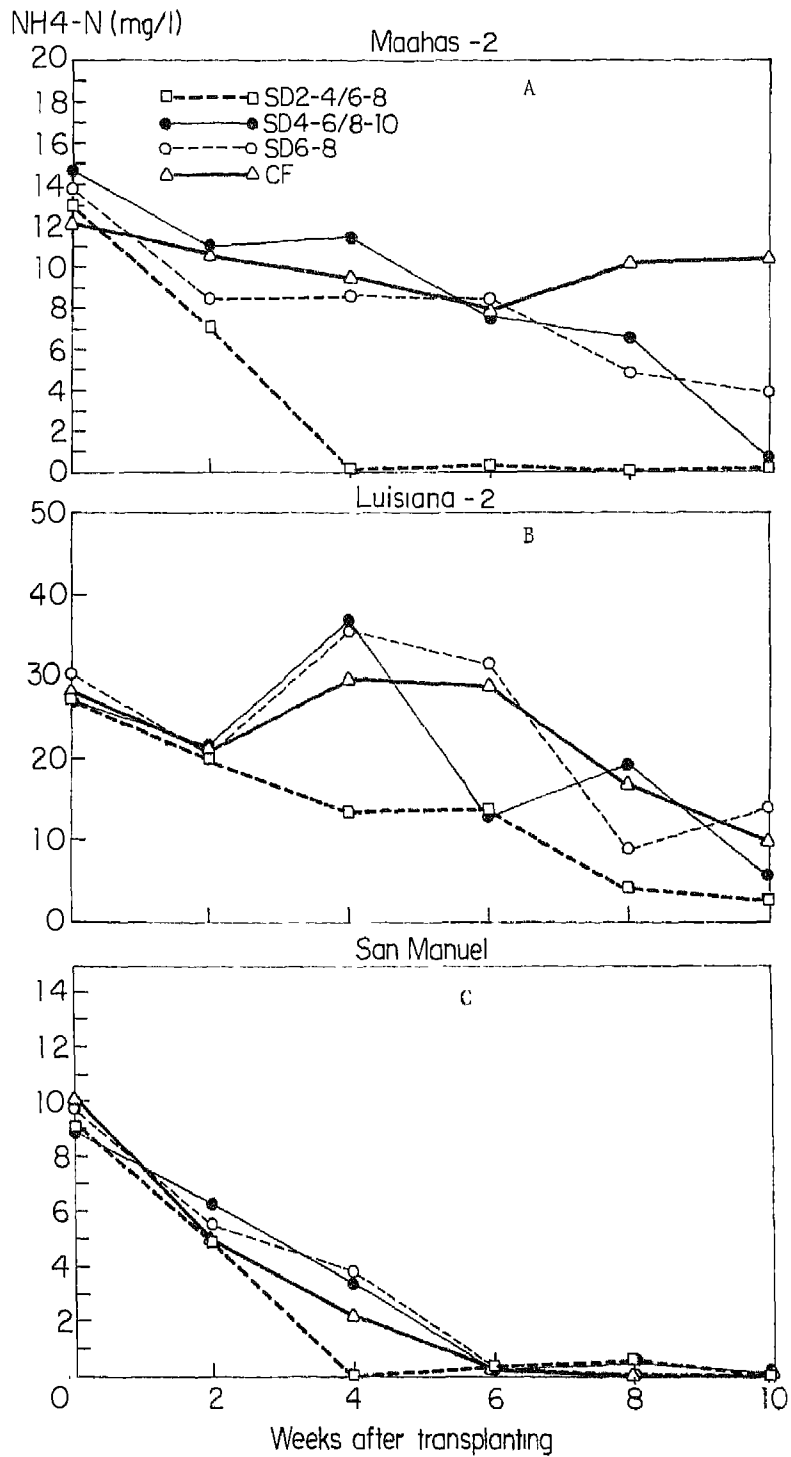


Fig. 41. Influence of four water regimes on kinetics of water-soluble NH_4^+ -N in three soils.

Under continuously flooded water regime no NH_4^+ -N could be detected after 6 WAT in San Manuel soil while small amounts of NH_4^+ -N were found in the other water regimes. This may be attributed to accelerated mineralization of organic nitrogen during soil drying and/or less plant uptake.

Phosphorus (P)

All the soils were treated with phosphorus @25 mg P/kg soil on the day of transplanting. The drop in water soluble P in San Manuel (Fig. 42C) and Maahas-2 soil (Fig. 42A) during the first two weeks after transplanting could be due to adsorption and/or precipitation. A small increase in water soluble P two weeks after flooding in acid Luisiana-2 soil (Fig. 42B) could be due to less fixation of the added P because of increase in pH. Hydrolysis of some iron and aluminum bonded phosphates and desorption by clays and aluminum oxides due to increase in pH (Stumm and Morgan, 1970), desorption following reduction of Fe(III) oxides (Mandal and Mandal, 1973; Patrick and Khalid, 1974) could also be the reasons. The increase in water soluble P eight weeks after transplanting in all the three soils could be because of decrease in plant uptake due to harvesting of two plants from each pot six weeks after transplanting. Decay of the roots of two plants harvested at 6 WAT might also be one of the reasons.

Alternate flooding and drying decreased P concentration of soil solution as was observed in the earlier experiments.

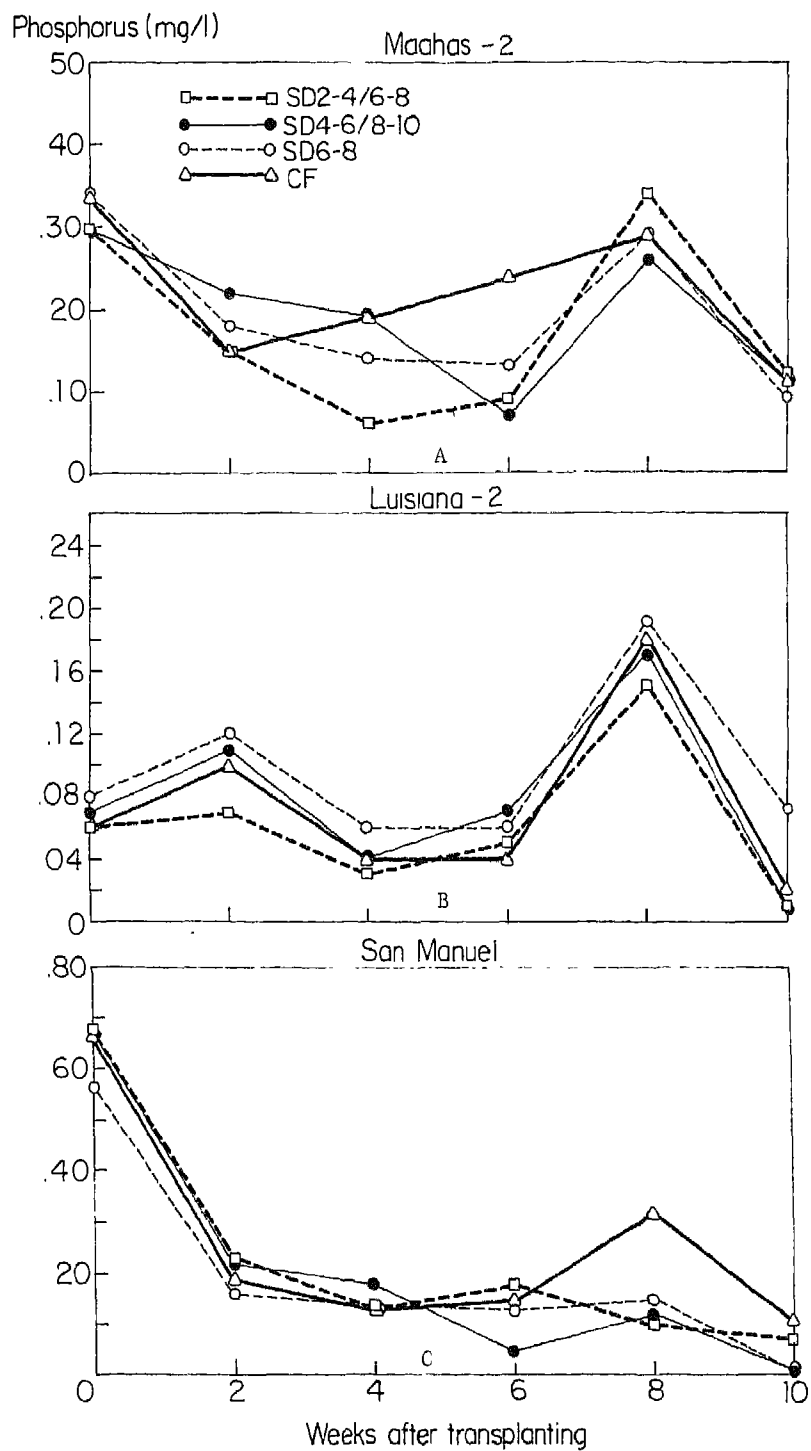


Fig. 42. Influence of four water regimes on kinetics of water-soluble P in three soils.

Potassium (K^+)

Potassium concentration of the soil solution increased gradually with flooding in Maahas-2 soil (Fig. 43A) but it decreased in San Manuel soil (Fig. 43C). In acid Luisiana-2 soil (Fig. 43B) K^+ concentration of soil solution decreased for the first two weeks of flooding, then increased for the next two weeks and decreased gradually thereafter (Fig. 43B).

Soil drying and reflooding decreased soil solution K^+ in Maahas-2 and Luisiana-2 soil but slightly increased it in San Manuel soil.

Calcium and magnesium (Ca^{2+} and Mg^{2+})

Calcium and Mg^{2+} concentrations of the soil solution increased on flooding in all the three soils (Figs. 44,45). While Maahas-2 (Fig. 44A, 45A) and San Manuel soil (Fig. 44C, 45C) maintained the build up of soil solution Ca^{2+} and Mg^{2+} up to 10 WAT, Luisiana-2 soil (Fig. 44B, 45B) showed a decline four weeks after transplanting. The change in soil solution Ca^{2+} and Mg^{2+} corresponded to the change in soil solution Fe^{2+} (Fig. 47) and Mn^{2+} (Fig. 48) and HCO_3^- (Fig. 39). The large quantities of Fe^{2+} and Mn^{2+} and NH_4^+-N ions released upon flooding might have displaced Ca^{2+} and Mg^{2+} from the exchange sites into the soil solution as was reported earlier in experiments 1 and 2.

Soil drying and reflooding decreased the Ca^{2+} and Mg^{2+} concentrations of the soil solution probably because of their transfer onto the exchange sites due to oxidation and reprecipitation of Fe^{2+} and Mn^{2+} on soil drying.

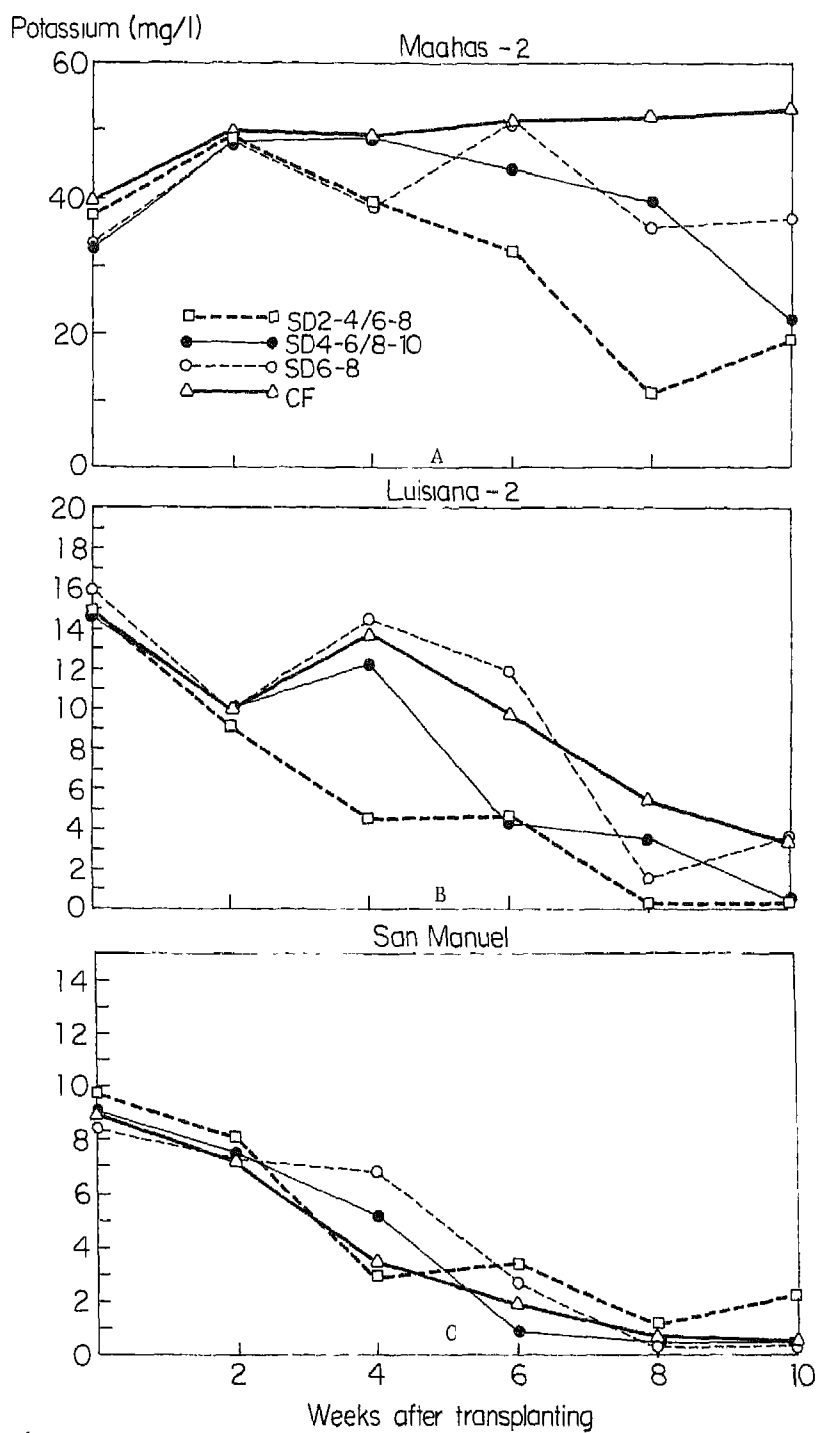


Fig. 43. Influence of four water regimes on kinetics of water-soluble K in three soils.

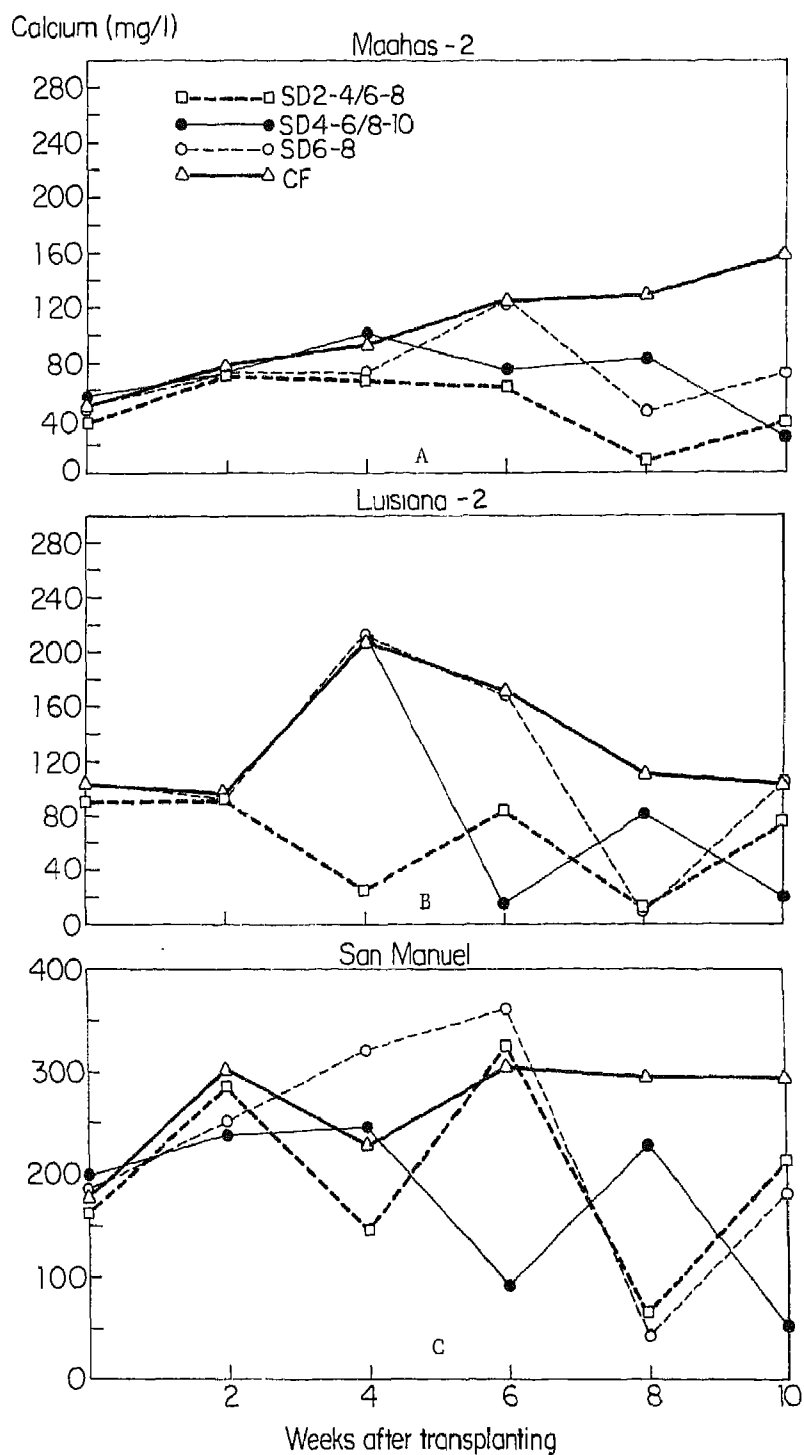


Fig. 44. Influence of four water regimes on kinetics of water-soluble Ca in three soils.

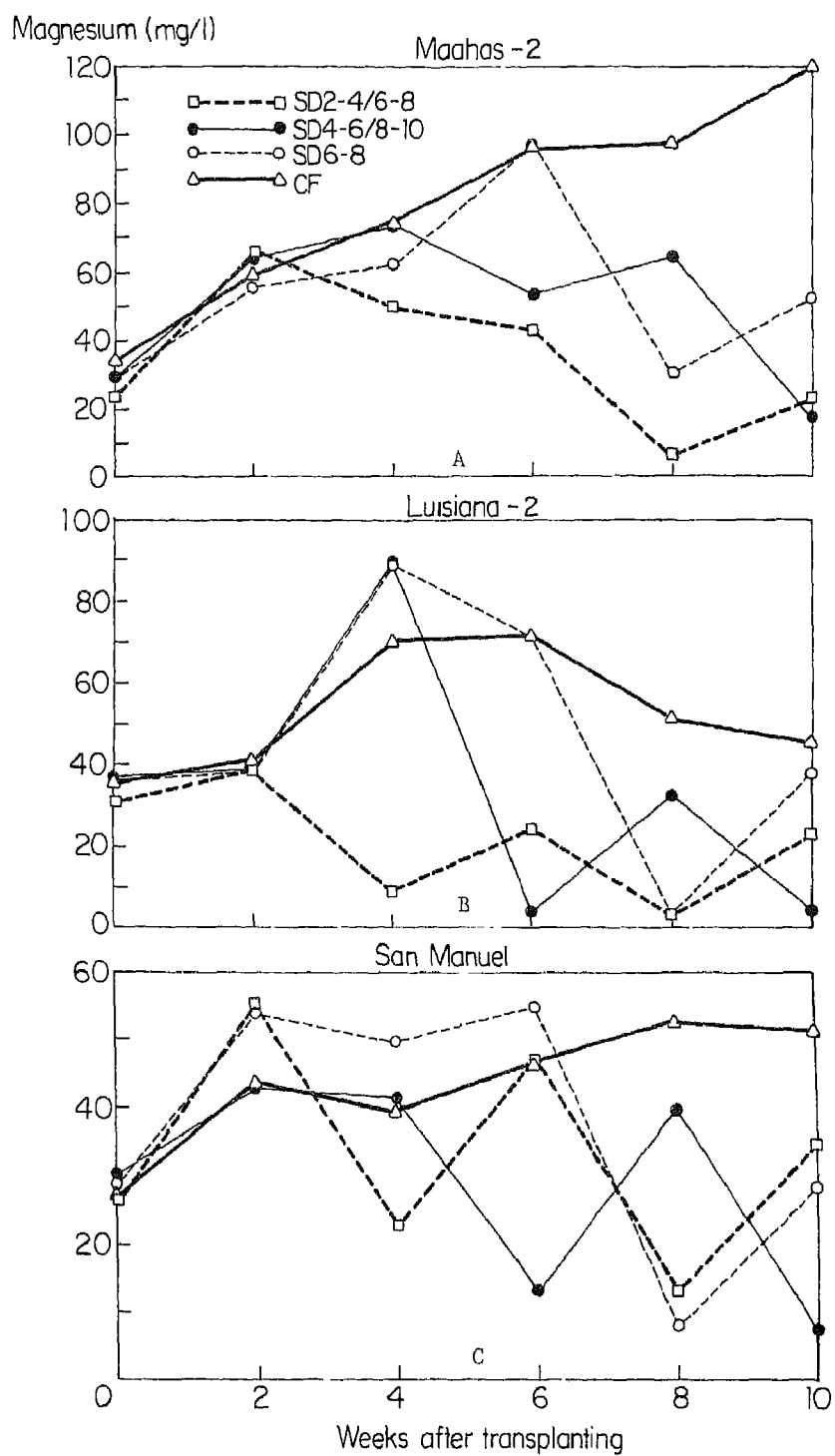
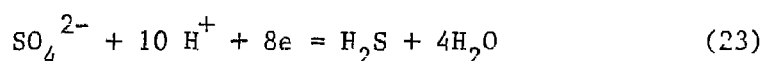


Fig. 45. Influence of four water regimes on kinetics of water-soluble Mg in three soils.

Sulfate (SO_4^{2-} -S)

Sulfate in soil solution decreased with time in Maahas-2 and San Manuel soils (Fig. 46A, 46C). In acid Luisiana-2 soil (Fig. 46B) however, there was an increase in SO_4^{2-} -S during the first two weeks after transplanting which also decreased thereafter. The decrease in the SO_4^{2-} -S concentration in continuously flooded soils can be explained by reduction of SO_4^{2-} to H_2S



The initial increase in SO_4^{2-} -S concentration of soil solution in acid soil could be attributed to release of sorbed SO_4^{2-} on clay and hydrous oxides of Fe and Al (Harvard and Reisenauer, 1966). Drying and reflooding increased the SO_4^{2-} -S concentration of soil solution due to mineralization of organic sulfur (McLaren et al., 1985; Mukhopadhyaya and Mukhopadhyay, 1980) and oxidation of inorganic sulfides.

Iron (Fe^{2+})

The peak concentration of Fe^{2+} was obtained between 4 and 10 weeks after flooding (Fig. 47). In acid Luisiana-2 soil (Fig. 47B), Fe^{2+} concentration first increased to a maximum within 4 weeks and decreased gradually. In near neutral Maahas-2 (Fig. 47A) and calcareous San Manuel soil (Fig. 47C), Fe^{2+} increased gradually with time of flooding. The increase in water soluble Fe^{2+} concentration is related to the $\text{Fe}(\text{OH})_3$ - Fe^{2+} system while the later decrease can be due to formation of $\text{Fe}_3(\text{OH})_8$ and/or FeCO_3 as shown in experiments 1 and 2.

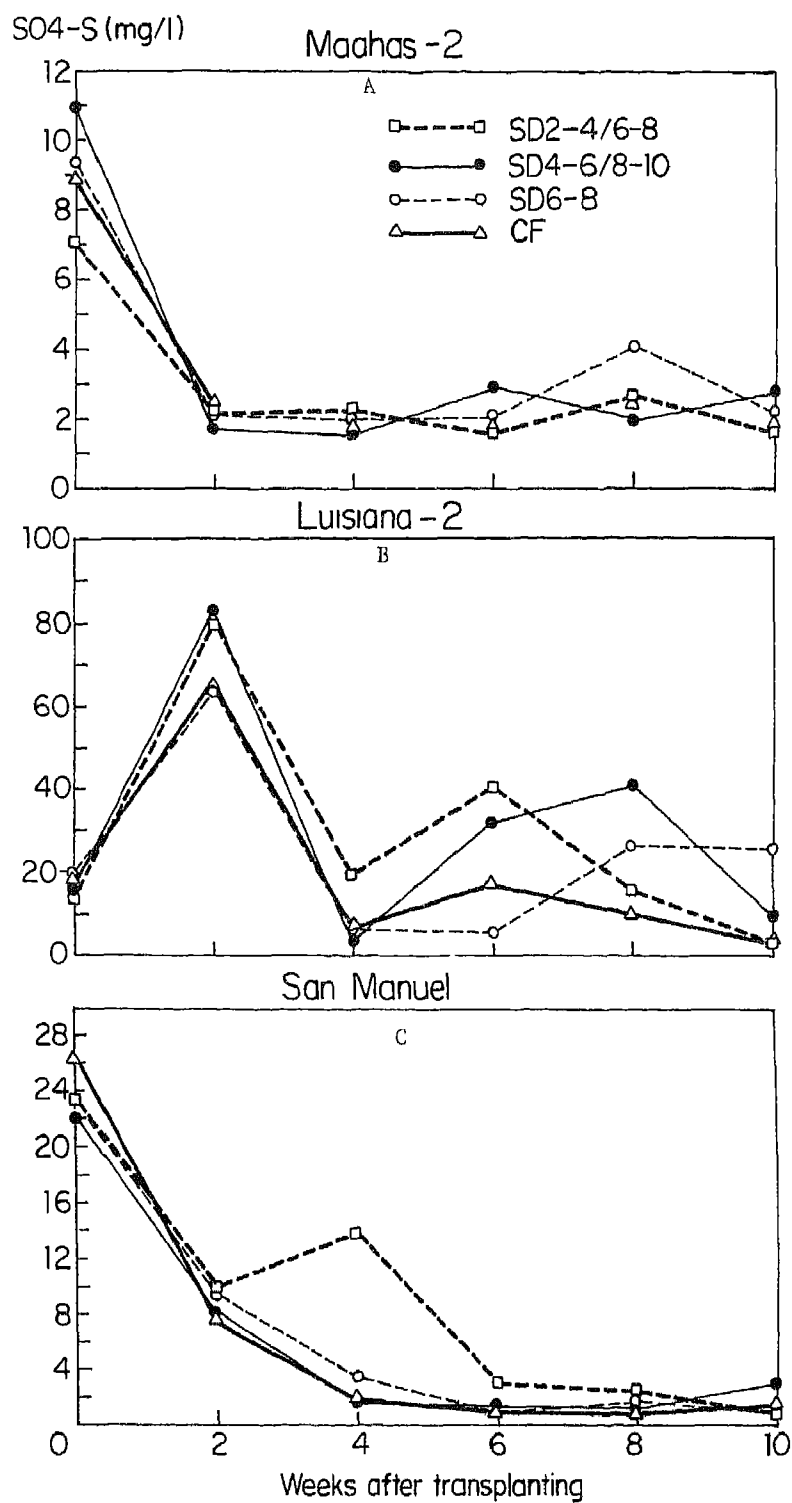


Fig. 46. Influence of four water regimes on kinetics of water-soluble SO₄²⁻-S in three soils.

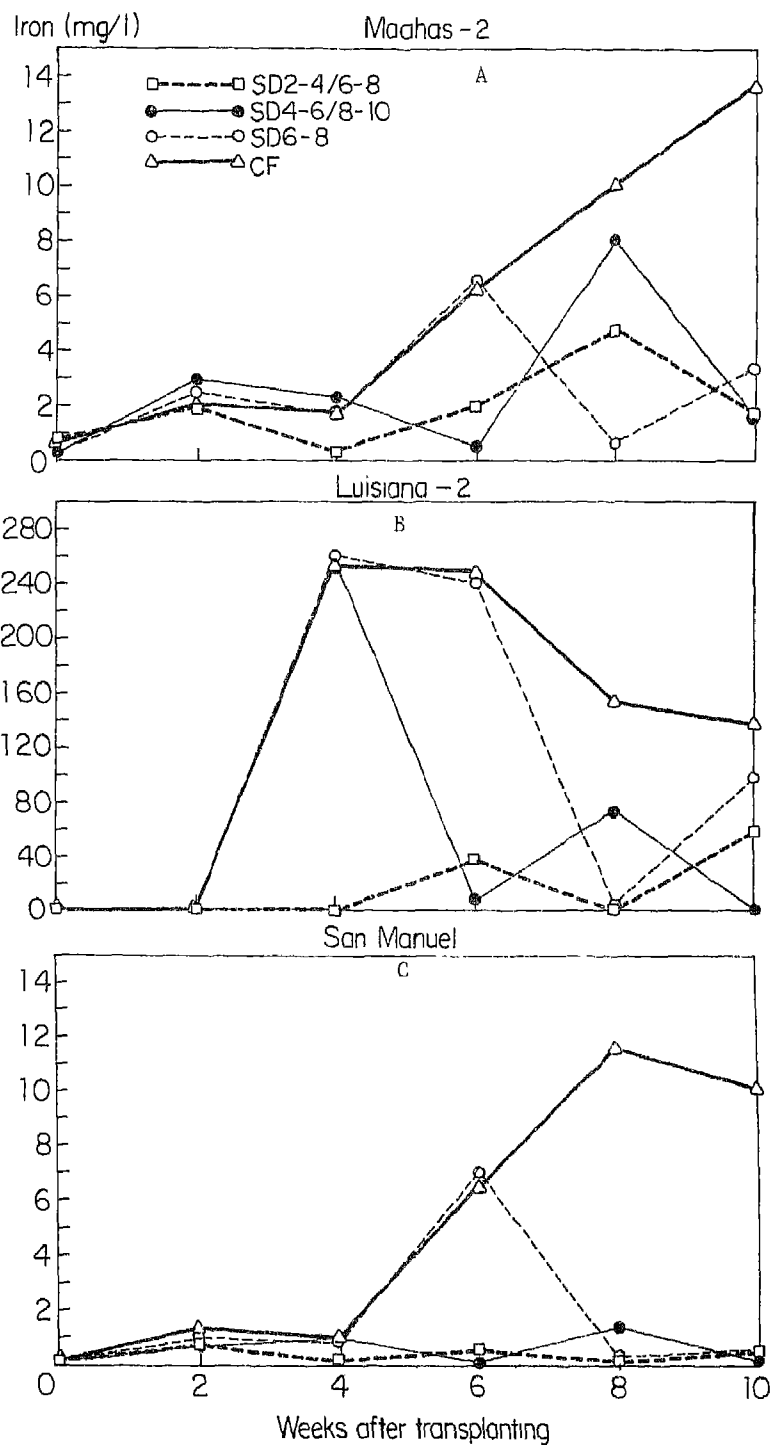


Fig. 47. Influence of four water regimes on kinetics of water-soluble Fe in three soils.

Drying drastically reduced the Fe^{2+} concentration of soil solution. Reflooding the dry soil could not increase the water soluble Fe^{2+} concentration of the soils to the level of that in continuously flooded water regime.

Manganese (Mn^{2+})

Manganese concentration of soil solution increased on flooding (Fig. 48). While the Mn^{2+} concentration of soil solution in Luisiana-2 soil (Fig. 48B) decreased 4 weeks after transplanting, that in the Maahas-2 (Fig. 48A) and San Manuel (Fig. 48C) soil maintained the increasing trend throughout the 10 weeks experimental period. The increase in water soluble Mn^{2+} concentration was related to the MnO_2 - Mn^{2+} system while the decrease in Mn^{2+} at the later stage was due to precipitation of MnCO_3 and/or Mn oxides

The decrease in Mn^{2+} concentration of soil solution due to soil drying was due to its reoxidation. Reflooding the dry soil caused reduction of the oxidized Mn, as indicated by the increase in Mn^{2+} concentration.

In Luisiana-2 soil declining phase of Fe^{2+} and Mn^{2+} ran parallel to $^{\text{P}}\text{CO}_2$ plots suggesting formation of FeCO_3 and MnCO_3 at 4 WAT onwards.

Zinc (Zn^{2+})

Zinc concentration of soil solution decreased gradually with time of flooding except in calcareous San Manuel soil, where it increased during the first few weeks of flooding and decreased gradually

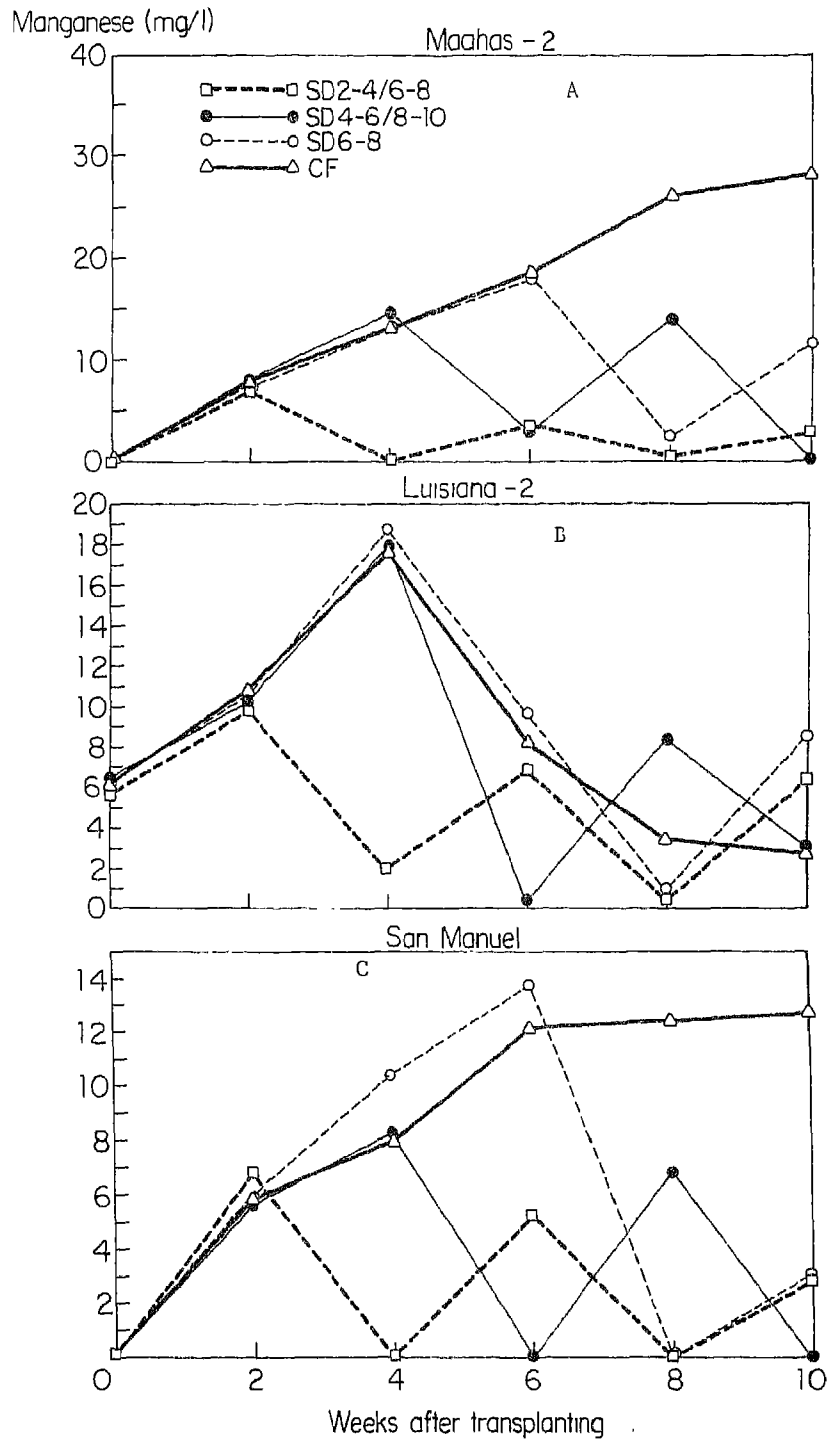


Fig. 48. Influence of four water regimes on kinetics of water-soluble Mn in three soils.

thereafter (Fig. 49). Soil drying and reflooding increased the Zn^{2+} concentration of soil solution and this was more pronounced in the Maahas-2 soil (Fig. 49A).

Silicon (Si)

In calcareous San Manuel soil water soluble Si concentration (Fig. 50C) remained almost constant throughout the experimental period. In acid Luisiana-2 soil (Fig. 50B) and near neutral Maahas-2 (Fig. 50A) soil Si concentration in soil solution decreased gradually with time of flooding.

Soil drying and reflooding decreased Si concentration of the soil solution.

To summarize, the study of the soil solution kinetics in these three soils showed that compared to that under continuously flooded water regime, in alternately dried and reflooded water regimes:

- i. availability of N was lower in all three soils
- ii. solubility of P in Maahas-2 and San Manuel soils decreased due to soil drying and reflooding them did not improve it.
- iii. K^{2+} , Ca^{2+} and Mg^{2+} availability decreased in all the three soils during the dry spell but reflooding improved their availability slightly.
- iv. sulfate availability increased due to soil drying and reflooding.
- v. Fe^{2+} and Si availability decreased during the dry spell but reflooding improved their availability.

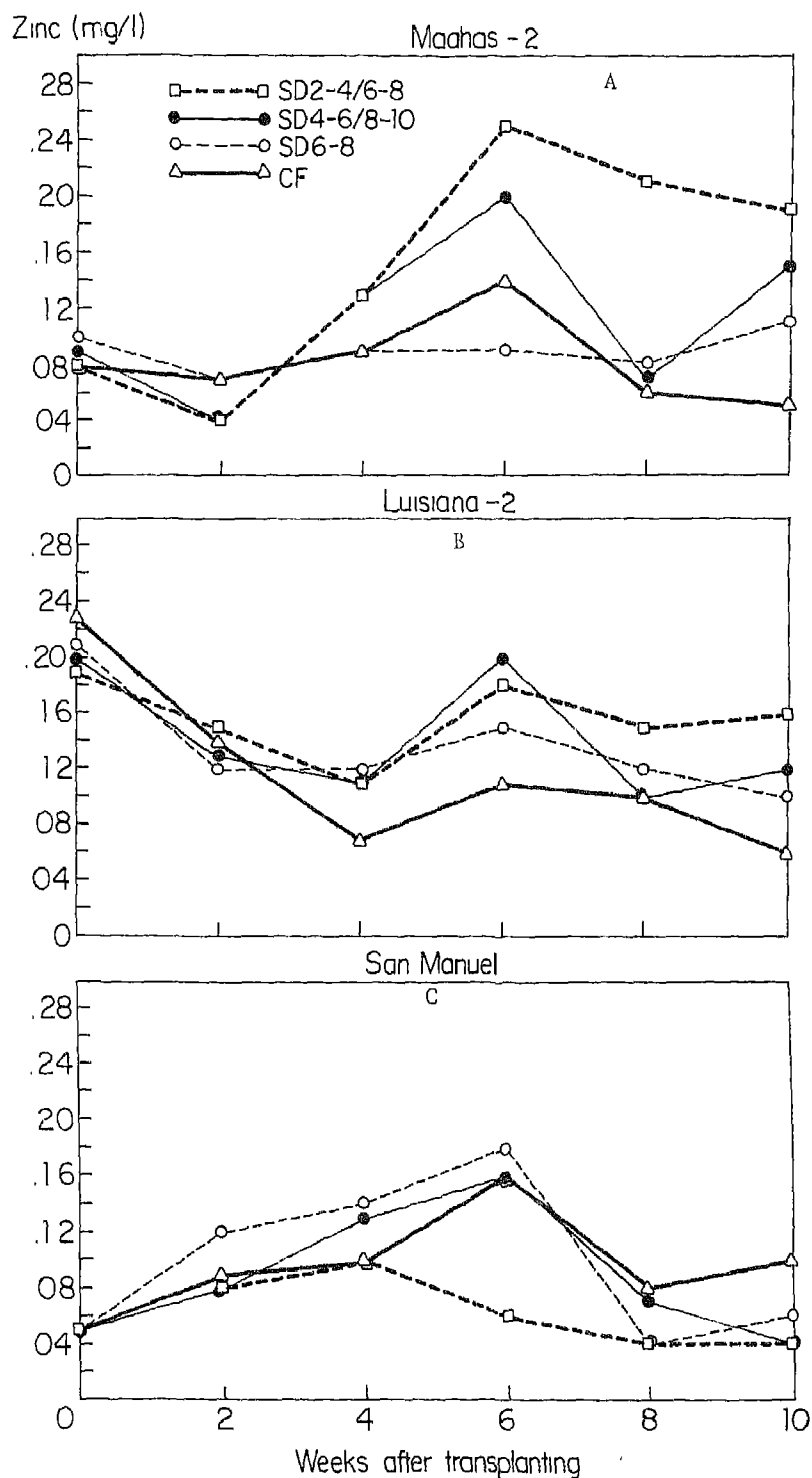


Fig. 49. Influence of four water regimes on kinetics of water-soluble Zn in three soils.

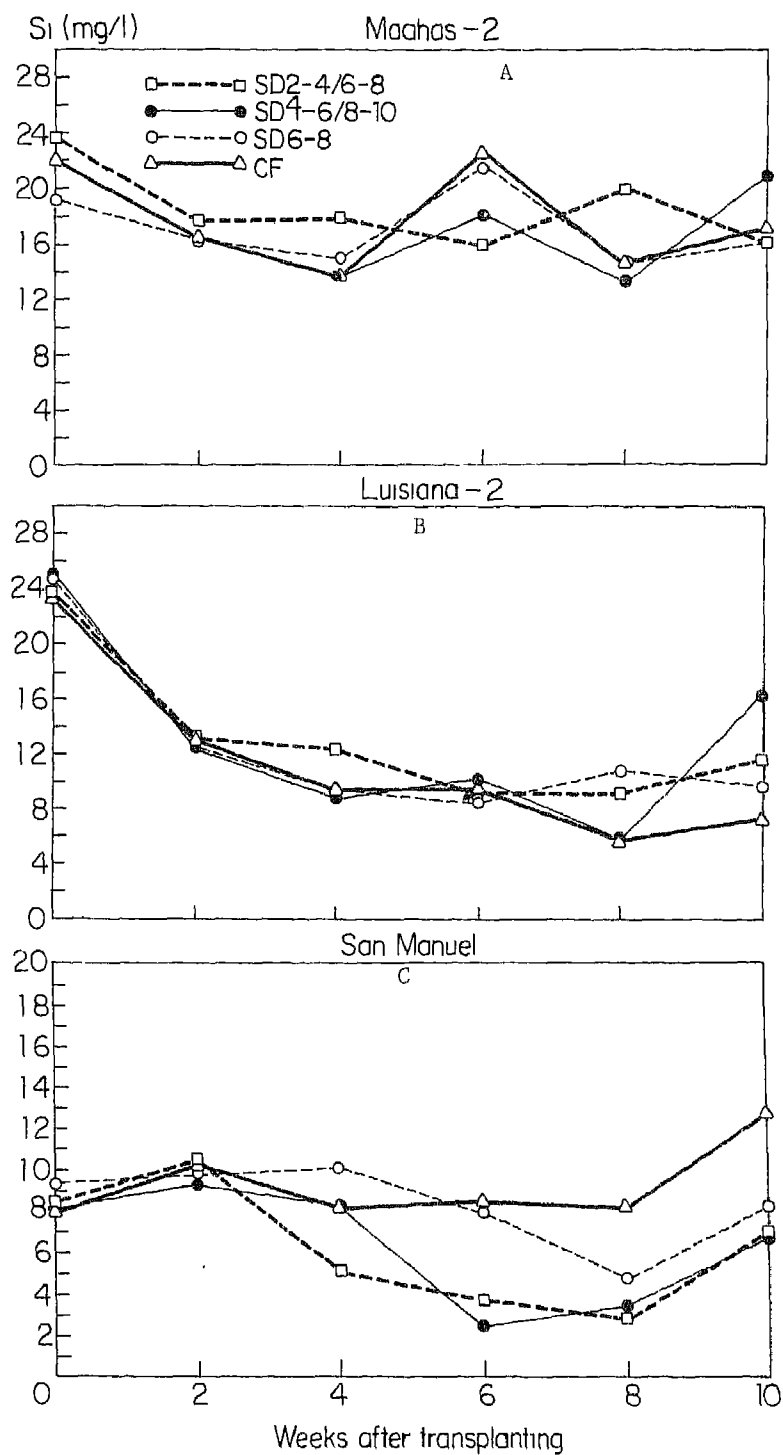


Fig. 50. Influence of four water regimes on kinetics of water-soluble Si in three soils.

- vi. Zn^{2+} availability was low during the dry spell but reflooding increased it considerably.
- vii. Mn^{2+} concentration in soil solution was almost undetectable during the dry spell but on reflooding there was a big flush of Mn^{2+} .

Mineral Nutrition of Rice

Concentration of mineral nutrients in 6 week-old rice shoots and straw at maturity are presented in Tables 15 and 16. As the dry matter yields were different under different water regimes the nutrient concentrations may not reflect the true picture of mineral nutrition. Therefore total uptake of the nutrients by shoots were also computed and are presented in Table 17. However, due to lack of enough grains in Maahas-2 soil under continuously flooded condition, grain analyses were not done for all nutrient elements and thus the total uptake at harvest could not be computed. The results of the analyses are presented in the following pages.

Nitrogen

The N concentration of rice shoots suggested N deficiency in all treatments in San Manuel soil and soil drying and reflooding treatments in Maahas-2 and Luisiana-2 soils. In Maahas-2 soil, soil drying and reflooding decreased the N concentration of shoot and straw (Tables 15,16) but in San Manuel soil, water regime had no effect on N concentration of shoot or straw. In Luisiana-2 soil 2 weeks soil drying imposed at 2 WAT (SD 2-4/6-8) decreased N concentration of shoot. The N

Table 15. Influence of four water regimes on the mineral nutrient concentration of six week old rice (IR54) shoots in three soils.

	N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	SiO ₂ %
				%					ppm		
	<u>Maahas-2</u>										
CF	2.41 C	0.237 AB	2.8 C-E	0.170 A	0.316 B	0.049 D	181 BC	489 B	34.7 B	29.7 BC	9.5 A
SD 6-8	2.32 CD	0.222 AB	2.6 DE	0.140 AB	0.293 BC	0.045 D	274 AB	483 BC	31.7 B-E	27.7 C	10.2 A
SD 4-6/8-10	1.95 EF	0.239 AB	2.6 DE	0.163 A	0.279 B-D	0.152 B	187 A-C	417 CD	33.3 B-D	26.0 C	9.8 A
SD 2-4/6-8	1.39 G	0.239 AB	3.4 A	0.081 D	0.233 CD	0.074 D	157 C	273 G-H	29.0 B-E	25.7 C	9.5 A
	<u>Luisiana-2</u>										
CF	2.88 AB	0.132 CD	2.4 F	0.116 BC	0.273 B-D	0.144 BC	292 AB	341 E-G	34.3 B-C	15.5 D	7.4 C
SD 6-8	2.64 BC	0.131 CD	2.4 E	0.114 B-D	0.252 B-D	0.152 B	297 A	316 F-H	32.7 B-D	13.7 D	7.7 BC
SD 4-6/8-10	3.12 A	0.114 D	3.2 A-C	0.100 CD	0.295 BC	0.209 A	204 A-C	716 A	56.5 A	35.2 B	10.2 A
SD 2-4/6-8	1.83 EF	0.148 CD	3.4 AB	0.092 CD	0.216 D	0.227 A	139 C	547 B	53.2 A	52.5 A	9.2 AB
	<u>San Manuel</u>										
CF	1.83 EF	0.246 AB	2.9 B-E	0.154 A	0.296 BC	0.062 D	116 C	408 DE	23.5 EF	22.5 C	6.8 C
SD 6-8	1.91 EF	0.261 A	3.1 A-D	0.157 A	0.297 BC	0.067 D	183 C	390 DE	25.0 D-F	24.5 C	7.4 C
SD 4-6/8-10	2.08 DE	0.157 C	3.6 A	0.149 A	0.404 A	0.154 D	180 BC	256 H	19.2 F	27.2 C	7.8 BC
SD 2-4/6-8	1.72 F	0.211 B	3.2 A-C	0.157 A	0.320 B	0.114 C	102 C	347 D-F	25.3 C-F	27.2 C	7.5 C
	<u>S</u>										
S	0.07	0.009	0.019	0.1	0.2	0.007	0.015	0.015	0.008	0.016	0.4
W	0.09	0.011	0.022	0.1	0.3	0.009	0.018	0.017	0.009	0.018	0.4
SxW	0.15	0.019	0.039	0.2	0.5	0.015	0.031	0.030	0.015	0.032	0.4
											0.9
											0.7
											1.5

*In a column treatment means having a common letter are not significantly different by DMRT at alpha = 5%.

Table 16. Influence of four water regimes on the mineral nutrient concentration of rice (IR54) straw at maturity in three soils.

	%				ppm				SiO ₂ %													
	N	P	K	Ca	Mg	S	Fe	Mn		Zn	Cu											
<u>Maahas-2</u>																						
CF 6-8	2.03 A	0.217 A	1.9 D	0.104 D-F	0.347 AB	0.029 E	155 CD	476 CD	40.3 C	19.0 B	11.7 D											
SD 4-6/8-10	1.22 C	0.180 A	3.2 B	0.113 C-F	0.306 B-D	0.041 DE	192 EC	829 B	30.3 C-E	20.8 AB	17.5 AB											
SD 2-4/6-8	0.84 DE	0.215 A	3.6 B	0.099 EF	0.302 B-D	0.081 BC	178 CD	675 B	39.3 C	23.3 AB	19.1 A											
	0.51 EF	0.074 CD	3.6 B	0.087 F	0.213 E	0.039 E	128 D	322 D	26.5 DE	21.7 AB	16.9 B											
<u>Luisiana-2</u>																						
CF 6-8	1.05 CD	0.067 C-E	1.8 D	0.132 B-D	0.290 CD	0.108 AB	238 AB	441 CD	56.2 B	20.0 B	14.2 C											
SD 4-6/8-10	1.15 CD	0.084 BC	1.9 D	0.116 C-F	0.275 CD	0.119 A	262A	483 CD	61.2 B	22.5 AB	14.1 C											
SD 2-4/6-8	1.67 B	0.124 B	2.0 CD	0.120 C-F	0.314 BC	0.139 A	194 BC	686 B	61.5 B	21.5 AB	15.9 BC											
	1.28 C	0.103 BC	2.4 C	0.142 BC	0.367 A	0.120 A	172 CD	1137 A	86.2 A	27.7 A	17.1 B											
<u>San Manuel</u>																						
CF 6-8	0.63 EF	0.116 BC	3.2 E	0.179 A	0.376 A	0.027 E	147 CD	504 C	39.7 C	20.8 AB	11.9 D											
SD 4-6/8-10	0.50 EF	0.088 BC	3.7 A	0.177 A	0.373 A	0.079 BC	173 CD	413 CD	37.0 CD	22.3 AB	12.2 D											
SD 2-4/6-8	0.37 F	0.028 DE	3.3 AB	0.169 AB	0.309 B-D	0.055 C-E	132 D	360 CD	24.5 E	19.0 B	10.6 D											
	0.31 F	0.025 E	3.5 AB	0.152 AB	0.265 D	0.075 B-D	135 D	325 D	21.5 E	20.3 AB	10.9 D											
<u>Summary</u>																						
N	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05											
P	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05											
K	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05											
Ca	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05											
Mg	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05											
S	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05											
Fe	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05											
Mn	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05											
Zn	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05											
Cu	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05											
SiO ₂	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SFmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05	SEmt LSD 0.05											
S	0.08	0.17	0.011	0.022	0.1	0.2	0.007	0.014	0.010	0.021	0.008	0.017	11	24	37	77	2.7	5.6	1.6	3.3	0.4	0.5
W	0.09	0.19	0.012	0.025	0.1	0.2	0.008	0.016	0.012	0.024	0.009	0.019	13	28	43	89	3.1	6.5	1.8	3.8	0.5	1.0
SxN	0.16	0.34	0.021	0.044	0.2	0.4	0.014	0.028	0.020	0.041	0.016	0.033	23	49	74	155	5.4	11.2	3.2	6.6	0.9	1.8

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 17. Influence of four water regimes on the mineral nutrient uptake by six week-old rice shoots in three soils.

		N	P	K	Ca	Mg	S mg/pot		Fe	Mn	Zn	Cu	SiO ₂
<u>Maahas-2</u>													
CF	89.6 F	8.9 E	108.7 E	6.0 C	11.9 E	1.76 G	0.72 G	1.84 D	0.13 C	0.11 D	0.11 D	356 D	
SD 6-8	92.1 F	8.7 E	104.9 E	5.4 C	11.4 E	1.67 G	1.01 FG	1.93 D	0.13 C	0.11 D	0.11 D	400 D	
SD 4-6/8-10	59.7 F	8.0 E	87.0 E	5.0 C	9.3 E	5.99 FG	0.65 G	1.38 D	0.11 C	0.09 D	0.09 D	323 D	
SD 2-4/6-8	257.3 E	43.9 AB	662.2 AB	14.9 B	43.0 B-D	13.86 DE	2.89 C-E	5.06 C	0.53 B	0.47 B	0.47 B	1728 A	
<u>Luisiana-2</u>													
CF	513.3 A	23.6 CD	435.9 CD	20.8 B	49.0 B-D	25.80 BC	5.21 A	6.12 C	0.61 B	0.27 C	0.27 C	1320 C	
SD 6-8	423.8 A-C	21.3 D	394.6 D	18.4 B	41.0 CD	24.49 BC	4.72 AB	5.14 C	0.53 B	0.27 C	0.27 C	1239 C	
SD 4-6/8-10	475.4 A	17.2 DE	489.4 CD	15.2 B	45.2 B-D	31.76 AB	3.12 CD	10.93 A	0.87 A	0.54 B	0.54 B	1560 AC	
SD 2-4/6-8	276.6 D-E	22.5 CD	507.6 B-D	13.8 B	32.8 D	34.52 A	2.06 D-F	8.20 B	0.81 A	0.79 A	0.79 A	1388 BC	
<u>San Manuel</u>													
CF	361.6 B-D	48.6 A	581.7 BC	30.4 A	58.5 B	12.32 EF	2.31 DE	8.10 B	0.47 B	0.45 B	0.45 B	1351 C	
SD 6-8	336.3 C-E	47.2 A	551.2 E-L	28.1 A	53.1 BC	11.64 FF	3.15 CD	6.91 BC	0.45 B	0.44 B	0.44 B	1310 C	
SD 4-6/8-10	453.4 AB	34.5 BC	783.9 A	32.3 A	87.8 A	33.54 A	3.90 BC	5.61 C	0.42 B	0.59 B	0.59 B	1682 AB	
SD 2-4/6-8	300.8 D-E	36.7 AB	557.9 BC	27.4 A	55.7 BC	19.91 CD	1.75 E-G	6.06 C	0.44 B	0.47 B	0.47 B	1304 C	
<u>Maahas-2</u>													
S	21.7 45.1	2.8 5.8	35.0 72.5	1.6 3.2	3.6 7.6	1.70 3.52	0.29 0.60	0.44 0.92	0.05 0.10	0.03 0.07	0.03 0.07	70 145	
W	25.1 52.1	3.2 6.7	40.4 83.7	1.8 3.7	4.2 8.7	1.96 4.07	0.33 0.69	0.51 1.06	0.05 0.11	0.04 0.08	0.04 0.08	81 168	
SxW	43.5 90.2	5.6 11.5	69.9 145.0	3.1 6.5	7.3 15.1	3.40 7.05	0.57 1.19	0.89 1.84	0.09 0.19	0.07 0.14	0.07 0.14	140 290	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

concentration of shoot in all other treatments in Luisiana-2 soil were comparable. In Luisiana-2 soil 2 cycles of soil drying at the later stages (SD 4-6/8-10) increased the N concentration in straw, but other drying treatments had no effect. In Maahas-2 soil compared to that under continuously flooded water regime, soil drying and reflooding increased total N uptake by shoot but in Luisiana-2 soil it decreased (Table 17). While in Maahas-2 soil 2 weeks soil drying at 2 WAT (SD 2-4/6-8) and reflooding increased total N uptake by shoot, the same treatment did not affect N uptake by shoots in San Manuel soil. On the other hand, soil drying for 2 weeks at 4 WAT (SD4-6/8-10) effectively increased N uptake by shoots in San Manuel soil but did not affect that in Maahas-2 soil. In Luisiana-2 and San Manuel soil, soil drying and reflooding decreased the total N uptake by rice at harvest but in Maahas-2 soil the opposite was true (Table 18).

Phosphorus

Compared to that under continuously flooded condition (CF) soil drying and reflooding for 2 weeks during vegetative growth stage did not affect the P concentration of rice shoot in Maahas-2 and Luisiana-2 soil but decreased that in San Manuel soil (Table 15). While soil drying increased the P concentration of rice straw in Luisiana-2 soil, it decreased that in San Manuel and Maahas-2 soil (Table 16). Soil drying and reflooding did not significantly influence the P uptake by shoot in Luisiana-2 soil. While in Maahas-2 soil 2 weeks soil drying increased the P uptake, that in San Manuel soil decreased due to soil drying (Table 17).

Table 18. Influence of four water regimes on the total N and S uptake by grains plus straw at harvest and N to S ratio in six week-old rice (IR54) shoot and straw in three soils.

	S Uptake at harvest ----- g/pot -----	N Uptake at harvest -----	N:S in shoot	N:S in straw
<u>Maahas-2</u>				
CF	0.003 E	0.17 F	50.6 A	71.4 A
SD 6-8	0.025 D	0.61 CD	53.8 A	30.4 B
SD 4-6/8-10	0.036 D	0.70 C	13.7 CD	11.2 C
SD 2-4/6-8	0.030 D	0.48 DE	19.0 C	13.2 C
<u>Luisiana-2</u>				
CF	0.108 AB	1.83 A	20.0 C	9.5 C
SD 6-8	0.120 A	1.88 A	17.4 C	10.2 C
SD 4-6/8-10	0.114 A	1.88 A	15.0 CD	12.1 C
SD 2-4/6-8	0.091 B	1.45 B	8.1 D	10.9 C
<u>San Manuel</u>				
CF	0.022 DE	0.62 CD	29.5 B	26.5 B
SD 6-8	0.062 C	0.61 CD	28.8 B	6.9 C
SD 4-6/8-10	0.042 CD	0.41 E	13.6 CD	7.1 C
SD 2-4/6-8	0.035 D	0.36 E	15.2 CD	4.2 C

	S Uptake		N uptake		N:S in shoot		N:S in straw	
	SEm±	LSD	SEm±	LSD	SEm±	LSD	SEm±	LSD
		0.05		0.05		0.05		0.05
S	0.005	0.010	0.04	0.08	1.6	3.3	2.6	5.3
W	0.006	0.012	0.05	0.09	1.8	3.8	3.0	6.1
SxW	0.010	0.021	0.08	0.16	3.1	6.5	5.1	10.6

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Potassium

As compared to that under continuously flooded condition (CF) in all the three soils the K concentration of rice shoot at vegetative growth stage as well as of straw increased due to soil drying and reflooding (Tables 15,16). Soil drying and reflooding did not significantly affect the total K uptake by shoots in Luisiana-2 soil but these treatments generally increased K uptake by shoot in Maahas-2 and San Manuel soil (Table 17).

Calcium

Calcium concentration of rice shoot and straw in Luisiana-2 and San Manuel soil were not affected by soil drying and reflooding (Tables 15 and 16). In Maahas-2 soil, soil drying and reflooding for 2 weeks at the early stage (SD 2-4/6-8) decreased the Ca concentration of shoot. Soil drying and reflooding did not affect the Ca uptake of shoot in Luisiana-2 and San Manuel soil but in Maahas-2 soil, soil drying and reflooding at the early stage increased Ca uptake (Table 17).

Magnesium

As compared to that under continuously flooded condition (CF) soil drying for 2 weeks imposed 2 weeks after transplanting (SD 2-4/6-8) decreased Mg concentration of rice shoot in Maahas-2 soil (Table 15). However, when soil drying treatment for 2 weeks was imposed 4 weeks after transplanting (SD 4-6/8-10) it did not decrease Mg concentration of shoot in Maahas-2 but increased Mg concentration at that stage in San

Manuel soil. Two soil drying cycles of 2 weeks each (SD 2-4/6-8 and SD 4-6/8-10) decreased the Mg concentration of straw in the Maahas-2 and San Manuel soil while these treatments increased Mg concentration in Luisiana-2 soil (Table 16). Total Mg uptake by shoot in Luisiana-2 soil was not affected by soil drying and reflooding. In Maahas-2 soil, 2 weeks soil drying at 2 WAT and reflooding (SD 2-4/6-8) increased the Mg uptake by shoot while in San Manuel soil, 2 weeks soil drying at 4 WAT (SD 4-6/8-10) increased the Mg uptake at that stage (Table 17).

Total sulfur

At 6 weeks after transplanting, the total S concentration of rice shoot grown in Maahas-2 soil under continuously flooded water regime was only 0.049% (Table 15) which is much lower than the critical limit at this stage (0.11%, Islam and Ponnampereuma, 1982). The plants showed symptoms of sulfur deficiency (Plate 5). Soil drying for 2 weeks (SD 4-6/8-10) increased the total-S concentration of rice shoot to around the critical limit of total S in plant. In Luisiana-2 soil, under continuously flooded condition plants were not sulfur deficient (Table 15) and soil drying further increased the total S concentration of rice shoots. In San Manuel soil where rice plants under continuous flooded condition were deficient in total S, soil drying increased the concentration of total S in plants. In Luisiana-2 soil total S concentration of straw was more than the critical limit (0.055%, Islam and Ponnampereuma, 1982) and soil drying and reflooding cycles did not affect it (Table 16).

In Maahas-2 and San Manuel soil, the total S concentration of straw under continuously flooded condition suggested S-deficiency (Table 16). In San Manuel soil, soil drying cycles eliminated S deficiency but in Maahas-2 soil S deficiency was corrected only when 2 weeks soil drying was imposed at 4 WAT and again at 8 WAT (SD 4-6/8-10) (Table 16).

In all the three soils drying and reflooding increased the total S uptake by rice shoots (Table 17) as well as by grains plus straw at harvest (Table 18).

N:S ratio

The N:S ratio in shoots and straw at maturity are presented in Table 18. The critical limit of this ratio in shoots at tillering and in straw at maturity are 15 and 14 respectively and value higher than the critical limit cause S-deficiency (Islam and Ponnampuruma, 1982). Under continuously flooded water regime, the N:S ratio in shoots was >15 in Maahas-2 as well as in San Manuel soil, which suggest S deficiency in these two soils. Soil drying for 2 weeks decreased this ratio in both these soils and thereby eliminated S-deficiency. Analyses of shoot, although suggested S deficiency in SD2-4/6-8 in both the soils but deficiency symptoms were not observed perhaps because of the interaction between N and S. In Luisiana-2 soil, also, the N:S ratio in shoot was >15 in CF and SD 6-8 water regimes and soil drying and reflooding (SD 2-4/6-8; SD 4-6/8-10) decreased this ratio.

The N:S ratio in straw was <14 in Luisiana-2 soil. This suggests no S-deficiency in Luisiana-2 soil. In Maahas-2 as well as San Manuel soil, the N:S ratio in straw was >14 suggesting S deficiency under

continuously flooded condition in both these soils. In Maahas-2 soil, 2 cycles of soil drying (SD2-4/6-8; SD4-6/8-10) significantly decreased the N:S ratio in straw to less than 14 but only 2 weeks soil drying at 6 WAT (SD6-8) could not bring down the N:S ratio to critical value. In San Manuel soil soil drying at any stage effectively decreased the N:S ratio to less than the critical value.

Iron

In Maahas-2 and Luisiana-2 soil, soil drying and reflooding decreased the total Fe concentration of the rice plants both at vegetative as well as maturity stage as was evident from the analyses of rice shoot and mature straw (Tables 15,16). However, in San Manuel soil water regime did not affect the Fe concentration of rice plant at any stage. In Luisiana-2 soil, soil drying and reflooding decreased the total Fe uptake by shoot but opposite was true in Maahas-2 and San Manuel soil (Table 17).

Manganese

In Maahas-2 soil, soil drying and reflooding decreased the Mn concentration of shoot but it increased that of straw (Tables 15,16). While the total Mn concentration of rice plant at vegetative as well as at maturity increased due to drying and reflooding in Luisiana-2 soil that in San Manuel soil was not affected by water regimes. Soil drying and reflooding increased the total Mn uptake by shoots in Maahas-2 and Luisiana-2 soils but decreased it in San Manuel soil (Table 17).

Zinc

The total Zn concentration of rice shoot in Maahas-2 and San Manuel soil were not affected by water regime but that in Luisiana-2 soil increased due to soil drying and reflooding (Table 15). In Luisiana-2 soil, soil drying and reflooding increased the Zn concentration of straw but the opposite was true in Maahas-2 and San Manuel soil (Table 16). Soil drying and reflooding increased the total Zn uptake by shoot in Maahas-2 and Luisiana-2 soils but had no effect on that in San Manuel soil (Table 17).

Copper

In Maahas-2 and San Manuel soil, total Cu concentration of shoot and straw were not affected by water regime but in Luisiana-2 soil, soil drying and reflooding increased Cu concentration of shoot as well as of straw (Tables 15,16). While water regime had no effect on Cu uptake by shoots in San Manuel soil, soil drying and reflooding generally increased it in Maahas-2 and Luisiana-2 soils (Table 17).

Silica

Crude silica (SiO_2) concentration of 6 weeks old rice plant on Luisiana-2 soil increased on soil drying and reflooding (Table 15). However, in the other two soils soil drying and reflooding had no effect on SiO_2 concentration of rice plants at that stage.

Crude silica concentration of mature straw on Maahas-2 and Luisiana-2 soil increased due to soil drying and reflooding (Table 16) but that on San Manuel soil was not affected.

Soil drying and reflooding generally increased the SiO_2 uptake by shoots in all the three soils (Table 17).

Growth and Yield of Rice

Plant height

Height of IR54 under different water regimes in the three soils are presented in Table 19. Tallest plants were observed in San Manuel soil while the plants in Maahas-2 were the shortest. Plants in Luisiana-2 soil had intermediate height. At harvest, however, the shortest plant was observed in Maahas-2 soil under continuously flooded water regime but the plants in all other treatment in the three soils had comparable height. While in Maahas-2 soil, soil drying generally increased plant height, in other two soils water regime had no effect on plant height.

Tiller number

Changes in the number of tillers per hill at different stages were recorded and are presented in Table 19. In Maahas-2 soil compared to that in continuously flooded water regime, soil drying and reflooding increased the number of tillers per hill but in San Manuel soil water regime had no effect on tillering. Upto 10 WAT, in Luisiana-2 soil also soil drying and reflooding had no effect on tillering but at harvest number tillers was significantly low in SD2-4/6-8 water regime.

Visual symptoms

Healthy and vigorously growing plants were observed under continuously flooded water regime in Luisiana-2 soil. In Maahas-2 soil rice plants had very poor growth under continuously flooded condition. The plants showed light yellow discoloration starting from the tip of the leaves which spread to the base. This disorder, which is characteristic symptom of S deficiency, gave the entire plant a chlorotic appearance (Plate 5). Plant analysis at 6 WAT stage revealed only 0.049% total S in shoot which is much lower than the critical limit for S reported in the literature (0.11%, Islam and Ponnampereuma, 1982. Associated with this chlorotic appearance was reduction in plant height and tiller number (Table 19). Soil drying even for 2 weeks improved crop growth -- the plants started becoming green, and height and tillers increased (Plate 6).

In San Manuel soil, the plants were deficient both in N as well as S. As a result, upto 4 WAT no clear symptoms were observed but 6 WAT onwards plants showed marginal N deficiency symptoms (Plate 7) under continuously flooded condition and soil drying for 2 weeks at 6 WAT improved plant growth.

Two cycles of soil drying adversely affected plant growth in Luisiana-2 and San Manuel soil but improved it in Maahas-2 soil.

Grain yield of rice

Water regime influenced rice grain yield differently in different soils (Table 20). Continuously flooded condition produced highest grain yield in Luisiana-2 soil while it produced lowest grain yield in



Plate 5. Acute S-deficiency of rice (IR54) in Maahas-2 soil under continuously submerged condition (a) and correction of S-deficiency by soil drying for 2 weeks.



Plate 6. Influence of water regimes on rice (IR54) growth in Maahas-2 soil.



Plate 7. Influence of water regimes on rice (IR54) growth in San Manuel soil.

Table 19. Influence of four water regimes on the number of tillers per hill and plant height at different stages of rice growth in three soils.

	Number of tillers per hill				Plant height (cm)											
	Weeks after t ransplanting				Weeks after transplanting											
	4	6	10	Harvest	4	6	10	Harvest								
<u>Maahas-2</u>																
CF	4.0 F	4.0 C	3.7 G	5.0 G	59.7 EF	60.0 C	68.0 C	71.7 C								
SD 6-8	4.3 F	4.7 C	7.0 F	12.0 EF	59.3 EF	60.3 C	84.3 B	92.7 AB								
SD 4-6/8-10	3.7 F	4.7 C	7.7 EF	17.7 D	54.3 F	55.0 C	91.7 AB	91.7 AB								
SD 2-4/6-8	12.0 A	14.7 A	10.7 B-D	11.7 EF	73.0 A-C	94.7 A	98.3 A	98.7 AB								
<u>Luisiana-2</u>																
CF	10.7 A-C	12.0 B	13.0 AB	33.3 B	67.0 CD	86.3 AB	97.3 AB	97.3 AB								
SD 6-8	10.0 CD	11.0 B	11.7 BC	38.7 A	64.0 DE	79.7 B	92.3 AB	92.3 AB								
SD 4-6/8-10	8.7 DE	10.3 B	14.7 A	37.3 AB	64.7 DE	80.0 B	89.0 AB	89.0 B								
SD 2-4/6-8	7.7 E	12.3 AB	13.0 AB	28.0 C	71.0 BC	89.0 A	96.0 AB	96.0 AB								
<u>San Manuel</u>																
CF	11.7 AB	12.7 AB	10.3 CD	9.0 FG	78.7 A	92.0 A	102.3 A	102.3 A								
SD 6-8	11.3 A-C	12.7 AB	11.7 BC	13.7 DE	76.7 AB	94.0 A	96.7 AB	96.7 AB								
SD 4-6/8-10	10.3 BC	12.3 AB	10.0 C-E	9.3 E-G	77.3 AB	90.7 A	101.7 A	101.7 A								
SD 2-4/6-8	11.0 A-C	12.0 B	9.0 D-F	7.7 FG	76.0 AB	94.0 A	98.7 A	98.7 AB								
	Number of tillers								Plant height							
	Weeks after transplanting								Weeks after transplanting							
	4 WAT	6 WAT	10 WAT	Harvest	4 WAT	6 WAT	10 WAT	Harvest	4 WAT	6 WAT	10 WAT	Harvest	4 WAT	6 WAT	10 WAT	Harvest
	SEm± LSD 0.05	SEm± LSD 0.05	SEm± LSD 0.05	SEm± LSD 0.05	SEm± LSD 0.05	SEm± LSD 0.05	SEm± LSD 0.05	SEm± LSD 0.05	SEm± LSD 0.05	SEm± LSD 0.05	SEm± LSD 0.05	SEm± LSD 0.05	SEm± LSD 0.05	SEm± LSD 0.05	SEm± LSD 0.05	SEm± LSD 0.05
S	0.3 0.7	0.6 1.2	0.5 1.1	1.0 2.1	1.4 3.0	1.9 3.9	2.9 6.1	2.5 5.3								
W	0.4 0.8	0.7 1.4	0.6 1.3	1.1 2.4	1.6 3.4	2.2 4.5	3.4 7.0	2.9 6.1								
SxW	0.7 1.4	1.1 2.4	1.1 2.3	2.0 4.1	2.8 5.9	3.7 7.7	5.9 12.1	5.1 10.5								

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 20. Influence of four water regimes on the yield of rice (IR54) in three soils.

	Dry weight of 6-week- old shoot (g/pot)	Grain yield ----- g/pot -----	Straw yield -----						
<u>Mashas-2</u>									
CF	3.7 C	1.6 G	7.1 F						
SD 6-8	4.0 C	21.3 F	23.4 E						
SD 4-6/8-10	3.2 C	25.0 F	21.9 E						
SD 2-4/6-8	18.5 AB	36.4 DE	31.5 C						
<u>Luisiana-2</u>									
CF	17.9 AB	64.7 A	52.5 A						
SD 6-8	16.2 B	59.5 AB	53.3 A						
SD 4-6/8-10	15.2 B	51.6 BC	51.3 A						
SD 2-4/6-8	15.1 B	50.3 BC	41.0 B						
<u>San Manuel</u>									
CF	19.8 AB	35.4 D-E	28.9 CD						
SD 6-8	17.8 AB	44.6 CD	32.8 C						
SD 4-6/8-10	21.8 A	24.5 DE	24.5 DE						
SD 2-4/6-8	17.4 AB	20.9 EF	20.9 E						
	Shoot weight			Grain yield			Straw yield		
	S	W	SxW	S	W	SxW	S	W	SxW
SE m±	1.1	1.3	2.3	2.4	2.7	4.7	1.2	1.4	2.4
LSD (0.05)	2.4	2.7	4.7	4.9	5.7	9.8	2.5	2.9	5.0
LSD (0.01)	3.2	3.7	6.4	6.7	7.7	13.3	3.4	3.9	6.8

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Maahas-2 soil. Highest grain yield in San Manuel soil was obtained with soil drying for 2 weeks from 6 WAT. In both, the Luisiana-2 and San Manuel soil, lowest grain yield was obtained under two cycles of drying and reflooding for two weeks imposed 2 and 6 WAT (SD2-4/6-8) while the same treatment produced highest grain yield in Maahas-2 soil. Drying and reflooding generally decreased rice grain yield in Luisiana-2 and San Manuel soil but improved grain yield in sulfur deficient Maahas-2 soil.

Straw yield

Straw yield was also influenced by water regimes differently in different soils (Table 20). Continuously submerged water regime produced highest straw yield in San Manuel and Luisiana-2 soil while it produced the lowest straw yield in Maahas-2 soil. Two soil drying cycles increased straw yield in Maahas-2 soil but decreased that in San Manuel and Luisiana-2 soils.

Relationship Between Soil Solution Nutrient Kinetics and Mineral Nutrition, Growth and Yield of Rice

This study shows that the influence of water regime on nutrient kinetics, growth and yield of rice is soil specific and that soil solution kinetics can effectively explain the mineral nutrition, growth and yield of rice.

In Luisiana-2 soil grain yield was low under continuously flooded condition. But soil drying and reflooding resulted in decreased availability of N, Ca, Mg and Fe in soil solution which also adversely

affected the uptake of these nutrients by plants and produced lower yields than continuously flooded water regime. The concentration of Ca in the straw sample under continuously flooded water regime was lower than the critical concentration 0.15% by Yoshida et al., 1976. Soil drying and reflooding brought about further decline in the Ca concentration in straw. In San Manuel soil, under continuously flooded condition, plants suffered from deficiency of N and S. Soil drying and reflooding increased S availability but decreased that of N.

In Maahas-2 soil, mineral nutrition of plants was largely governed by sulfur. Under continuously flooded water regime, the water soluble SO_4^{2-} -S in soil was very low and plants suffered from S-deficiency. On soil drying and reflooding water soluble SO_4^{2-} -S and S uptake by plants increased resulting in better plant growth.

Experiment 4

Influence of Sulfur Application and Five Water Management Practices on the Growth and Yield of Rice in Six Soils

In the third greenhouse experiment soil drying followed by reflooding was found to improve rice growth and increase rice grain yield on soils which were deficient in both sulfur and zinc while it decreased rice yield on an acid soil. This experiment was conducted at the same greenhouse to further verify the effect of soil drying on rice growth and yield on six zinc and sulfur deficient soils. In order to see whether soil drying and reflooding result in the improvement of sulfur status of plants, an additional treatment with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ as sulfur source was included.

MATERIALS AND METHODS

Design

This experiment was laid out in 6 x 6 factorial randomized complete block design replicated three times.

Factors and levels

A. Soils. The soils were collected from:

i. Bancal, Batolan, Zambales (Tropaquept)	(S1)
ii. San Ildefonso, Bulacan, Bulacan (Tropudalf)	(S2)
iii. Cabangan, Zambales (Tropaquept)	(S3)
iv. Kalikid, Cabanatuan City, Nueva Ecija (Haplustalf)	(S4)
v. Pao, Manaoag, Pangasinan (Eutropept)	(S5)
vi. San Agustin, Iba, Zambales (Tropaquept)	(S6)

Some characteristics of the soils are presented in Table 21.

B. Water management practices

- i. Continuously flooded (CF)
- ii. Continuously flooded with 100 mg S/kg soil (CF + S)
- iii. Continuously saturated (CS)
- iv. Continuously flooded with a drying period of 2 weeks imposed 2 weeks after transplanting (WAT) (SD 2-4)
- v. Continuously flooded with a drying period of 2 weeks imposed 4 WAT (SD 4-6).
- vi. Continuously flooded with a drying period of 2 weeks imposed 8 WAT (SD 8-10).

Greenhouse procedure

Bulk soil samples were collected from the field from 0-20 cm depth, air dried and crushed to 0.6 cm clods and mixed thoroughly. Four liter plastic pots were thoroughly cleaned, acid washed and rinsed with demineralized water. Three kg portion of the soils were treated with N, P and K at the rate of 50, 25 and 75 mg/kg soil and transferred into each pot. Urea, KH_2PO_4 and KCl were used as sources of N, P and K. In one treatment, 100 mg S/kg soil was applied through $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. A top-dressing of 50 mg N as urea/kg soil was given at 45 days after transplanting.

Four healthy seedlings were transplanted in each pot. The pots were irrigated with demineralized water as and when needed. In flooded treatments a standing water of 2 cm was continuously maintained.

Table 21. Some characteristics of the six soils used in experiment 4.

	Soils					
	1	2	3	4	5	6
pH (1:1)	6.5	6.3	5.7	5.8	7.5	6.1
Organic C (%)	0.86	0.71	1.18	0.51	0.86	1.77
Total N (%)	0.06	0.08	0.12	0.05	0.08	0.13
Total S (%)	0.029	0.034	0.039	0.038	0.039	0.040
Available						
N (mg/kg)	49.0	65.1	88.0	20.9	13.6	71.6
P Olsen (mg/kg)	0.9	4.3	1.7	0.9	5.7	6.3
S (mg/kg)	0.7	5.3	4.9	1.3	1.5	10.9
Zn (mg/kg)	0.28	0.88	0.70	0.44	0.10	0.28
Cu (mg/kg)	0.14	0.40	1.04	1.18	0.06	0.08
Exchangeable						
K (me/100 g)	0.15	0.22	0.29	0.12	0.26	0.10
Ca (me/100 g)	1.08	11.08	3.95	5.63	34.90	3.69
Mg (me/100 g)	12.19	3.42	7.27	1.92	4.93	20.56
Active						
Fe (%)	3.77	1.67	0.57	0.67	1.15	5.08
Mn (%)	0.06	0.38	0.01	0.10	0.06	0.06
Water soluble Si (mg/kg)	126.9	90.9	65.2	50.1	92.0	149.1
CEC (me/100 g)	18.2	21.8	16.2	10.7	44.9	36.4
Mechanical analysis						
Clay (%)	16	22	15	15	32	31
Silt (%)	22	16	44	51	53	31
Sand (%)	62	62	41	34	15	38
Textural class	Sandy loam	Sandy clay loam	Loam	Silty loam	Clay	Clay

Soils were collected from:

1. Bancal, Batolan, Zambales
2. San Ildefonso, Bulacan, Bulacan
3. Cabangan, Zambales
4. Kalikid, Cabanatuan City, Nueva Ecija
5. Pao, Manaoag, Pangasinan
6. San Agustín, Iba, Zambales

For soil drying treatments, the flood water of the designated pot was siphoned out on the day of start of the drying treatment and the water was stored for later use for irrigating the same pot. The pots were allowed to dry up to the point when small cracks started developing on the soil surface. At that time the pots were saturated with demineralated water (or the stored floodwater of the same pot). Soil solution sample were not collected from pots in this experiment. All other greenhouse procedures were same as in experiment 1.

Two plants were harvested from each pot at 8 WAT and the remaining two plants were grown to maturity and grain and straw yields were recorded.

Growth observations and yield data

Growth and yield of rice in the pots were observed for:

- i. Plant height and tiller number every two weeks before panicle exertion and at harvest.
- ii. Dry matter yield of shoot at 8 WAT
- iii. Grain yield
- iv. Straw yield
- v. Number of panicles

Analytical Procedures

1. Soil

Soil samples were analyzed for pH; organic C; total N, S; available N, P, S, Zn and Cu; exchangeable K, Ca and Mg; active Fe and Mn; water soluble silica; CEC; and particle size distribution, following the methods described in the earlier experiments.

2. Plant samples

Eight weeks old shoots, mature straw and grain samples were analyzed for total N, P, K, Ca, Mg, S, Fe, Mn, Zn and Cu contents.

Calculations

The methods of calculations were same as in experiment 1.

RESULTS AND DISCUSSION

Mineral Nutrition of Rice

In general, the mineral nutrient concentration in shoots and straw at maturity were significantly different in different soils and water regimes also influenced them. Similarly, the uptake of nutrients by shoot and at harvest were also significantly different in different soils and water regimes influenced them significantly. The results are discussed in the following pages.

Nitrogen

Nitrogen concentration of rice shoot was lowest under flooded condition (CF) and sulfur application (CF + S) did not change it. Nitrogen concentration of shoots in flooded (CF) and saturated soils (CS) were comparable but soil drying for two weeks increased it (Table 22).

Nitrogen concentration of straw was highest in flooded soils and addition of sulfur decreased it. Nitrogen concentration of straw in saturated and flooded and dried water regimes were lower (Table 22).

Total N uptake by shoots was lowest under continuously flooded water regime. Highest N uptake was observed in S treated flooded soils. Continuously saturated water regime also resulted in increased N uptake by shoots. However, soil drying at this stage did not affect N uptake by plants (Table 23).

Nitrogen uptake by rice at harvest was highest under continuously flooded condition and addition of sulfur or drying the soil for 2 weeks at 4 or 8 WAT did not affect it. But keeping the soil saturated (CS)

Table 22. Influence of sulfur application and five water management practices on the N concentration of eight week-old shoot and mature rice (IR54) straw in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>% N in 8 week-old shoot</u>							
CF	2.83	2.42	2.46	2.46	2.04	2.64	2.47 C
CF + S	2.68	2.43	2.34	2.30	2.31	2.82	2.48 C
CS	2.63	2.34	2.61	2.48	2.67	2.32	2.51 C
SD 2-4	2.77	2.52	2.59	2.79	2.79	2.63	2.68 B
SD 4-6	3.02	2.61	2.84	2.86	2.91	3.04	2.88 A
SD 8-10	2.61	2.22	2.52	2.44	2.06	2.83	2.45 C
Mean	2.76	2.42	2.56	2.56	2.46	2.71	
<u>% N in straw</u>							
CF	1.44	0.67	1.01	0.84	0.91	0.85	0.95 A
CF + S	0.67	0.67	0.84	0.78	0.52	0.85	0.72 B
CS	0.59	0.66	0.57	0.58	0.55	0.81	0.63 C
SD 2-4	0.67	0.58	0.61	0.72	0.39	0.77	0.62 C
SD 4-6	0.76	0.61	0.68	0.65	0.49	0.79	0.66 C
SD 8-10	1.06	0.59	0.82	0.60	0.64	0.89	0.77 B
Mean	0.86	0.63	0.76	0.70	0.58	0.83	
<u>Shoot</u>				<u>Straw</u>			
	S	W	SxW	S	W	SxW	
SE m±	0.07	0.07	0.18	0.03	0.03	0.07	
LSD (0.01)	0.19	0.19	0.48	0.08	0.08	0.19	
LSD (0.05)	0.15	0.15	0.36	0.06	0.06	0.14	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 23. Influence of sulfur application and five water management practices on N uptake by eight week-old shoot and grain plus straw at harvest of rice (IR54) in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>N uptake (mg/pot) by 8-week-old shoot</u>							
CF	118.1	218.2	135.1	170.8	136.1	286.5	177.4 C
CF + S	211.4	234.2	282.1	188.2	200.8	286.2	233.8 A
CS	159.1	262.0	242.6	209.4	177.6	208.8	209.9 F
SD 2-4	85.8	166.9	204.6	217.7	151.6	196.1	170.4 C
SD 4-6	139.3	209.0	227.9	188.5	163.9	247.6	196.0 FC
SD 8-10	130.6	110.8	182.1	200.2	135.2	267.0	187.6 BC
Mean	140.7	216.8	212.4	195.8	160.9	248.7	
<u>N uptake (g/pot) at harvest</u>							
CF	0.27	0.38	0.40	0.26	0.22	0.24	0.30 A
CF + S	0.34	0.29	0.40	0.30	0.24	0.34	0.32 A
CS	0.26	0.26	0.31	0.20	0.20	0.25	0.25 B
SD 2-4	0.19	0.26	0.34	0.24	0.16	0.26	0.24 B
SD 4-6	0.29	0.47	0.37	0.26	0.23	0.35	0.33 A
SD 8-10	0.38	0.32	0.39	0.23	0.26	0.35	0.32 A
Mean	0.29	0.33	0.37	0.25	0.22	0.30	
<u>N Uptake by shoot</u>				<u>N Uptake at harvest</u>			
	S	W	SxW	S	W	SxW	
SE m±	12.0	12.0	29.3	0.02	0.02	0.05	
LSD (0.01)	31.6	31.6	77.5	0.05	0.05	0.12	
LSD (0.05)	23.8	23.8	58.4	0.04	0.04	0.09	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

and drying the soil for 2 weeks at 2 WAT (SD 2-4) decreased N uptake by the crop at harvest (Table 23).

Phosphorus

Phosphorus concentration of rice shoot and straw were highest under continuously flooded condition (CF). Addition of sulfur (CF + S), keeping the soils saturated (CS) or drying for 2 weeks at different stages decreased the P concentration of rice shoot and straw at maturity (Table 24).

Phosphorus uptake by rice at vegetative stage and at harvest were highest under sulfur treated flooded soils (Table 25). Keeping the soils saturated (CS) or drying the soil for 2 weeks at 2 WAT (SD 2-4) decreased P uptake by shoot and at harvest. While 2 weeks soil drying at 4 WAT and reflooding (SD 4-6) decreased the P uptake by shoot, that at harvest was not affected (Table 25).

Potassium

Potassium concentration of rice shoot was lowest in sulfur treated flooded soils (CF + S) (Table 26) and it improved a little when sulfur was not applied. Keeping the soil saturated (CS) or drying the soil for 2 weeks at 2 (SD 2-4) and 4 WAT (SD 4-6) increased the K concentration of rice shoot (Table 26).

Potassium concentration of rice straw was lowest in continuously flooded soils (CF) and sulfur application (CF + S) did not change it. However, reducing the water content of soil from flooding (CF) to

Table 24. Influence of sulfur application and five water management practices on the P concentration of eight week-old shoot and mature rice (IR54) straw in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>% P in 8 week-old shoot</u>							
CF	0.225	0.250	0.302	0.231	0.241	0.225	0.246 A
CF + S	0.157	0.254	0.249	0.198	0.235	0.222	0.219 B
CS	0.135	0.177	0.165	0.141	0.236	0.155	0.168 D
SD 2-4	0.132	0.167	0.240	0.162	0.240	0.173	0.186 C
SD 4-6	0.123	0.197	0.202	0.143	0.215	0.161	0.174 CD
SD 8-10	0.209	0.273	0.324	0.220	0.250	0.214	0.248 A
Mean	0.164	0.220	0.247	0.183	0.236	0.192	
<u>% P in straw</u>							
CF	0.144	0.089	0.124	0.108	0.161	0.112	0.123 A
CF + S	0.060	0.086	0.125	0.100	0.083	0.103	0.093 B
CS	0.045	0.076	0.064	0.059	0.071	0.093	0.068 D
SD 2-4	0.076	0.066	0.101	0.096	0.062	0.104	0.084 BC
SD 4-6	0.079	0.056	0.103	0.070	0.061	0.086	0.076 CD
SD 8-10	0.087	0.054	0.097	0.065	0.074	0.087	0.077 CD
Mean	0.082	0.071	0.102	0.083	0.085	0.098	
<u>Shoot</u>				<u>Straw</u>			
	<u>S</u>	<u>W</u>	<u>SxW</u>		<u>S</u>	<u>W</u>	<u>SxW</u>
SE m±	0.006	0.006	0.015		0.006	0.006	0.015
LSD (0.01)	0.017	0.017	0.041		0.017	0.017	0.041
LSD (0.05)	0.013	0.013	0.031		0.013	0.013	0.031

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 25. Influence of sulfur application and five water management practices on P uptake by eight week-old shoot and grain plus straw at harvest of rice (IR54) in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>P uptake (mg/pot) by 8-week-old shoot</u>							
CF	9.3	22.7	16.3	16.1	16.1	24.6	17.5 B
CF + S	12.6	24.9	29.8	16.3	20.9	22.6	21.2 A
CS	8.3	20.0	15.3	11.8	15.7	14.0	14.2 C
SD 2-4	4.1	11.1	19.2	12.8	13.1	13.1	12.2 C
SD 4-6	5.7	16.2	16.3	9.5	12.1	13.1	12.2 C
SD 8-10	10.5	25.6	23.4	18.2	16.6	19.7	19.0 AB
Mean	8.4	20.1	20.0	14.1	15.8	17.9	
<u>P uptake (mg/pot) at harvest</u>							
CF	31.0	67.0	54.3	39.3	37.0	44.7	45.6 A
CF + S	35.3	45.3	60.3	48.0	46.3	54.0	48.2 A
CS	25.0	36.3	44.0	28.0	34.3	39.7	34.6 C
SD 2-4	30.0	41.3	57.3	38.0	29.7	42.0	39.7 B
SD 4-6	38.3	45.0	64.0	38.0	37.3	49.0	45.3 A
SD 8-10	45.0	46.7	54.7	32.0	41.7	47.0	44.5 AB
Mean	34.1	46.9	55.8	37.2	37.7	46.1	
<u>P Uptake by shoot</u>				<u>P Uptake at harvest</u>			
	S	W	SxW	S	W	SxW	
SE m±	1.2	1.2	2.8	2.5	2.5	6.2	
LSD (0.01)	3.1	3.1	7.5	6.7	6.7	16.3	
LSD (0.05)	2.3	2.3	5.6	5.0	5.0	12.3	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 26. Influence of sulfur application and five water management practices on the K concentration of eight week-old shoot and mature rice (IR54) straw in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>% K in 8 week-old shoot</u>							
CF	3.40	2.50	3.82	2.21	3.83	1.79	2.92 D
CF + S	2.98	2.68	2.62	2.05	4.04	1.90	2.71 E
CS	3.59	2.72	3.43	2.43	4.25	2.12	3.09 C
SD 2-4	5.12	3.54	3.98	2.74	4.33	2.61	3.72 A
SD 4-6	4.02	3.03	3.62	2.69	4.45	2.19	3.33 B
SD 8-10	3.44	2.55	3.71	2.15	3.79	1.96	2.93 D
Mean	3.76	2.84	3.53	2.38	4.12	2.09	
<u>% K in straw</u>							
CF	2.73	1.16	3.17	1.46	2.60	1.58	2.12 C
CF + S	2.34	0.65	2.52	1.55	3.56	1.33	1.99 C
CS	2.91	1.40	3.14	1.76	3.72	1.65	2.43 AB
SD 2-4	3.66	1.88	2.98	1.60	3.60	1.63	2.56 A
SD 4-6	2.93	1.35	2.79	1.73	3.57	1.54	2.32 B
SD 8-10	3.12	1.60	3.43	1.52	4.66	1.25	2.60 A
Mean	2.95	1.34	3.01	1.60	3.62	1.50	
<u>Shoot</u>				<u>Straw</u>			
	<u>S</u>	<u>W</u>	<u>SxW</u>		<u>S</u>	<u>W</u>	<u>SxW</u>
SE m±	0.06	0.06	0.16		0.09	0.09	0.23
LSD (0.01)	0.17	0.17	0.42		0.25	0.25	0.61
LSD (0.05)	0.13	0.13	0.32		0.19	0.19	0.46

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

saturation (CS) or drying the soils for 2 weeks (SD 2-4; SD 4-6; SD 8-10), increased the K concentration of straw (Table 26).

Total K uptake by rice at vegetative (8 WAT) as well as at maturity stage were also lowest in flooded soils and drying or keeping the soil saturated increased it (Table 27).

Calcium

Calcium concentration of shoot and straw and Ca uptake by shoot and at harvest were highest in sulfur treated flooded soils (CF + S) while these were lowest when the soils were kept saturated (CS) (Tables 28 and 29). Soil drying for 2 weeks imposed at 2 WAT (SD 2-4) decreased the Ca concentration of shoot and straw and Ca uptake at harvest but imposition of soil drying at 4 (SD 4-6) or 8 WAT (SD 8-10) had no effect on these values (Tables 28 and 29). The Ca uptake by shoot under continuously flooded (CF), saturated (CS) and dried and reflooded water regimes were comparable. The higher values of Ca concentration and uptake in sulfur treated pots were because of increased availability of Ca due to application of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ as S source (Table 29).

Magnesium

The effect of water management practices and sulfur addition on different soils on Mg nutrition was similar to that on Ca nutrition (Tables 30 and 31).

Table 27. Influence of sulfur application and five water management practices on K uptake by eight week-old shoot and grain plus straw at harvest of rice (IR54) in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>K uptake (mg/pot) by 8-week-old shoot</u>							
CF	141.4	226.6	206.1	153.8	255.9	194.1	196.3 B
CF + S	237.9	261.7	314.3	168.1	360.7	191.5	255.7 A
CS	217.7	306.6	317.9	204.7	282.6	191.5	253.5 A
SD 2-4	158.7	234.7	316.5	212.8	234.0	192.8	224.9 AB
SD 4-6	184.4	241.5	291.1	178.0	251.1	178.0	220.7 AB
SD 8-10	170.8	241.6	268.0	177.7	251.4	187.4	216.2 B
Mean	185.2	252.1	285.6	182.5	272.6	189.2	
<u>K uptake (g/pot) at harvest</u>							
CF	0.33	0.35	0.62	0.27	0.36	0.29	0.37 D
CF + S	0.49	0.19	0.61	0.28	0.67	0.32	0.43 BC
CS	0.45	0.30	0.62	0.24	0.50	0.31	0.40 BD
SD 2-4	0.41	0.35	0.61	0.25	0.43	0.27	0.39 CD
SD 4-6	0.48	0.37	0.63	0.29	0.53	0.32	0.44 B
SD 8-10	0.56	0.40	0.69	0.25	0.75	0.27	0.49 A
Mean	0.45	0.33	0.63	0.26	0.54	0.30	
	K Uptake by shoot			K Uptake at harvest			
	S	W	SxW	S	W	SxW	
SE m±	14.8	14.8	36.3	0.02	0.02	0.05	
LSD (0.01)	39.2	39.2	96.1	0.05	0.05	0.12	
ISD (0.05)	29.5	29.5	72.4	0.04	0.04	0.09	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 28. Influence of sulfur application and five water management practices on the Ca concentration of eight week-old shoot and mature rice (IR54) straw in six soils

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>% Ca in 8 week-old shoot</u>							
CF	0.119	0.235	0.187	0.263	0.417	0.141	0.227 B
CF + S	0.115	0.242	0.216	0.336	0.390	0.152	0.242 A
CS	0.091	0.201	0.177	0.239	0.319	0.112	0.190 D
SD 2-4	0.098	0.238	0.177	0.257	0.378	0.127	0.213 C
SD 4-6	0.103	0.218	0.192	0.271	0.347	0.126	0.210 C
SD 8-10	0.114	0.224	0.191	0.285	0.329	0.135	0.213 C
Mean	0.107	0.226	0.190	0.275	0.363	0.132	
<u>% Ca in mature straw</u>							
CF	0.161	0.307	0.311	0.346	0.233	0.183	0.257 BC
CF + S	0.165	0.294	0.330	0.428	0.345	0.175	0.290 A
CS	0.137	0.213	0.242	0.338	0.311	0.138	0.230 D
SD 2-4	0.159	0.256	0.242	0.329	0.352	0.173	0.252 C
SD 4-6	0.165	0.280	0.289	0.355	0.345	0.184	0.270 A-C
SD 8-10	0.175	0.261	0.298	0.439	0.335	0.160	0.278 AB
Mean	0.161	0.268	0.285	0.373	0.320	0.169	
<u>Shoot</u>			<u>Straw</u>				
	S	W	SxW	S	W	SxW	
SE m±	0.005	0.005	0.013	0.010	0.010	0.025	
LSD (0.01)	0.014	0.014	0.034	0.027	0.027	0.066	
LSD (0.05)	0.010	0.010	0.025	0.020	0.020	0.050	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 29. Influence of sulfur application and five water management practices on Ca uptake by eight week-old shoot and grain plus straw at harvest of rice (IR54) in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>Ca uptake (mg/pot) by 8-week-old shoot</u>							
CF	5.0	21.2	10.1	18.3	27.9	15.5	16.3 B
CF + S	9.2	23.5	25.9	27.5	35.2	15.5	22.8 A
CS	5.6	22.6	16.4	20.3	21.3	10.1	16.0 B
SD 2-4	3.0	15.8	14.2	20.3	20.5	9.7	13.9 B
SD 4-6	4.8	17.6	15.4	17.9	19.6	10.4	14.3 B
SD 8-10	5.7	21.1	13.9	23.6	22.0	12.6	16.5 B
Mean	5.5	20.3	16.0	21.3	24.4	12.3	
<u>Ca uptake (mg/pot) at harvest</u>							
CF	16.7	70.0	53.3	66.3	33.3	30.0	44.4 B
CF + S	33.3	53.3	70.0	66.7	60.0	36.7	53.3 A
CS	20.0	40.0	46.7	43.3	40.0	23.3	35.6 C
SD 2-4	16.7	43.3	46.7	43.3	40.0	26.7	36.1 C
SD 4-6	26.7	60.0	63.3	50.0	50.0	33.3	47.2 B
SD 8-10	30.0	53.3	60.0	60.0	53.3	33.3	48.3 AB
Mean	23.9	53.3	56.7	54.4	46.1	30.6	
<u>Ca Uptake by shoot</u>				<u>Ca Uptake at harvest</u>			
	S	W	SxW		S	W	SxW
SE m±	1.3	1.3	3.1		2.6	2.6	6.3
LSD (0.01)	3.4	3.4	8.3		6.8	6.8	16.6
LSD (0.05)	2.6	2.6	6.3		5.1	5.1	12.5

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 30. Influence of sulfur application and five water management practices on the Mg concentration of eight week-old shoot and mature rice (IR54) straw in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>% Mg in 8 week-old shoot</u>							
CF	0.509	0.311	0.348	0.402	0.311	0.748	0.438 B
CF + S	0.611	0.319	0.557	0.423	0.256	0.740	0.484 A
CS	0.400	0.273	0.357	0.348	0.336	0.590	0.384 C
SD 2-4	0.386	0.269	0.323	0.298	0.319	0.569	0.361 C
SD 4-6	0.444	0.294	0.390	0.390	0.357	0.656	0.422 B
SD 8-10	0.523	0.277	0.377	0.411	0.281	0.707	0.429 B
Mean	0.479	0.291	0.392	0.379	0.310	0.668	
<u>% Mg in straw</u>							
CF	0.304	0.257	0.376	0.346	0.284	0.573	0.357 B
CF + S	0.568	0.216	0.454	0.387	0.299	0.599	0.420 A
CS	0.578	0.227	0.428	0.345	0.273	0.650	0.417 A
SD 2-4	0.397	0.247	0.371	0.330	0.252	0.656	0.376 B
SD 4-6	0.552	0.268	0.449	0.325	0.273	0.717	0.431 A
SD 8-10	0.526	0.232	0.443	0.376	0.299	0.640	0.419 A
Mean	0.487	0.241	0.420	0.351	0.280	0.639	
<u>Shoot</u>				<u>Straw</u>			
	S	W	SxW	S	W	SxW	
SE m±	0.014	0.014	0.035	0.016	0.016	0.038	
LSD (0.01)	0.038	0.038	0.093	0.041	0.041	0.101	
LSD (0.05)	0.029	0.029	0.070	0.031	0.031	0.076	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 31. Influence of sulfur application and five water management practices on Mg uptake by eight week-old shoot and grain plus straw at harvest of rice (IR54) in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>Mg uptake (mg/pot) by 8-week-old shoot</u>							
CF	21.1	28.0	18.7	28.0	20.8	82.5	33.2 B
CF + S	49.2	31.1	66.8	34.5	22.8	74.8	46.5 A
CS	24.3	30.5	33.4	29.5	22.4	53.0	32.2 b
SD 2-4	11.9	17.8	26.0	23.7	17.3	43.6	23.4 C
SD 4-6	20.5	23.6	31.5	25.6	20.1	54.2	29.2 B
SD 8-10	26.2	25.9	27.4	34.1	18.7	66.2	33.1 B
Mean	25.6	26.1	34.0	29.2	20.3	62.4	
<u>Mg uptake (mg/pot) at harvest</u>							
CF	43.3	80.0	86.7	73.3	50.0	110.0	73.9 BC
CF + S	123.3	56.7	113.3	76.7	70.0	133.3	95.6 A
CS	96.7	53.3	100.0	50.0	50.0	126.7	79.4 B
SD 2-4	53.3	56.7	86.7	56.7	40.0	116.7	68.3 C
SD 4-6	100.0	76.7	116.7	60.0	53.3	150.0	92.8 A
SD 8-10	103.3	70.0	100.0	66.7	66.7	136.7	90.6 A
Mean	86.7	65.6	100.6	63.9	55.0	128.9	
<u>Mg Uptake by shoot</u>				<u>Mg Uptake at harvest</u>			
	S	W	SxW	S	W	SxW	
SE m±	2.7	2.7	6.5	4.7	4.7	11.6	
LSD (0.01)	7.1	7.1	17.3	12.5	12.5	30.7	
LSD (0.05)	5.3	5.3	13.0	9.4	9.4	23.1	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Sulfur

Sulfur concentration of shoot and straw and S uptake by shoots and grains plus straw at harvest were lowest in continuously flooded soils (CF) while these were highest in flooded soils where sulfur was added (CF + S) (Tables 32 and 33). Reducing the water content of soil from flooding (CF) to saturation (CS) improved the S status of shoot and straw and its uptake. Soil drying for 2 weeks at the early stage (2 WAT) increased the S concentration of shoots and its uptake at 8 WAT stage but did not influence the S concentration of straw and its uptake at harvest. However, soil drying for 2 weeks at 4, 6 and 8 WAT increased S concentration in shoot and straw and its uptake by shoots and by grains plus straw at harvest (Tables 32 and 33).

N:S ratio

The ratios of N to S in shoot and straw at maturity are presented in Table 34. The N:S value in shoot as well as in straw were highest in continuously flooded water regime (CF). This ratio decreased on S addition (CF + S). Soil drying for 2 weeks during the vegetative growth stage decreased this ratio both in shoot and in straw. Although the S concentration in shoot was more than the critical limit (0.11%) but the N:S ratio greater than 15 suggests S deficiency at this stage. Soil drying for 2 weeks from 2 or 4 WAT (SD2-4; SD 4-6) or keeping the soil saturated (CS) increased the S concentration and decreased the N:S ratio in shoot thereby, eliminating S deficiency. The S concentrations in straw at maturity were higher than the critical limit (0.055% S) and the N:S ratios were also less than 14 in all the water regimes. These

Table 32. Influence of sulfur application and five water management practices on the S concentration of eight week-old shoot and mature rice (IR54) straw in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>% S in 8 week-old shoot</u>							
CF	0.098	0.165	0.107	0.173	0.105	0.171	0.136 D
CF + S	0.229	0.202	0.227	0.313	0.294	0.264	0.255 A
CS	0.150	0.222	0.129	0.247	0.173	0.247	0.195 C
SD 2-4	0.203	0.221	0.169	0.227	0.266	0.267	0.226 B
SD 4-6	0.142	0.270	0.192	0.287	0.224	0.275	0.232 AB
SD 8-10	0.110	0.159	0.107	0.162	0.128	0.222	0.148 D
Mean	0.155	0.206	0.155	0.235	0.198	0.241	
<u>% S in straw</u>							
CF	0.077	0.111	0.099	0.094	0.067	0.077	0.088 C
CF + S	0.105	0.098	0.165	0.146	0.150	0.122	0.131 A
CS	0.097	0.128	0.106	0.108	0.086	0.152	0.113 B
SD 2-4	0.096	0.146	0.058	0.096	0.083	0.106	0.098 C
SD 4-6	0.126	0.106	0.091	0.113	0.068	0.109	0.102 BC
SD 8-10	0.127	0.133	0.125	0.119	0.108	0.164	0.129 A
Mean	0.105	0.121	0.107	0.112	0.094	0.122	
<u>Shoot</u>				<u>Straw</u>			
	S	W	SxW	S	W	SxW	
SE m±	0.012	0.012	0.030	0.007	0.007	0.017	
LSD (0.01)	0.032	0.032	0.079	0.019	0.019	0.046	
LSD (0.05)	0.024	0.024	0.060	0.014	0.014	0.034	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 33. Influence of sulfur application and five water management practices on S uptake by eight week-old shoot and grain plus straw at harvest of rice (IR54) in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>S uptake (mg/pot) by 8-week-old shoot</u>							
CF	4.0	15.1	5.8	12.0	7.1	18.6	10.4 D
CF + S	17.4	19.6	27.1	25.6	25.7	27.1	23.8 A
CS	9.0	24.9	12.2	21.1	11.4	22.2	16.8 B
SD 2-4	6.3	14.6	13.7	18.0	14.8	18.9	14.4 BC
SD 4-6	6.4	20.8	15.6	18.9	12.6	22.5	16.1 B
SD 8-10	5.5	15.0	7.7	13.8	8.5	21.6	12.0 CD
Mean	8.1	18.3	13.7	18.3	13.3	21.8	
<u>S uptake (mg/pot) at harvest</u>							
CF	12.7	39.7	29.7	26.7	12.7	22.3	23.9 D
CF + S	40.7	29.7	54.7	39.7	41.7	45.0	41.9 A
CS	25.7	33.3	34.3	24.7	21.0	40.7	29.9 BC
SD 2-4	20.0	35.0	29.0	26.0	18.7	30.3	26.5 CD
SD 4-6	28.7	31.0	36.3	32.7	21.0	40.0	31.6 B
SD 8-10	33.7	42.0	44.0	29.3	32.0	51.7	38.8 A
Mean	26.9	35.1	38.0	29.8	24.5	38.3	
<u>S Uptake by shoot</u>				<u>S Uptake at harvest</u>			
	S	W	SxW		S	W	SxW
SE m±	1.4	1.4	3.5		2.0	2.0	5.0
LSD (0.01)	3.8	3.8	9.3		5.4	5.4	13.2
LSD (0.05)	2.8	2.8	7.0		4.1	4.1	13.2

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 34. Influence of sulfur application and five water management practices on N:S ratio in eight week-old shoots and straw at maturity of rice (IR54) in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>N:S in shoots</u>							
CF	29.6	14.7	23.1	14.2	20.0	15.5	19.5 A
CF + S	12.0	12.0	11.5	7.4	7.9	10.6	10.2 C
CS	17.6	10.5	21.6	10.4	16.1	9.4	14.3 B
SD 2-4	13.8	11.4	15.6	12.3	10.9	10.2	12.4 BC
SD 4-6	22.5	9.9	14.9	10.0	13.1	11.1	13.6 B
SD 8-10	24.9	14.1	24.6	16.8	16.1	12.9	18.2 A
Mean	20.1	12.1	18.5	11.9	14.0	11.6	
<u>N:S in straw</u>							
CF	19.6	6.2	11.0	9.2	13.6	11.4	11.8 A
CF + S	6.5	7.3	5.2	5.4	3.5	7.0	5.8 E
CS	6.0	5.6	5.7	5.6	6.5	5.4	5.8 B
SD 2-4	7.1	4.0	10.9	7.7	4.7	7.3	6.9 F
SD 4-6	6.0	12.8	7.5	5.8	7.3	7.3	7.8 E
SD 8-10	9.8	4.5	6.6	5.1	6.0	5.5	6.2 E
Mean	9.2	6.7	7.8	6.5	6.9	7.3	
<u>N:S in shoot</u>				<u>N:S in straw</u>			
	S	W	SxW		S	W	SxW
SE m±	1.1	1.1	2.7		1.0	1.0	2.4
LSD (0.01)	3.0	3.0	7.3		2.6	2.6	6.3
LSD (0.05)	2.2	2.2	5.5		1.9	1.9	4.7

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

suggest absence of S deficiency. This suggests that the plants recovered from S deficiency at the later stage. But under continuously flooded water regime (CF), due to S deficiency in the vegetative growth stage, the plants had poor growth and less tillers and thus low yield.

Iron

Iron concentration of 8 week-old shoot and straw and Fe uptake by shoot and grain plus straw at harvest were different in different soils. While the Fe concentration of straw was not influenced by water management practices that of shoot and Fe uptake at harvest were influenced by water management practices (Tables 35 and 36).

The Fe concentration of shoot was highest under continuously flooded condition (CF) while sulfur addition to flooded soil (CF + S) decreased it (Table 35). Drying the soils for 2 weeks at 4 WAT (SD 4-6) decreased the Fe concentration of shoot while soil drying for 2 weeks at 2 WAT (SD 2-4) had no effect on it. Rice shoot on continuously saturated soils had lowest Fe (Table 35).

Total Fe uptake by rice shoots increased due to S addition in flooded soil. This was due to increased dry matter production when S was applied. Total Fe uptake by shoots in continuously saturated (CS) and dried and reflooded soils were comparable with continuously flooded soils (Table 36). Two weeks soil drying at 4 and 8 WAT and reflooding (SD 4-6; SD 8-10) increased the Fe uptake by grains plus straw at harvest but Fe uptake in other treatments were comparable.

Table 35. Influence of sulfur application and five water management practices on the Fe concentration of eight week-old shoot and mature rice (IR54) straw in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>ppm Fe in 8 week-old shoot</u>							
CF	303.3	263.3	325.0	271.7	246.7	323.3	288.9 A
CF + S	288.3	183.3	260.0	250.0	243.3	345.0	261.7 B
CS	261.7	156.7	235.0	241.7	250.0	246.7	231.9 C
SD 2-4	305.0	260.0	280.0	241.7	256.7	315.0	276.4 AB
SD 4-6	300.0	195.	295.0	255.0	231.7	285.0	260.3 P
SD 8-10	348.3	216.7	291.7	283.3	191.7	281.7	268.9 AB
Mean	301.1	212.5	281.1	257.2	236.7	299.4	
<u>ppm Fe in straw</u>							
CF	141.7	186.7	218.3	153.3	140.3	180.0	170.1 A
CF + S	140.0	125.0	181.7	143.3	143.3	151.7	147.5 A
CS	175.0	85.0	215.0	123.3	210.0	175.0	163.9 A
SD 2-4	171.7	171.7	203.3	125.0	168.3	216.7	176.1 A
SD 4-6	196.7	158.3	205.0	71.7	150.0	253.3	172.5 A
SD 8-10	180.0	136.7	125.0	175.0	220.0	208.3	174.2 A
Mean	167.5	143.9	191.4	131.9	172.0	197.5	
	<u>Shoot</u>			<u>Straw</u>			
	S	W	SxW	S	W	SxW	
SE m±	12.4	12.4	30.3	16.8	16.8	41.1	
LSD (0.01)	32.8	32.8	80.3	44.4	44.4	108.8	
LSD (0.05)	24.7	24.7	60.5	33.4	33.4	81.9	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 36. Influence of sulfur application and five water management practices on Fe uptake by eight week-old shoot and grain plus straw at harvest of rice (IR54) in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>Fe uptake (mg/pot) by 8-week-old shoot</u>							
CF	1.27	2.41	1.75	1.89	1.64	3.51	2.08 B
CF + S	2.23	1.89	3.11	2.06	2.14	3.52	2.49 A
CS	1.59	1.71	2.23	2.00	1.65	2.71	1.90 B
SD 2-4	0.95	1.71	2.28	1.91	1.38	2.26	1.75 B
SD 4-6	1.37	1.57	2.39	1.68	1.31	2.31	1.77 B
SD 8-10	1.77	2.01	2.09	2.36	1.28	2.72	2.04 B
Mean	1.53	1.89	2.31	1.98	1.57	2.75	
<u>Fe uptake (mg/pot) at harvest</u>							
CF	3.25	11.43	7.21	7.35	6.98	7.28	7.25 BC
CF + S	7.91	6.31	9.66	7.75	11.02	8.48	8.52 AB
CS	4.45	3.89	8.71	6.72	4.98	7.29	6.01 C
SD 2-4	6.25	7.11	5.38	4.75	5.52	8.17	6.20 C
SD 4-6	4.99	5.64	14.87	5.48	11.02	11.16	8.86 A
SD 8-10	11.35	11.06	4.86	9.03	8.63	9.36	9.05 A
Mean	6.37	7.57	8.45	6.85	8.03	8.62	
<u>Fe Uptake by shoot</u>			<u>Fe Uptake at harvest</u>				
	<u>S</u>	<u>W</u>	<u>SxW</u>	<u>S</u>	<u>W</u>	<u>SxW</u>	
SE m±	0.17	0.17	0.41	0.74	0.74	1.80	
LSD (0.01)	0.45	0.45	1.09	1.95	1.95	4.77	
LSD (0.05)	0.34	0.34	0.82	1.47	1.47	3.59	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Manganese

While decreasing the water content of soil from continuous flooding (CF) to continuous saturation (CS) decreased the Mn concentration of shoot and straw, soil drying for 2 weeks and reflooding significantly increased it in both, shoots and straw. Application of sulfur to flooded soil (CF + S) also increased the Mn concentration of shoot and straw (Table 37).

Sulfur application in continuously flooded soil increased Mn uptake by shoots but this effect was not seen in Mn uptake at harvest. Soil drying for 2 weeks during the vegetative growth stages significantly increased Mn uptake by shoots and grains plus straw at maturity (Table 38).

Zinc

Zinc concentration of 8 week-old shoot and straw were not influenced by sulfur application. Soil drying for 2 weeks increased the Zn concentration of shoot. However, these differences were not statistically significant. Concentration of zinc of mature rice straw was highest in soil where 2 weeks drying treatment was imposed at 4 WAT (Table 39).

Zinc uptake by rice at harvest was lowest under saturated water regime (Table 40). Soil drying for 2 weeks or sulfur application had zinc uptake comparable to flooded water regime (Table 40). However, Zn uptake by shoot was neither influenced by sulfur application nor by soil drying and reflooding.

Table 37. Influence of sulfur application and five water management practices on the Mn concentration of eight week-old shoot and mature rice (IR54) straw in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>ppm Mn in 8 week-old shoot</u>							
CF	621.7	1578.3	285.0	1340.7	624.2	540.0	831.6 C
CF + S	645.0	1486.5	581.7	1515.8	932.5	545.0	951.1 B
CS	520.0	1124.0	573.3	1295.0	445.0	261.7	703.2 E
SD 2-4	815.8	2349.2	655.0	2699.0	749.2	585.0	1308.9 A
SD 4-6	423.3	1303.3	553.3	1724.2	418.3	435.0	809.6 C
SD 8-10	358.3	1474.2	276.7	1361.7	646.7	555.0	778.8 CD
Mean	564.0	1552.6	487.5	1656.1	636.0	486.9	
<u>ppm Mn in straw</u>							
CF	521.8	2143.7	325.5	1493.2	289.3	496.0	878.3 CD
CF + S	795.7	1627.2	485.7	1741.2	868.0	485.7	1000.6 B
CS	511.5	1126.3	594.2	1798.0	341.0	237.7	768.1 D
SD 2-4	1002.3	2004.7	413.3	2056.3	826.7	573.5	1146.1 A
SD 4-6	1043.7	2159.7	485.7	2252.7	888.7	625.2	1242.6 A
SD 8-10	744.0	1741.2	604.5	1963.3	506.3	372.0	983.6 BC
Mean	769.8	1800.4	484.8	1884.1	620.0	465.0	
<u>Shoot</u>			<u>Straw</u>				
	S	W	SxW	S	W	SxW	
SE m±	45.5	45.5	111.5	56.2	56.2	137.7	
LSD (0.01)	120.6	120.6	295.3	148.9	148.9	364.7	
LSD (0.05)	90.8	90.8	222.5	112.1	112.1	274.7	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 38. Influence of sulfur application and five water management practices on Mn uptake by eight week-old shoot and grain plus straw at harvest of rice (IR54) in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>Mn uptake (mg/pot) by 8-week-old shoot</u>							
CF	2.59	14.20	1.56	9.37	4.19	5.97	6.31 B
CF + S	5.22	14.40	6.98	12.38	8.10	5.53	8.77 A
CS	3.18	12.77	5.32	10.87	2.97	2.38	6.25 B
SD 2-4	2.51	15.69	5.24	22.13	4.02	4.33	8.99 A
SD 4-6	1.90	10.18	4.42	11.36	2.36	3.52	5.62 B
SD 8-10	1.82	13.94	2.01	11.31	4.22	5.27	6.43 B
Mean	2.87	13.53	4.28	12.90	4.31	4.50	
<u>Mn uptake (mg/pot) at harvest</u>							
CF	6.40	47.58	6.24	25.12	4.27	8.36	16.33 B
CF + S	15.09	29.75	10.73	27.86	15.03	9.97	18.07 B
CS	7.47	20.64	11.27	21.76	4.53	4.40	11.68 C
SD 2-4	10.66	32.00	8.02	26.85	9.11	9.01	15.94 B
SD 4-6	16.25	44.64	10.57	31.57	12.50	11.95	21.25 A
SD 8-10	12.77	36.92	11.65	27.42	8.14	7.77	17.45 B
Mean	11.44	35.26	9.75	26.76	8.93	8.58	
<u>Mn Uptake by shoot</u>				<u>Mn Uptake at harvest</u>			
	S	W	SxW	S	W	SxW	
SE m±	0.74	0.74	1.80	1.11	1.11	2.71	
LSD (0.01)	1.95	1.95	4.77	2.93	2.93	7.18	
LSD (0.05)	1.47	1.47	3.60	2.21	2.21	5.41	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 39. Influence of sulfur application and five water management practices on the Zn concentration of eight week-old shoot and mature rice (IR54) straw in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>ppm Zn in 8 week-old shoot</u>							
CF	21.5	32.7	30.0	28.0	22.8	23.0	26.3 AB
CF + S	24.8	26.7	28.2	25.3	21.0	23.5	24.9 B
CS	19.8	32.3	27.5	41.8	20.0	25.8	27.9 AB
SD 2-4	26.3	42.7	34.7	33.3	22.2	25.3	30.8 A
SD 4-6	23.5	46.3	30.8	41.7	19.2	21.5	30.5 A
SD 8-10	15.2	36.8	23.0	55.5	20.5	19.8	28.5 AB
Mean	21.9	36.3	29.0	37.6	20.9	23.2	
<u>ppm Zn in straw</u>							
CF	36.5	74.5	46.0	61.8	44.0	29.7	48.8 B
CF + S	36.7	40.0	63.7	66.3	41.2	22.8	45.1 B
CS	44.5	60.5	61.3	55.3	32.3	19.0	45.5 B
SD 2-4	28.8	65.7	70.5	58.3	41.3	28.2	48.8 B
SD 4-6	29.3	92.7	71.5	62.5	48.0	29.5	55.6 A
SD 8-10	32.8	65.0	66.8	61.3	52.8	20.3	49.9 B
Mean	34.8	66.4	63.3	60.9	43.3	24.9	
<u>Shoot</u>				<u>Straw</u>			
	S	W	SxW		S	W	SxW
SE m±	2.2	2.2	5.4		2.7	2.7	6.5
LSD (0.01)	5.8	5.8	14.3		7.1	7.1	17.3
LSD (0.05)	4.4	4.4	10.8		5.3	5.3	13.0

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 40. Influence of sulfur application and five water management practices on Zn uptake by eight week-old shoot and grain plus straw at harvest of rice (IR54) in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>Zn uptake (mg/pot) by 8-week-old shoot</u>							
CF	0.09	0.30	0.16	0.19	0.15	0.25	0.19 A
CF + S	0.20	0.26	0.34	0.21	0.18	0.24	0.24 A
CS	0.12	0.37	0.26	0.35	0.14	0.23	0.25 A
SD 2-4	0.08	0.28	0.27	0.27	0.12	0.19	0.20 A
SD 4-6	0.11	0.37	0.25	0.28	0.11	0.18	0.22 A
SD 8-10	0.08	0.35	0.16	0.48	0.14	0.19	0.23 A
Mean	0.11	0.32	0.24	0.30	0.14	0.21	
<u>Zn uptake (mg/pot) at harvest</u>							
CF	0.64	2.50	1.31	1.32	0.79	0.76	1.22 BC
CF + S	1.08	1.10	1.98	1.52	1.09	0.83	1.27 AB
CS	0.97	1.44	1.58	0.93	0.79	0.57	1.05 C
SD 2-4	0.57	1.40	1.89	1.10	0.74	0.72	1.07 C
SD 4-6	0.92	2.40	1.05	1.24	1.00	0.95	1.43 A
SD 8-10	0.94	1.86	1.82	1.20	1.19	0.76	1.30 AB
Mean	0.85	1.78	1.77	1.22	0.93	0.77	
<u>Zn Uptake by shoot</u>				<u>Zn Uptake at harvest</u>			
	S	W	SxW	S	W	SxW	
SE m±	0.03	0.03	0.07	0.08	0.08	0.20	
LSD (0.01)	0.07	0.07	0.17	0.22	0.22	0.54	
LSD (0.05)	0.05	0.05	0.13	0.17	0.17	0.41	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Copper

Copper concentration of shoot was not influenced whether or not sulfur was applied to flooded soil but drying the soils for 2 weeks at 2 or 4 WAT increased it. Copper concentration of straw was lowest under flooded condition and application of sulfur did not affect it but keeping the soil saturated or soil drying for 2 weeks at 2, 4 or 8 WAT increased it (Table 41).

Copper uptake by rice at harvest was lowest under flooded as well as saturated condition. Sulfur application to flooded soils improved Cu uptake by the crop and soil drying for 2 weeks at 2, 4 or 8 WAT increased it further (Table 42). Copper uptake by shoots under continuously flooded condition, however, was not significantly different from other water regimes.

Growth and Yield of rice (IR54)

Plant height

Soil drying for 2 weeks at 2 WAT increased the plant height in all soils. In general, the plant height in other treatments were not different (Fig. 51A-F). At harvest, however, shortest plants were found in continuously flooded water regime (CF) and application of sulfur (CF + S) or keeping the soil saturated (CS) did not increase it. Soil drying for 2 weeks in the beginning (SD 2-4) and at a later stage (SD 8-10) increased plant height (Table 43).

Table 41. Influence of sulfur application and five water management practices on the Cu concentration of eight week-old shoot and mature rice (IR54) straw in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>ppm Cu in 8 week-old shoot</u>							
CF	20.7	21.0	21.7	34.3	29.8	25.2	25.4 CD
CF + S	21.7	23.5	22.2	19.5	26.2	23.8	22.8 D
CS	24.2	25.7	28.5	27.7	33.2	26.2	27.6 BC
SD 2-4	35.0	27.2	35.5	31.0	34.0	33.2	32.6 A
SD 4-6	29.5	33.8	28.8	32.7	33.8	25.3	30.7 AB
SD 8-10	19.3	21.2	20.7	20.8	31.0	23.8	22.8 D
Mean	25.1	25.4	26.2	27.7	31.3	26.3	
<u>ppm Cu in straw</u>							
CF	13.5	19.0	15.8	15.8	18.9	19.5	17.1 C
CF + S	15.5	15.5	17.2	16.3	21.7	16.2	17.1 C
CS	18.5	17.5	21.0	18.7	22.5	16.2	19.1 B
SD 2-4	19.2	19.8	21.7	19.0	22.3	18.5	20.1 AB
SD 4-6	17.7	20.0	23.2	19.7	24.7	21.5	21.1 A
SD 8-10	19.2	18.5	22.2	17.8	23.3	15.8	19.5 B
Mean	17.3	18.4	20.2	17.9	22.2	17.9	
<u>Shoot</u>			<u>Straw</u>				
	S	W	SxW	S	W	SxW	
SE m±	1.6	1.6	4.0	0.5	0.5	1.3	
LSD (0.01)	4.3	4.3	10.6	1.4	1.4	3.5	
LSD (0.05)	3.3	3.3	8.0	1.1	1.1	2.7	

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 42. Influence of sulfur application and five water management practices on Cu uptake by eight week-old shoot and grain plus straw at harvest of rice (IR54) in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean
<u>Cu uptake (mg/pot) by 8-week-old shoot</u>							
CF	0.09	0.21	0.11	0.16	0.20	0.27	0.17 B
CF + S	0.15	0.2	0.26	0.16	0.20	0.24	0.21 AB
CS	0.14	0.30	0.28	0.23	0.22	0.23	0.23 A
SD 2-4	0.11	0.18	0.30	0.25	0.17	0.23	0.21 AB
SD 4-6	0.13	0.24	0.23	0.22	0.19	0.21	0.20 AB
SD 8-10	0.10	0.21	0.15	0.18	0.20	0.25	0.18 B
Mean	0.12	0.23	0.22	0.20	0.20	0.24	
<u>Cu uptake (mg/pot) at harvest</u>							
CF	0.38	1.22	0.94	0.63	0.56	0.71	0.74 D
CF + S	0.82	0.84	1.10	0.76	0.92	0.87	0.88 BC
CS	0.77	0.78	1.04	0.59	0.72	0.58	0.75 D
SD 2-4	0.60	0.87	1.17	0.71	0.67	0.70	0.79 CD
SD 4-6	0.79	1.15	1.33	0.76	0.88	1.00	0.99 A
SD 8-10	0.93	1.06	1.13	0.66	0.88	0.81	1.91 AB
Mean	0.71	0.99	1.12	0.69	0.77	0.78	
<u>Cu Uptake by shoot</u>				<u>Cu Uptake at harvest</u>			
	<u>S</u>	<u>W</u>	<u>SxW</u>		<u>S</u>	<u>W</u>	<u>SxW</u>
SE m±	0.02	0.02	0.05		0.05	0.05	0.12
LSD (0.01)	0.05	0.05	0.12		0.13	0.13	0.33
LSD (0.05)	0.04	0.04	0.09		0.10	0.10	0.25

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Plant height (cm)

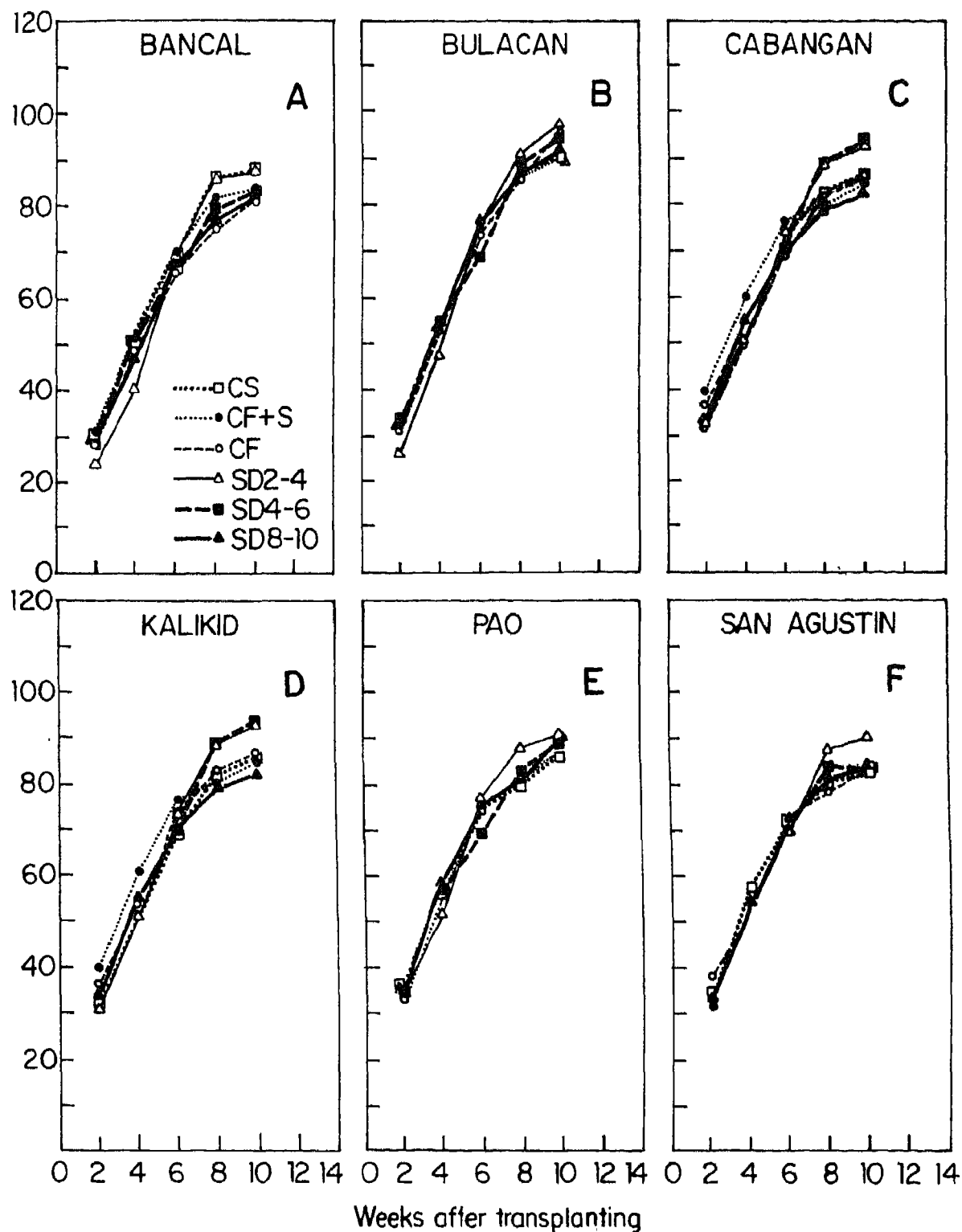


Fig. 51. Influence of sulfur application and five water management practices on height of rice plants at different growth stages in six soils.

Table 43. Influence of sulfur application and five water management practices on height and number of tillers at harvest and number of panicles of rice (IR54) grown in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean		
<u>Plant height at harvest (cm)</u>									
CF	94.0	108.0	99.7	94.0	99.3	92.3	97.9 C		
CF + S	94.3	101.0	94.7	98.7	100.3	89.3	96.4 C		
CS	101.0	103.3	101.0	96.3	100.7	94.3	99.4 BC		
SD 2-4	96.7	107.0	104.0	105.3	108.0	101.0	103.7 A		
SD 4-6	95.7	104.3	101.3	99.0	105.7	91.3	99.6 BC		
SD 8-10	108.0	106.0	99.0	105.3	103.3	92.0	102.3 AB		
Mean	98.3	104.9	99.9	99.8	102.9	93.4			
<u>Number of tillers per hill at harvest</u>									
CF	2.8	6.5	4.7	4.0	2.5	4.7	4.2 B		
CF + S	5.3	5.0	5.7	4.0	4.5	6.0	5.1 A		
CS	3.5	4.7	4.2	3.2	3.3	3.5	3.7 C		
SD 2-4	3.0	4.2	5.0	3.2	3.2	3.5	3.7 C		
SD 4-6	4.7	5.3	5.0	4.0	3.5	5.3	4.6 B		
SD 8-10	4.7	5.5	5.3	3.7	3.3	5.0	4.6 B		
Mean	4.0	5.2	5.0	3.7	3.4	4.7			
<u>Number of panicles per hill</u>									
CF	2.7	6.5	4.7	4.0	2.3	4.7	4.1 C		
CF + S	5.3	5.0	5.7	3.8	4.5	6.0	5.1 A		
CS	3.5	4.7	4.2	3.2	3.3	3.5	3.7 CD		
SD 2-4	3.1	4.2	4.8	3.2	2.8	3.5	3.6 D		
SD 4-6	4.7	5.3	5.0	4.0	3.5	5.3	4.6 B		
SD 8-10	4.7	5.6	5.2	3.7	3.3	5.0	4.6 B		
Mean	4.0	5.2	4.9	3.6	3.3	4.7			
	Height			Tillers			Panicle number		
	S	W	SxW	S	W	SxW	S	W	SxW
SE m±	1.7	1.7	4.2	0.2	0.2	0.5	0.2	0.2	0.5
LSD (0.01)	4.6	4.6	11.2	0.6	0.6	1.4	0.6	0.6	1.4
LSD (0.05)	3.4	3.4	8.4	0.4	0.4	1.1	0.4	0.4	1.0

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Tillering

Highest number of tillers were observed in sulfur treated flooded soils (CF + S). Soil drying for 2 weeks at 2 WAT (SD 2-4) produced lowest number of tillers (Fig. 52A-F). At harvest, highest number of tillers were observed in sulfur treated flooded soils while the fewest number of tillers were observed in CS and SD 2-4 water regimes. Number of tillers in other water regimes were comparable (Table 43).

Number of panicles

Highest number of panicles were found in sulfur treated flooded soils (CF + S) while the fewest panicles were found in SD 2-4 water regime. Soil drying for 2 weeks at 4 and 8 WAT (SD 4-6; SD 8-10) increased the number of panicles (Table 43).

Shoot dry matter yield

Dry weight of 8 week-old shoot were different on different soils and sulfur application and water management practices also influenced it. However, the interaction of soil and water management practices did not significantly affect shoot dry weight.

Sulfur application to flooded soil increased the shoot dry matter yield and it produced the highest dry matter among the treatments. Keeping the soil saturated instead of flooded and drying the soils for 2 weeks at 2 or 4 WAT increased dry weight of 8 week-old shoot (Table 44).

Tillers/hill

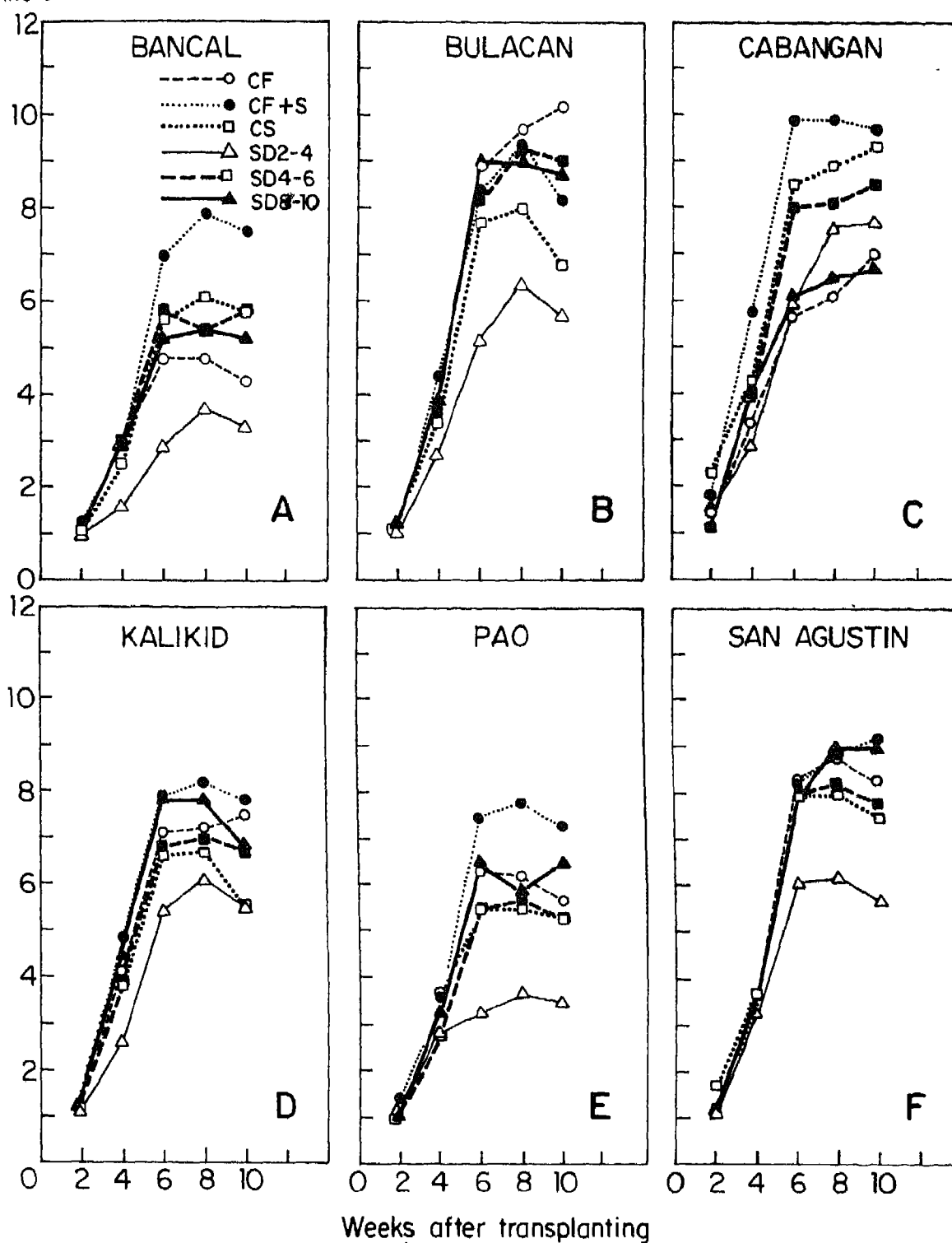


Fig. 52. Influence of sulfur application and five water management practices on tillering of rice at different growth stages in six soils.

Table 44. Influence of sulfur application and five water management practices on the yield of rice in six soils.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Mean		
<u>Dry matter yield of shoot (g/pot)</u>									
CF	4.2	9.1	5.4	7.0	6.7	11.0	7.2 CD		
CF + S	8.1	9.7	12.0	8.2	9.0	10.2	9.5 A		
CS	6.1	11.4	9.4	8.4	6.7	9.0	8.5 AB		
SD 2-4	3.1	6.6	8.0	8.0	5.4	7.5	6.4 D		
SD 4-6	4.6	8.0	8.0	6.6	5.6	8.2	6.8 CD		
SD 8-10	5.0	9.5	7.2	8.3	6.6	9.5	7.7 BC		
Mean	5.2	9.1	8.4	7.7	6.7	9.2			
<u>Straw yield (g/pot)</u>									
CF	11.3	21.2	17.0	16.9	13.1	15.5	15.8 AB		
CF + S	17.7	17.2	20.0	15.0	16.8	18.7	17.6 A		
CS	13.5	16.9	17.5	11.5	12.1	16.7	14.7 BC		
SD 2-4	10.0	15.0	17.6	12.3	10.3	14.8	13.3 C		
SD 4-6	14.5	19.8	19.8	13.3	13.1	17.5	16.3 AB		
SD 8-10	15.7	19.6	17.7	13.2	14.7	19.1	16.7 A		
Mean	13.8	18.3	18.2	13.7	13.4	17.1			
<u>Grain yield (g/pot)</u>									
CF	5.0	16.3	14.6	7.4	5.3	9.7	9.7 C		
CF + S	13.2	11.9	15.4	11.0	12.1	14.7	13.0 A		
CS	11.2	10.0	13.5	8.6	9.4	8.9	10.3 C		
SD 2-4	8.1	12.2	16.2	10.7	9.2	10.1	11.1 BC		
SD 4-6	12.1	15.8	16.4	11.9	11.7	14.4	13.7 A		
SD 8-10	11.9	14.2	16.3	10.0	11.8	11.7	12.6 AB		
Mean	10.2	13.4	15.4	9.9	9.9	11.6			
	Shoot			Straw			Grain		
	S	W	SxW	S	W	SxW	S	W	SxW
SE m±	0.6	0.6	1.4	0.9	0.9	2.1	0.8	0.8	1.9
LSD (0.05)	1.1	1.1	2.7	1.7	1.7	4.2	1.5	1.5	3.8
LSD (0.01)	1.5	1.5	3.6	2.3	2.3	5.5	2.0	2.0	5.0

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Grain yield

Rice grain yields were different on different soils and water management practices and sulfur application also exerted significant influence on rice grain yield.

Application of sulfur to flooded soils produced the highest grain yield while in flooded soil without sulfur application produced lowest grains. Although an increase in grain yield was observed on reducing the water availability from flooding to saturation and drying the soils for 2 weeks at 2 WAT, these increases were not statistically significant. But soil drying for 2 weeks at 4 and 8 WAT significantly increased rice grain yield (Table 44).

Straw yield

Rice straw yields were different in different soils.

Soil drying for 2 weeks at 2 WAT produced lowest straw yield but in all the other treatments straw yields were similar (Table 44).

Experiment 5

Influence of Six Water Regimes on the Chemical
Kinetics and Rice Growth in Four Soils

In the earlier experiments, soil drying and reflooding was found to adversely affect rice growth and decrease rice grain yield in fertile soils but favorably influenced them in zinc and/or sulfur deficient and iron-toxic acid soils. Soil drying and reflooding was also found to adversely affect rice growth and decrease rice grain yields on acid soil in which plants did not suffer from iron toxicity. This experiment was conducted at the same greenhouse to study if soil drying and reflooding would influence the chemical kinetics and rice growth and yield on sulfur and zinc deficient soils when both these elements were added. It was also intended to study if application of 0.25% rice straw (w/w) to the soil would reduce the chemical problems associated with soil drying and reflooding.

In addition to the sulfur and zinc deficient Maahas-2 soil (used in experiment 3) another fertile Maahas soil (Maahas-1 used in experiment 1) and two Luisiana soils (Luisiana-1 and Luisiana-3) one high in active iron, and the other high in organic matter, were included in this experiment. A pretransplanting flooding period of 2 weeks was used to reduce Fe-toxicity.

MATERIALS AND METHODS

Design

This experiment was laid out in 4 x 6 factorial randomized complete block design with three replications.

Factors and levels

Soils

1. Maahas -1 (Tropaqualf)
2. Maahas-2 (Tropudalf)
3. Luisiana-1 (Tropudult)
4. Luisiana-3 (Paleaquult)

Some characteristics of the soils are presented in Table 45.

Water regimes

- i. Continuously flooded (CF)
- ii. Four weeks soil drying imposed on the day of transplanting and reflooding (SD 0-4)
- iii. Four weeks soil drying imposed at 4 WAT and reflooding (SD 4-8)
- iv. Four weeks soil drying imposed at 6 WAT and reflooding (SD 6-10)
- v. Alternate drying and reflooding for 2 weeks imposed on the day of transplanting and 4 and 8 WAT (SD 0/4/8)
- vi. Alternate drying and reflooding for 2 weeks imposed at 2, 6 and 10 WAT (SD 2/6/10)

Greenhouse procedure

Bulk samples of the four soils were collected from the field from 0-20 cm depth, air dried, crushed to 0.6 cm clods and mixed thoroughly.

Twelve kg portions of these soils were treated with chopped rice straw (about an inch long) at the rate of 0.25% straw (w/w) and placed in 16-L glazed porcelain pots fitted with the similar set up for sampling of soil solution as described in experiment 1.

Table 45. Some characteristics of the six soils used in experiment 5.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3
pH (1:1)	6.4	6.6	4.8	4.8
Organic C (%)	2.00	1.65	2.20	3.49
Total N (%)	0.17	0.14	0.24	0.26
Total S (%)	0.09	0.10	0.07	0.10
Available				
N (mg/kg)	152.6	55.7	283.7	166.7
P Olsen (mg/kg)	5.5	30.9	2.1	2.9
S (mg/kg)	33.7	4.1	39.4	42.1
Zn (mg/kg)	0.52	0.36	2.64	3.06
Cu (mg/kg)	0.10	0.06	3.60	3.40
Exchangeable				
K (me/100 g)	2.28	1.80	0.38	0.23
Ca (me/100 g)	21.7	17.8	12.5	8.3
Mg (me/100 g)	15.8	12.6	6.2	2.6
Active				
Fe (%)	1.93	2.90	6.71	3.88
Mn (%)	0.12	0.19	0.04	0.09
Water soluble Si (mg/kg)	230.6	219.0	100.1	73.4
CEC (me/100 g)	60.0	47.0	41.4	46.6
Mechanical analysis				
Clay (%)	53	29	63	58
Silt (%)	33	50	35	35
Sand (%)	14	21	2	7
Textural class	Clay	Silty clay loam	Clay	Clay

Two weeks after flooding, the soil in each pot was treated with N, P, K and S @100, 50, 75 and 100 mg/kg soil respectively. Urea, KH_2PO_4 , KCl and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ were used as source of N, P, K and S. All these elements were applied in the form of solution to the soil. Sulfate sulfur was applied as a stirred suspension of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. After application of the fertilizers, the pots were drained and the drainage water was recycled for three times to ensure proper mixing of the fertilizer with the soil.

Healthy seedlings of IR54 were raised following the technique used in experiment 1 and six seedlings were transplanted in each pot 2 weeks after flooding. Two of these seedlings were removed after one week of transplanting and buried in the same pot. Before transplanting the seedlings were given a "root dip" in 2% ZnO suspension to correct zinc deficiency.

Water regimes were imposed at appropriate time. Soil solution samples were collected from each pot at 2 weeks before and 0, 2, 4, 6, 8, 10 and 12 weeks after transplanting.

Two plants were harvested at 8 WAT and analyzed for different nutrients. The remaining two plants were grown to maturity and grain and straw yields recorded.

Analytical Procedures

1. Soil

The initial soil samples were analyzed for pH; organic C; total N and S; available N, P, S, Zn and Cu; water soluble silica; active Fe and Mn; exchangeable K, Ca and Mg; CEC; and particle size distribution following methods described in experiment 1.

2. Soil solution

The soil solution samples were analyzed for pH; Eh; EC; bicarbonate; NH_4^+ -N; P; K^+ ; Ca^{2+} ; Mg^{2+} ; SO_4^{2-} ; Fe^{2+} ; Mn^{2+} ; Zn^{2+} and Si(OH)_4 following the methods described in experiments 1 and 2.

3. Plant samples

Eight week-old rice shoots, mature straw and grain samples were analyzed for total N, P, K, Ca, Mg, Fe, Mn, Zn, Cu and crude silica following methods described in experiment 1.

Calculations

Methods of calculations were same as in Experiment 1.

RESULTS AND DISCUSSION

Chemical Kinetics of Soil Solution

On the sampling dates soil solutions were collected from all three replications of each treatment and analyzed. The results presented graphically in the following pages are the mean of the three replications.

pH

In all the four soils, soil solution pH increased on flooding and came to neutral pH within two weeks of flooding (Fig. 53). In the two acid soils the pH increase was very sharp (Figs. 53C-D). This could be due to the application of straw which results in fast reduction of iron on flooding the soils. Soil drying depressed the soil solution pH in all the soils but the drop in pH was much greater in the acid soils. On reflooding soil solution pH started to rise again.

Eh

In all the four soils, soil solution Eh fell sharply and reached a value of around -100 mV within two weeks after flooding (Fig. 54). The soil Eh followed same pattern as the soil solution Eh but with much lower values (Fig. 55). Drying the soils for 2 to 4 weeks oxidized the soils as was evidenced from the high soil and soil solution Eh values. Like in earlier experiments, in these soils also soil Eh was much lower than soil solution Eh under continuously flooded water regime while under drying conditions soil Eh was much higher than soil solution Eh. The lower values of both soil and soil solution Eh under flooded

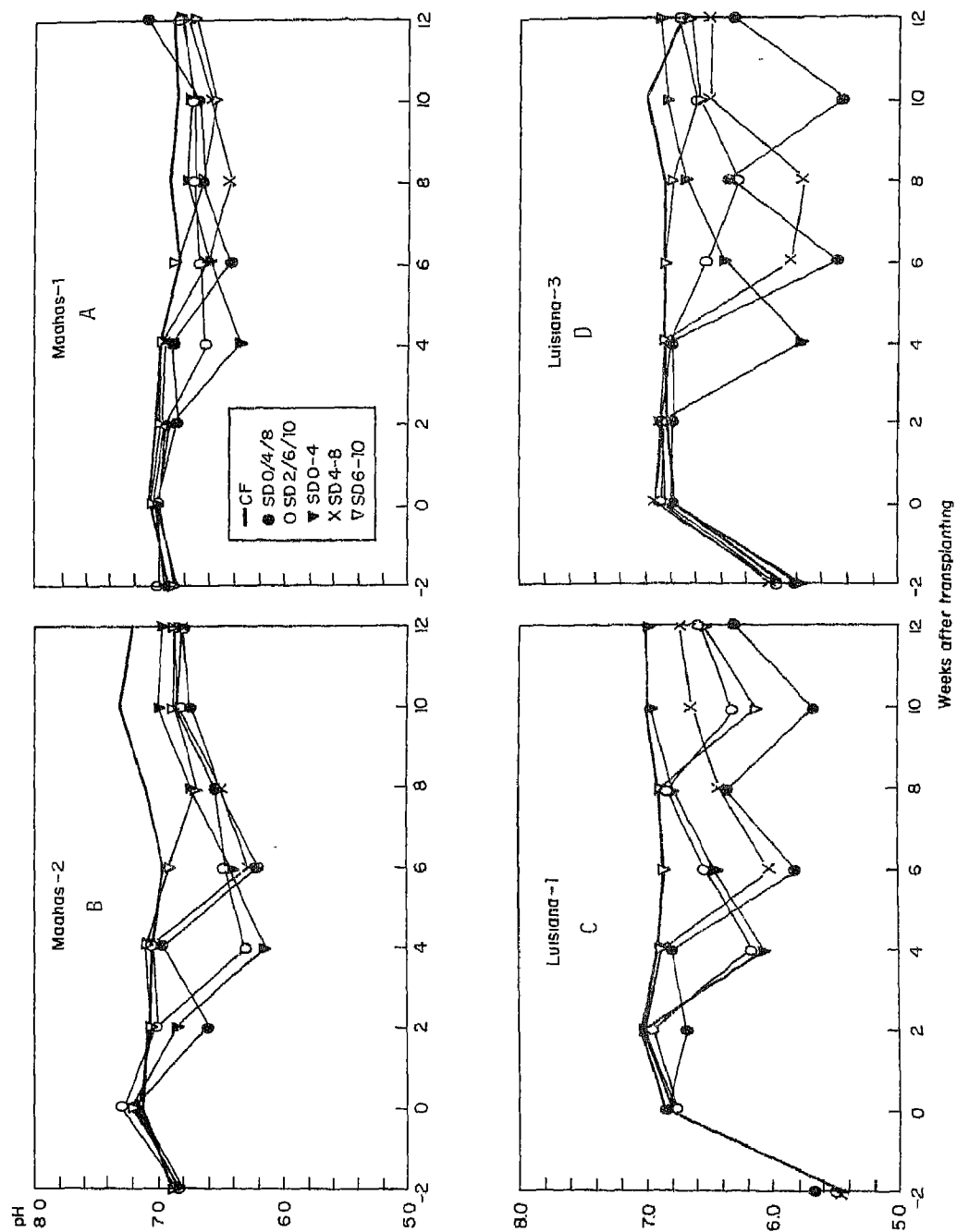


Fig. 53. Influence of six water regimes on the kinetics of solution pH in four soils.

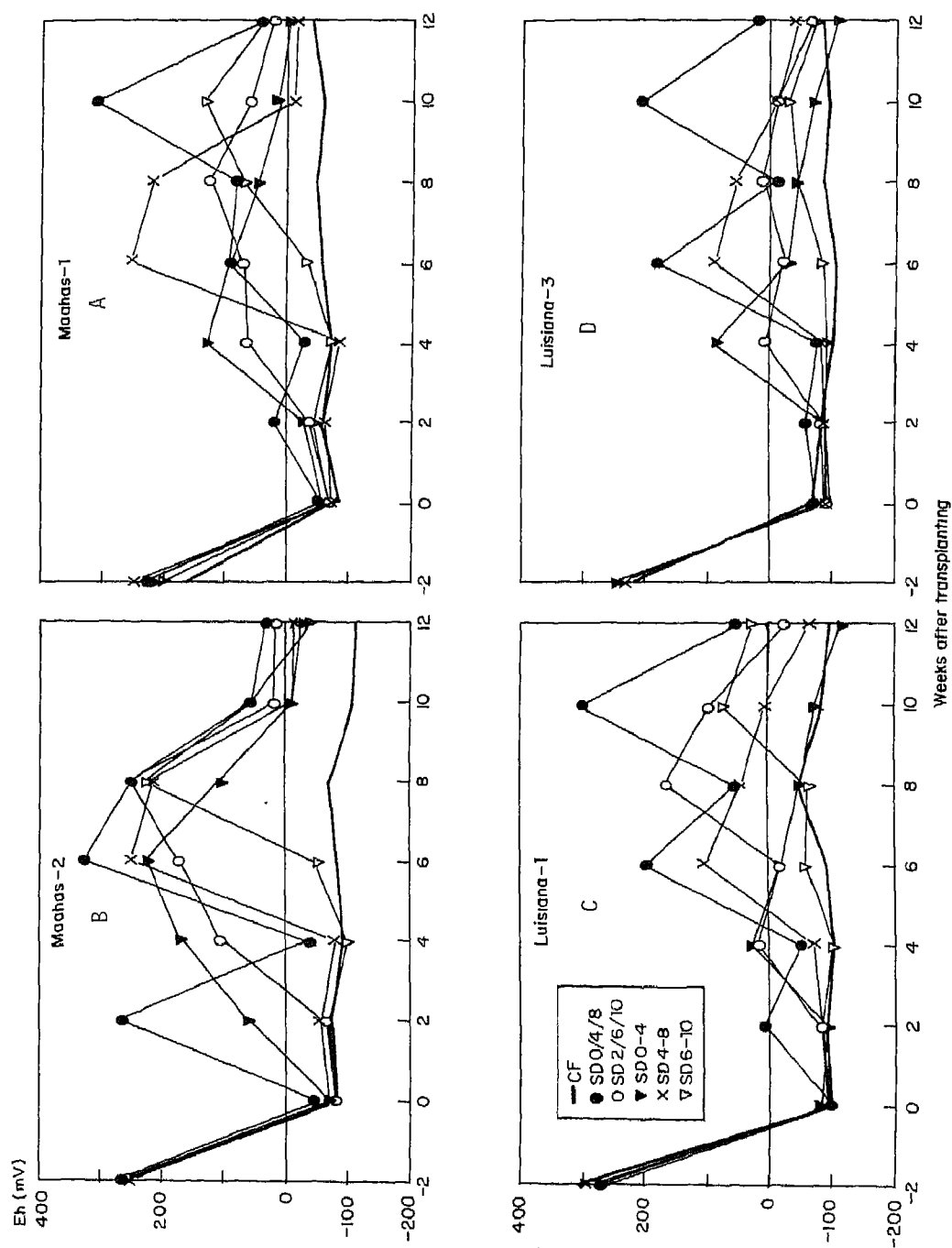


Fig. 54. Influence of six water regimes on the kinetics of solution Eh in four soils.

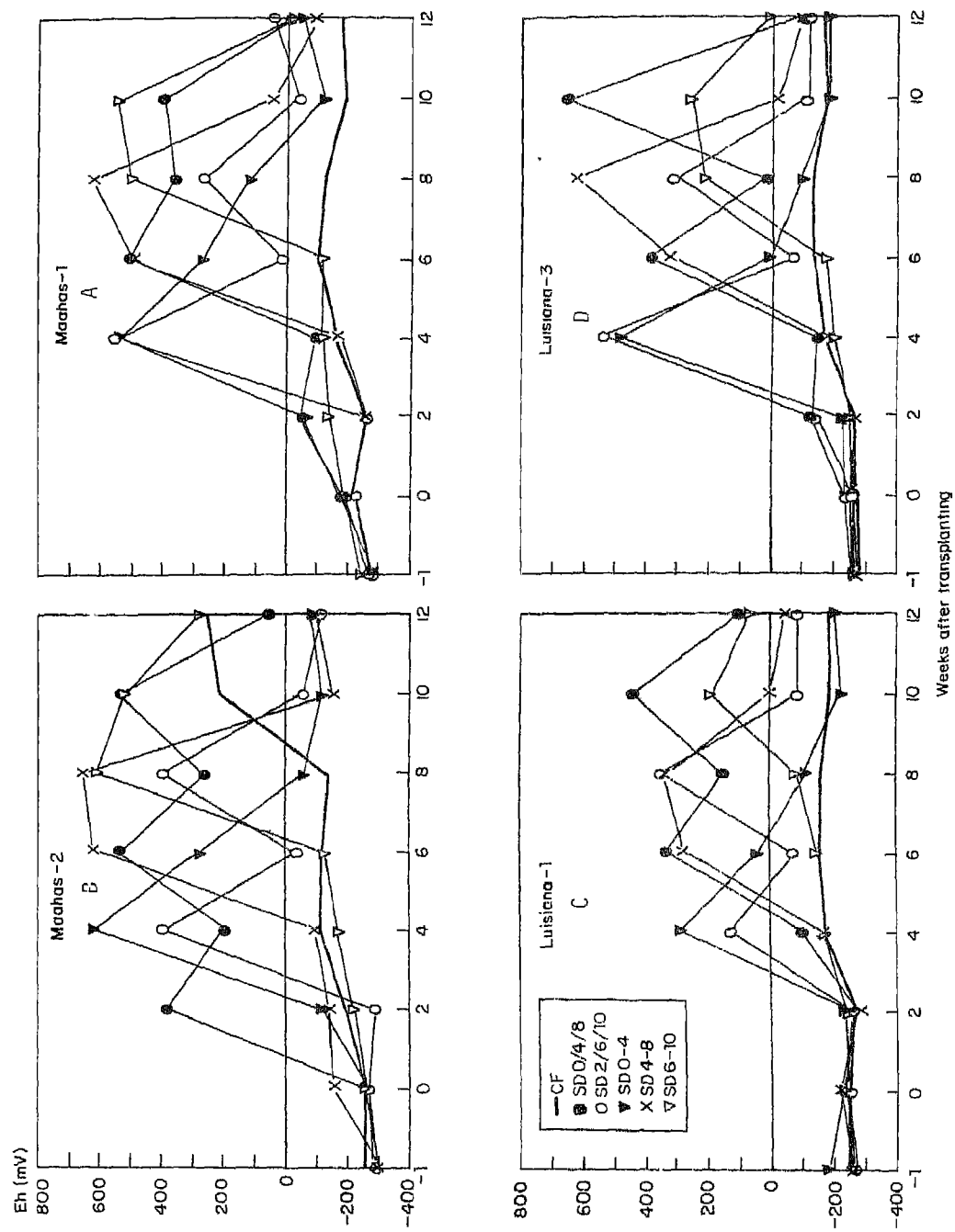


Fig. 55. Influence of six water regimes on the kinetics of Eh in four soils.

condition due to the increased microbial activity as a result of rice straw addition.

Electrical conductivity (EC)

Electrical conductivity (EC) reached a peak value in all the soils at 2 weeks after flooding which declined to fairly stable value in the next 4 weeks (Fig. 56). Soil drying for 2 to 4 weeks decreased the soil solution EC which started to rise again on reflooding. In Maahas-1 soil, reflooding the dry soil raised the EC beyond the level of that in continuously flooded water regime (Fig. 56A).

The increase in EC on flooding the soils was due to the reduction of Fe(III), Mn(IV), formation of organic acids, HCO_3^- and release of NH_4^+ , K^+ , Ca^{2+} and Mg^{2+} into the soil solution. In the Luisiana soils the effect of Fe^{2+} was very pronounced as will be seen from the Fe^{2+} kinetics in soil solution (Fig. 64C-D). The decrease in EC on soil drying was obviously due to reoxidation and precipitation of Fe^{2+} and Mn^{2+} and also precipitation of Ca^{2+} , Mg^{2+} , and loss of HCO_3^- and RCOO^- from the soil solution.

The increase in EC on reflooding the dry soil, especially the Maahas-1 was due to increase in HCO_3^- , K^+ , Ca^{2+} , Mg^{2+} , SO_4^{2-} and Mn^{2+} in soil solution.

Bicarbonate (HCO_3^-)

The peak values of HCO_3^- concentration in soil solution were observed 2 weeks after flooding which declined to nearly stable value 6 weeks after flooding (4 WAT) depending on the type of soil (Fig. 57).

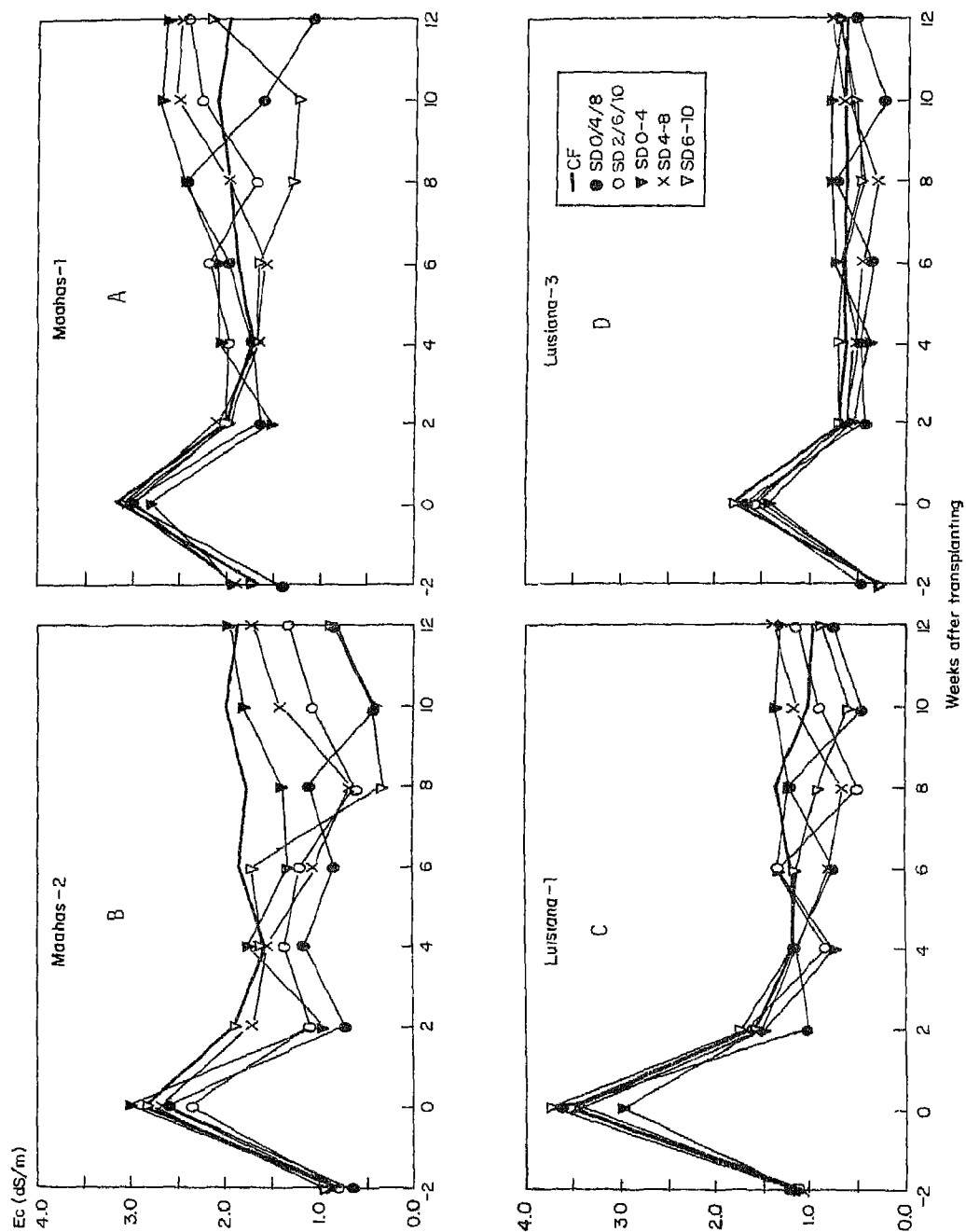


Fig. 56. Influence of six water regimes on the kinetics of solution electrical conductivity in four soils.

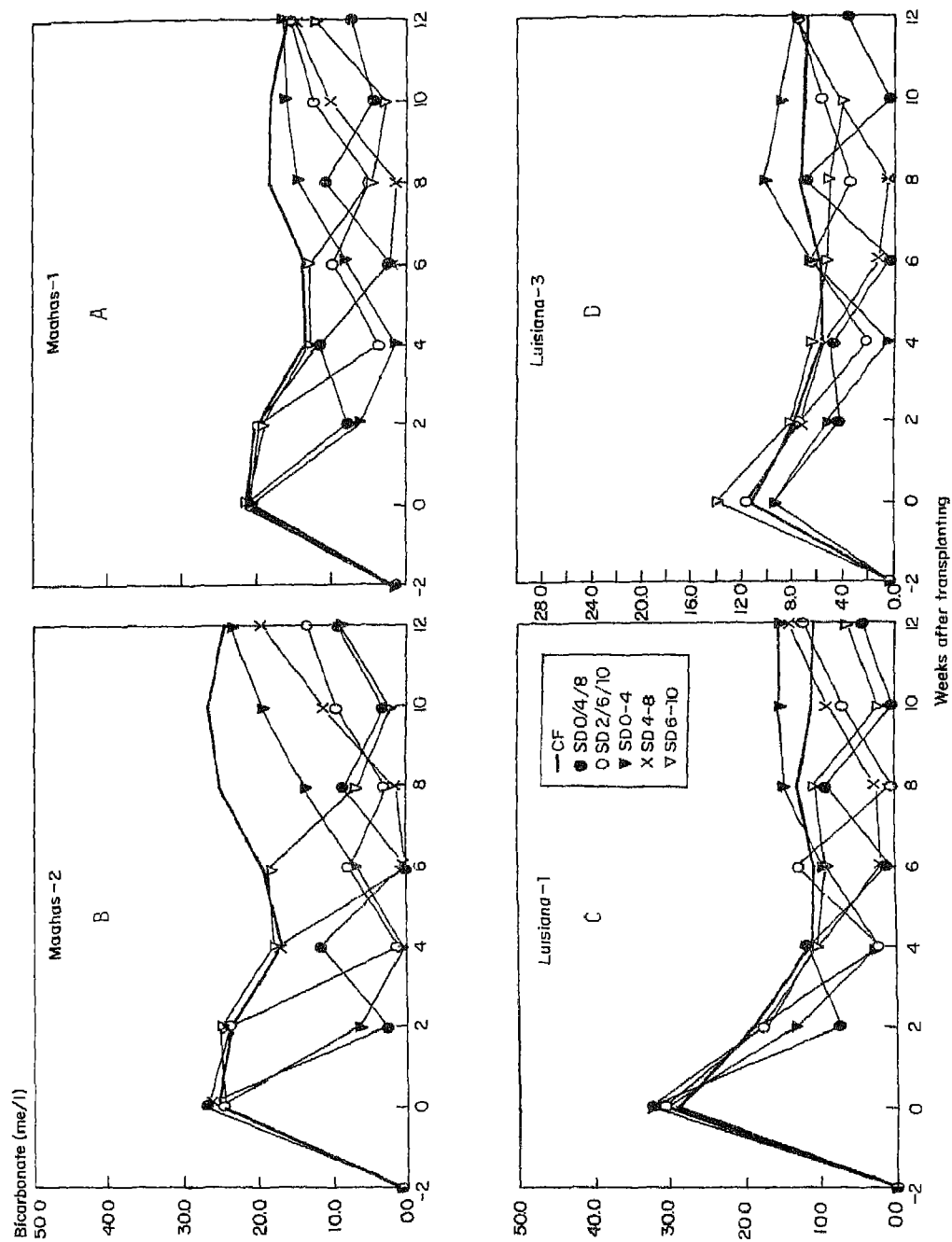


Fig. 57. Influence of six water regimes on the kinetics of water-soluble bicarbonate in four soils.

In the acid Luisiana-1 soil this decline was the sharpest among the four soils (Fig. 57C).

The initial increase in HCO_3^- concentration was due to the production of CO_2 on organic matter decomposition and the later decline due to loss of HCO_3^- due to formation of carbonates of Fe^{2+} and Mn and probably production of methane.

NH_4^+-N

In all the soils, the soil solution NH_4^+-N reached a peak value 2 weeks after flooding and declined thereafter (Fig. 58). Soil drying for 2 to 4 weeks decreased the soil solution NH_4^+-N in the two Maahas soils (Fig. 58A-B). In the two Luisiana soils however, the effect of soil drying on soil solution NH_4^+-N was not pronounced (Fig. 58C-D). Reflooding the dry Maahas soils did not increase the soil solution NH_4^+-N .

The peak NH_4^+-N in soil solution 2 weeks after flooding was due to the release of nitrogen from soil organic matter decomposition. Fertilizer nitrogen could not have come to soil solution because urea was applied on that day. The later decrease in soil solution NH_4^+-N could be due to adsorption of NH_4^+-N on to the exchange complex. Some amount of NH_4^+-N might have been immobilized and some portion might even have been lost through different loss mechanisms. At later stages (after 2 WAT) plant uptake would be the reason for the decline in NH_4^+-N concentration. The decrease in NH_4^+-N in soil drying treatments is attributed to nitrification of NH_4^+-N . The effect of soil drying on NH_4^+-N in the Luisiana soils was not pronounced

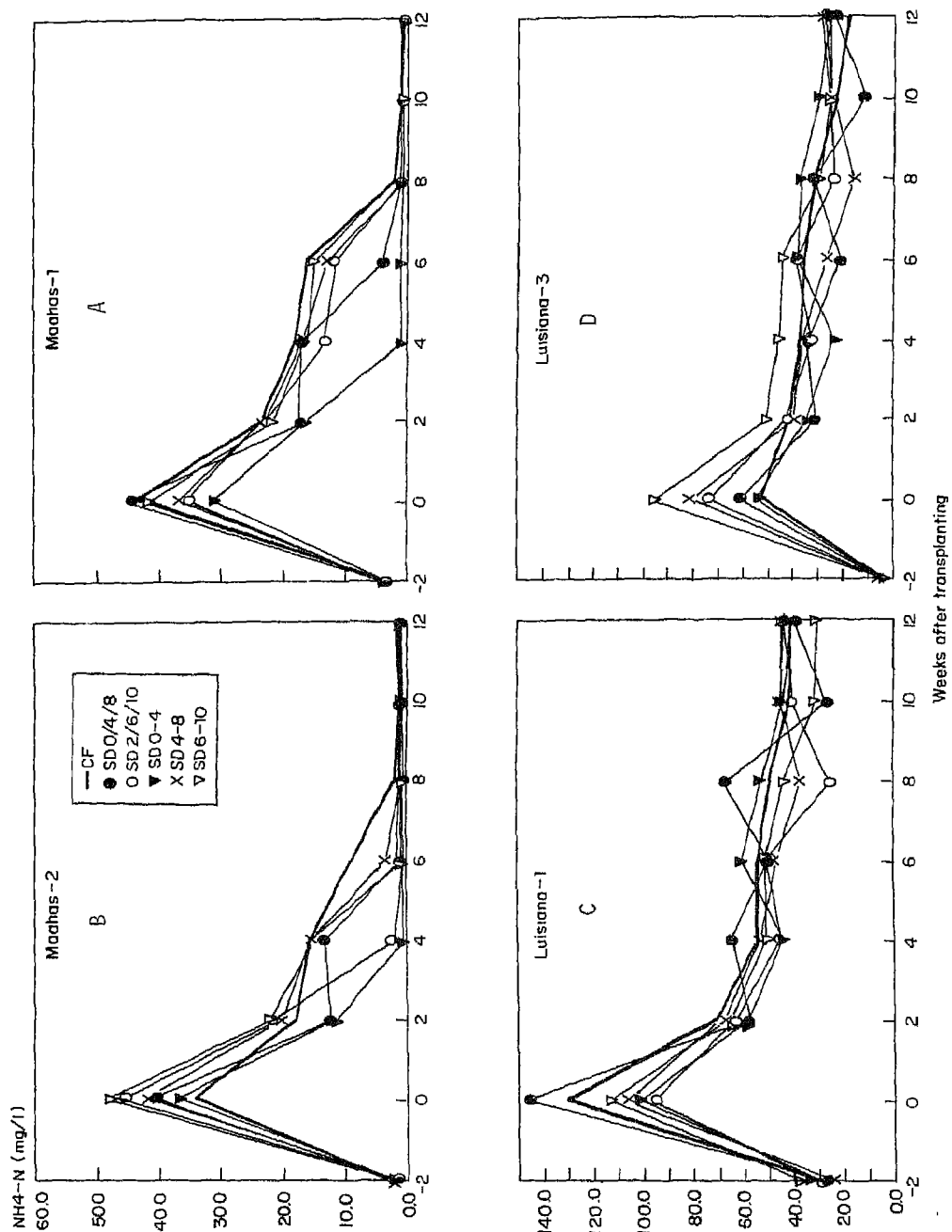


Fig. 58. Influence of six water regimes on kinetics of water-soluble NH_4^+-N in four soils.

probably because of more NH_4^+ -N release from organic matter mineralization on soil drying and reflooding.

Phosphorus (P)

Phosphorus @50 mg P/kg soil was applied to the soils on the day of transplanting. Figure 59 shows peak concentration of phosphorus in soil solution on this date in Maahas-1 and Luisiana-3 soils. The water soluble P, under continuously flooded condition, decreased with time. In Maahas-2 soil, the soil solution P increased for 2 weeks after fertilizer P application and declined thereafter (Fig. 59B). In Luisiana-1 soil however, the highest P under flooded condition was seen on the day of fertilizer P treatment and was maintained at that level up to 8 WAT and decreased thereafter (Fig. 59C). Soil drying decreased the concentration of water soluble P in the two Maahas soils, and reflooding could not raise the soil solution P level to that in continuous flooded condition. In Luisiana-1 soil, soil drying in the initial stage, caused a small increase in the soil solution P but in Luisiana-3 water regime had no effect on it.

The initial increase in water soluble P in flooded Maahas-2 soil could be attributed to the reduction of ferric phosphates, hydrolysis of iron and aluminum phosphates, release of occluded phosphates and phosphate sorbed on amorphous iron and manganese oxides. The decrease in P solubility thereafter was due to its refixation as calcium bonded phosphates or precipitation as iron phosphates. This resembles the results of the earlier experiments.

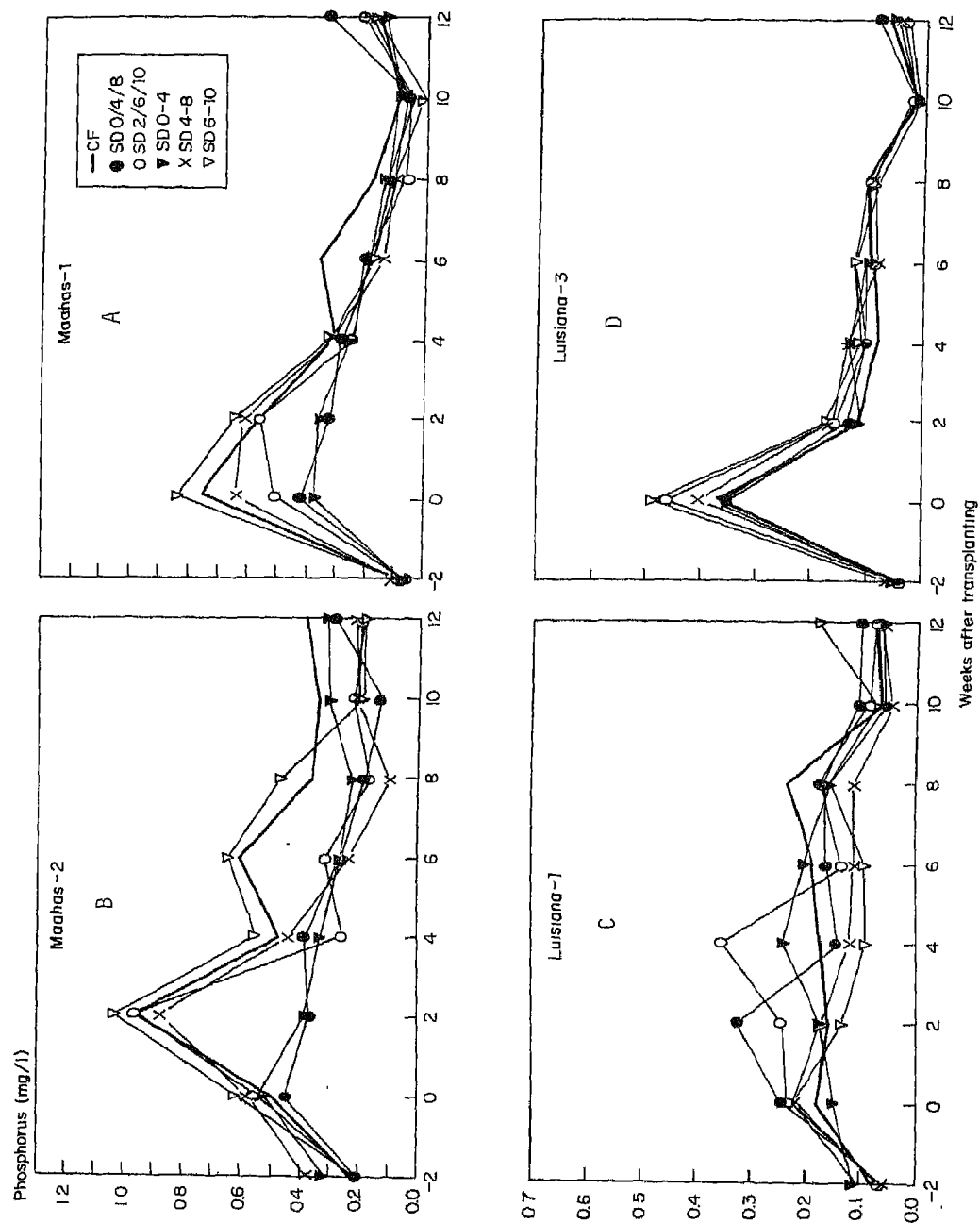


Fig. 59. Influence of six water regimes on the kinetics of water-soluble P in four soils.

The decrease in P solubility on soil drying was due to precipitation as ferric phosphates and adsorption on iron and Mn oxides, hydroxides and carbonates. The lack of increase in soil solution P after reflooding the dry soils demonstrates the irreversible nature of P fixation under intermittent flooding conditions in a soil like Maahas-1 and Maahas-2. Luisiana-3 shows no effect on Fe-phosphates on reflooding.

Potassium (K^+)

Potassium concentration of soil solution was highest on the day of transplanting when 75 mg K/kg soil was applied. Under flooded water regime in all the soils K^+ concentration decreased gradually with time of flooding. Soil drying for 2 or 4 weeks or three soil drying cycles of 2 weeks each depressed the soil solution K^+ during the dry periods but reflooding increased it beyond the level in flooded water regime (Fig. 60). This observation resembles closely to the observations in Experiments 1, 2 and 3.

Calcium (Ca^{2+})

Soil solution Ca^{2+} concentration increased sharply within 2 weeks of flooding (Fig. 61). So, in all the four soils Ca^{2+} concentration was at its peak value on the day of transplanting and it started declining with time and reached fairly stable value depending on the type of the soil. The initial decrease in soil solution Ca^{2+} was faster in the two acid Luisiana soils (Fig. 61C-D) while this rate was gradual in the two Maahas soils (Fig. 61A-B). Soil drying for 2 to 4

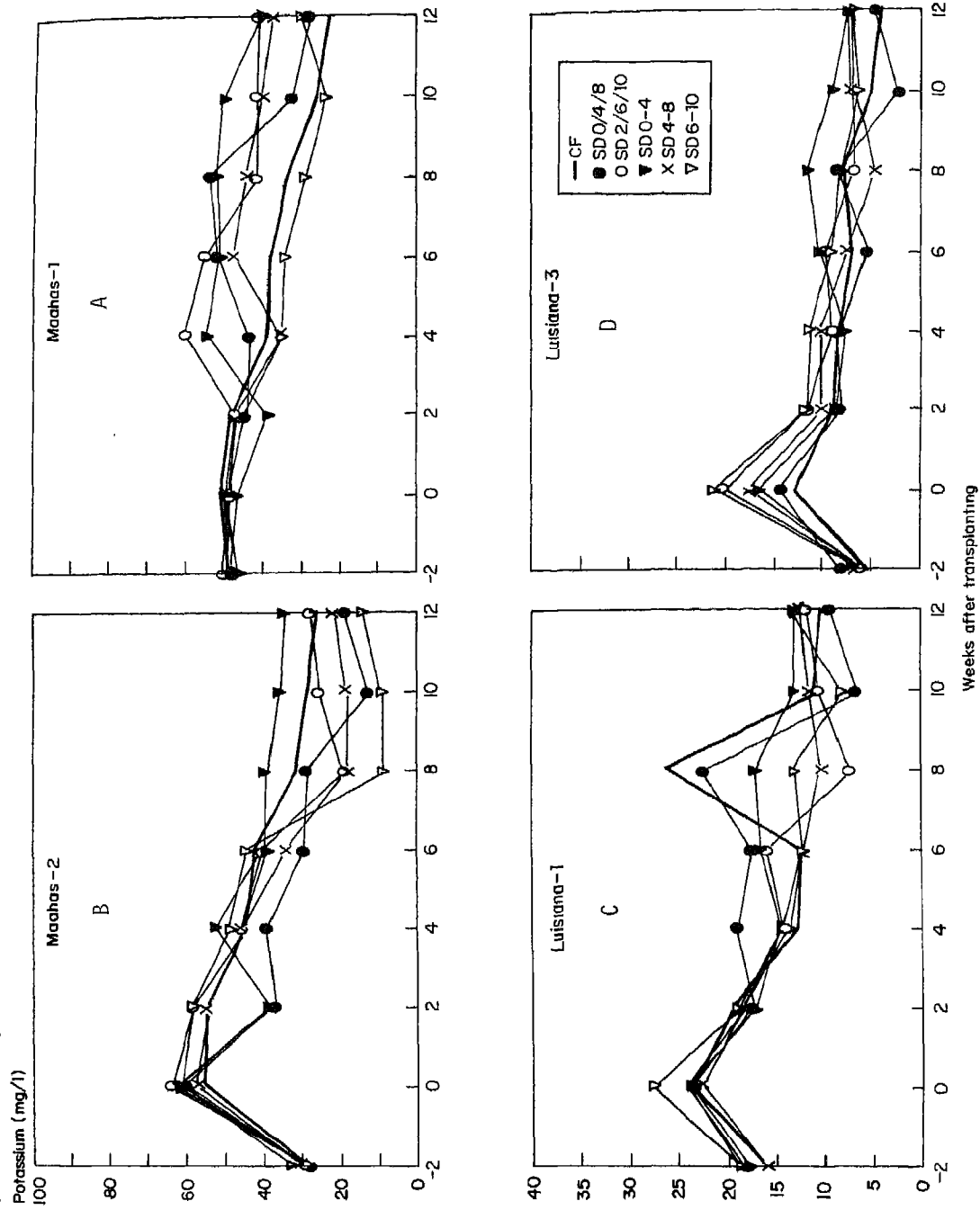


Fig. 60. Influence of six water regimes on the kinetics of water-soluble K in four soils.

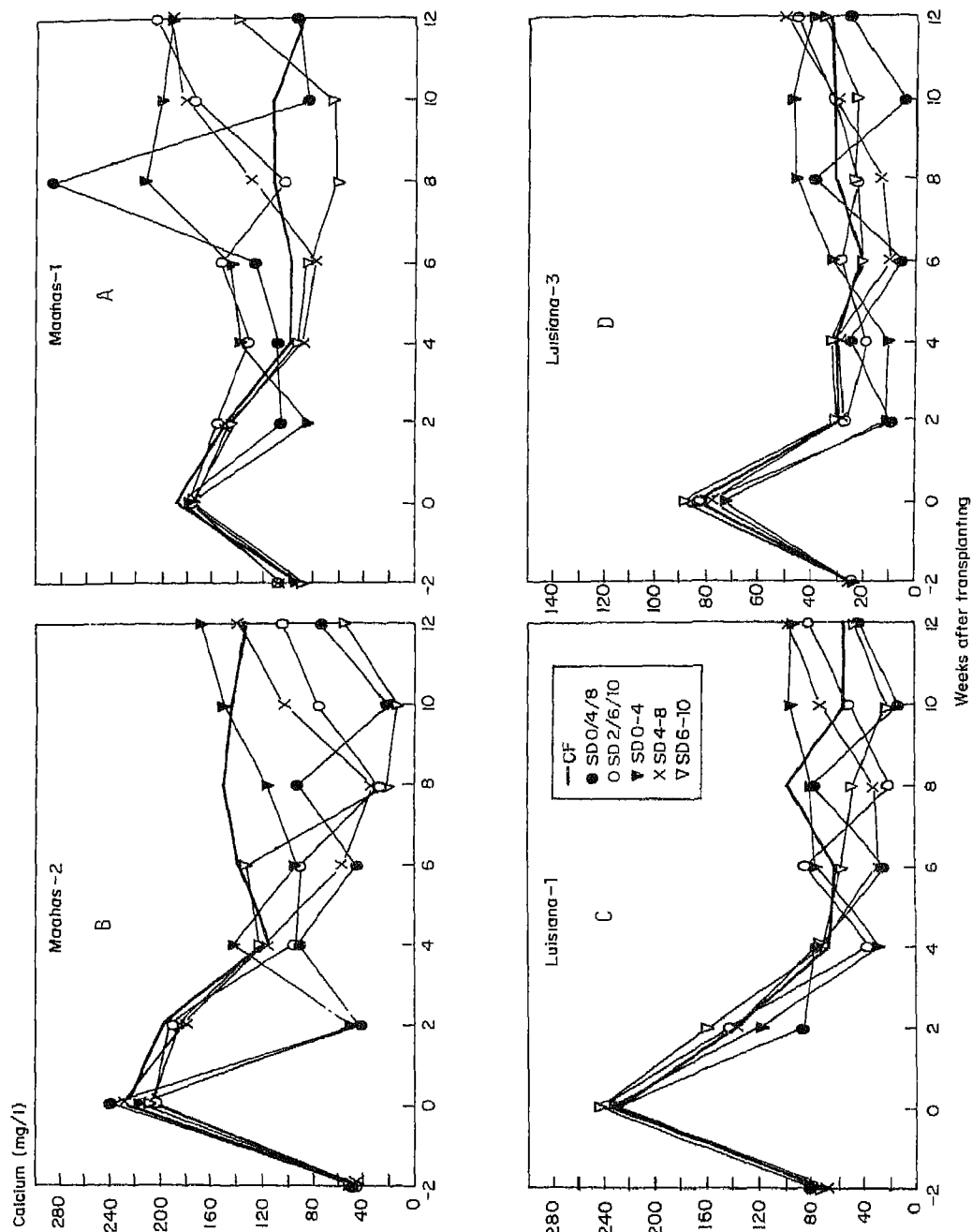


Fig. 61. Influence of six water regimes on the kinetics of water-soluble Ca in four soils.

weeks or 3 soil drying cycles of 2 weeks each decreased the soil solution Ca^{2+} and reflooding raised it again. While reflooding the dry soil did not increase the Ca^{2+} to the level of that in flooded water regime in Maahas-2 and Luisiana-1 soils, it raised the Ca^{2+} level beyond that in flooded water regime in the Maahas-1 and Luisiana-3 soils.

The initial increase in soil solution Ca^{2+} in continuously flooded soils was due to the replacement of Ca^{2+} from the exchange complex by the Fe^{2+} and Mn^{2+} produced due to soil reduction. The declining trend was due to readsorption of Ca^{2+} on to the exchange complex when Fe^{2+} and Mn^{2+} got precipitated as their respective carbonates and hydroxides.

The decrease on soil drying was due also to readsorption of Ca^{2+} on to the exchange complex when Fe^{2+} and Mn^{2+} were oxidized and precipitated in the soil while the later increase on reflooding the dry soil can be attributed to the release of Ca^{2+} from exchange complex. These observations closely resemble to those in experiments 1, 2 and 3.

Magnesium (Mg^{2+})

Magnesium followed the same pattern as Ca^{2+} and was due to similar reasons (Fig. 62).

Sulfate (SO_4^{2-} -S)

To all the soils S was applied as $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ @100 mg S/kg soil on the day of transplanting i.e. two weeks after flooding. Sulfate concentration of soil solution declined sharply within 2 weeks of its

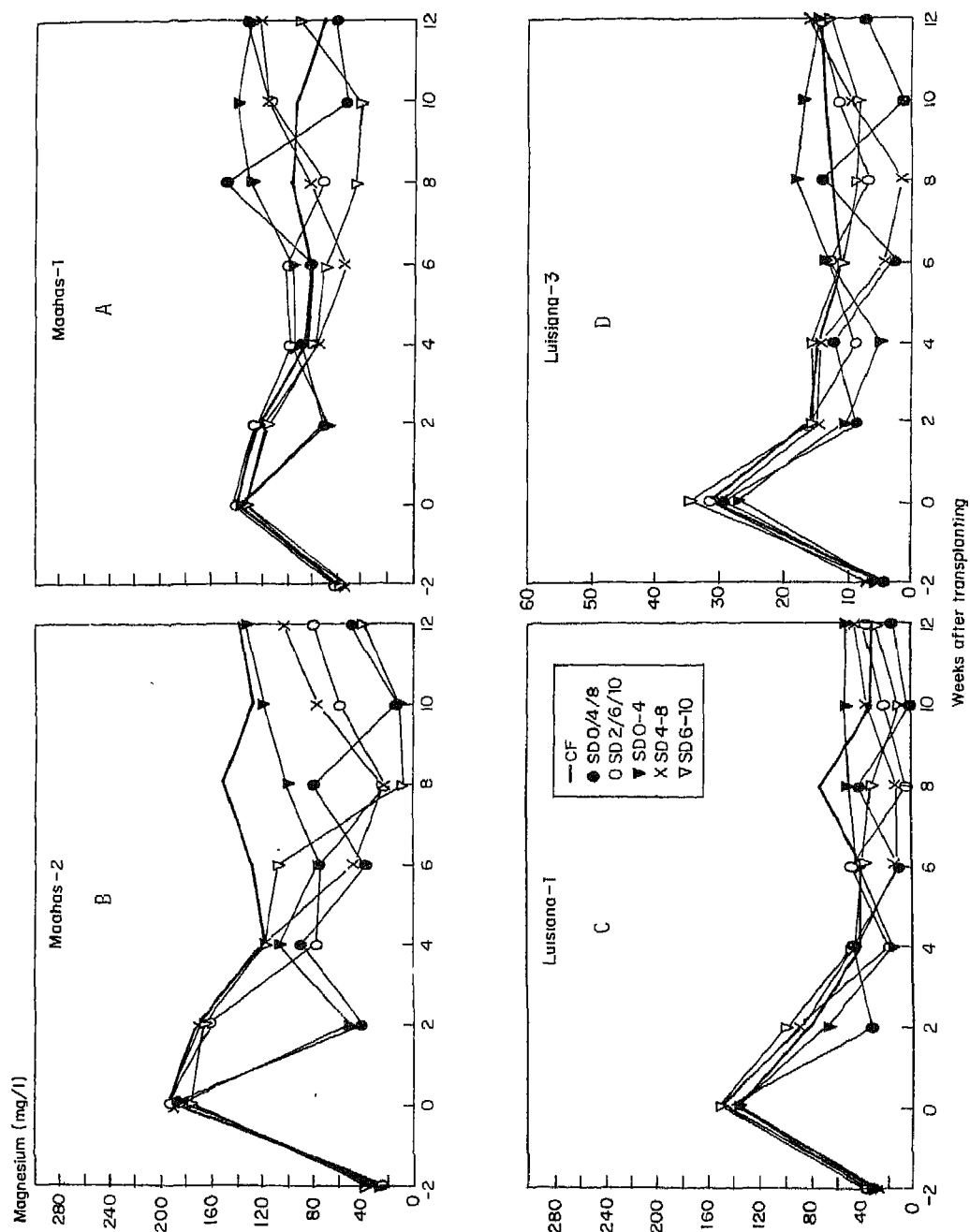


Fig. 62. Influence of six water regimes on the kinetics of water-soluble Mg in four soils.

application, to a negligible value and was maintained at that level (Fig. 63).

Soil drying for 2 to 4 weeks or three drying cycles of 2 weeks each increased the water soluble SO_4^{2-} -S concentration markedly in all soils. Reflooding the dry soils although decreased the SO_4^{2-} -S of the soil solution but still the concentration were much higher than under flooded conditions (Fig. 63).

The decrease in the sulfate concentration under flooding was due largely to its reduction to sulfide, mostly in H_2S form. Under the present experiment sulfate reduction did not cause S deficiency probably because bacteria present in the oxidized surface soil and rhizosphere could have oxidized sulfides to sulfate.

The increase in SO_4^{2-} -S concentration in soil solution on soil drying, was due to oxidation of sulfides in soil.

Iron (Fe^{2+})

Water soluble Fe^{2+} concentration increased sharply on flooding and came to peak of different values depending on the type of soil within 2 weeks (Fig. 64). The highest concentration was found in Luisiana-1 soil where Fe^{2+} concentration went up to 380 ppm while the lowest one was in Maahas-1 soil which was less than 50 ppm. In the two acid Luisiana soils Fe^{2+} concentration went down sharply in the next 2 weeks and came to a fairly stable value within 6 weeks after flooding (i.e. 4 WAT) (Fig. 64C-D). In the two Maahas soils soluble Fe^{2+} maintained a broad peak for 2 weeks which declined slowly to also fairly stable value later (Fig. 64A-B).

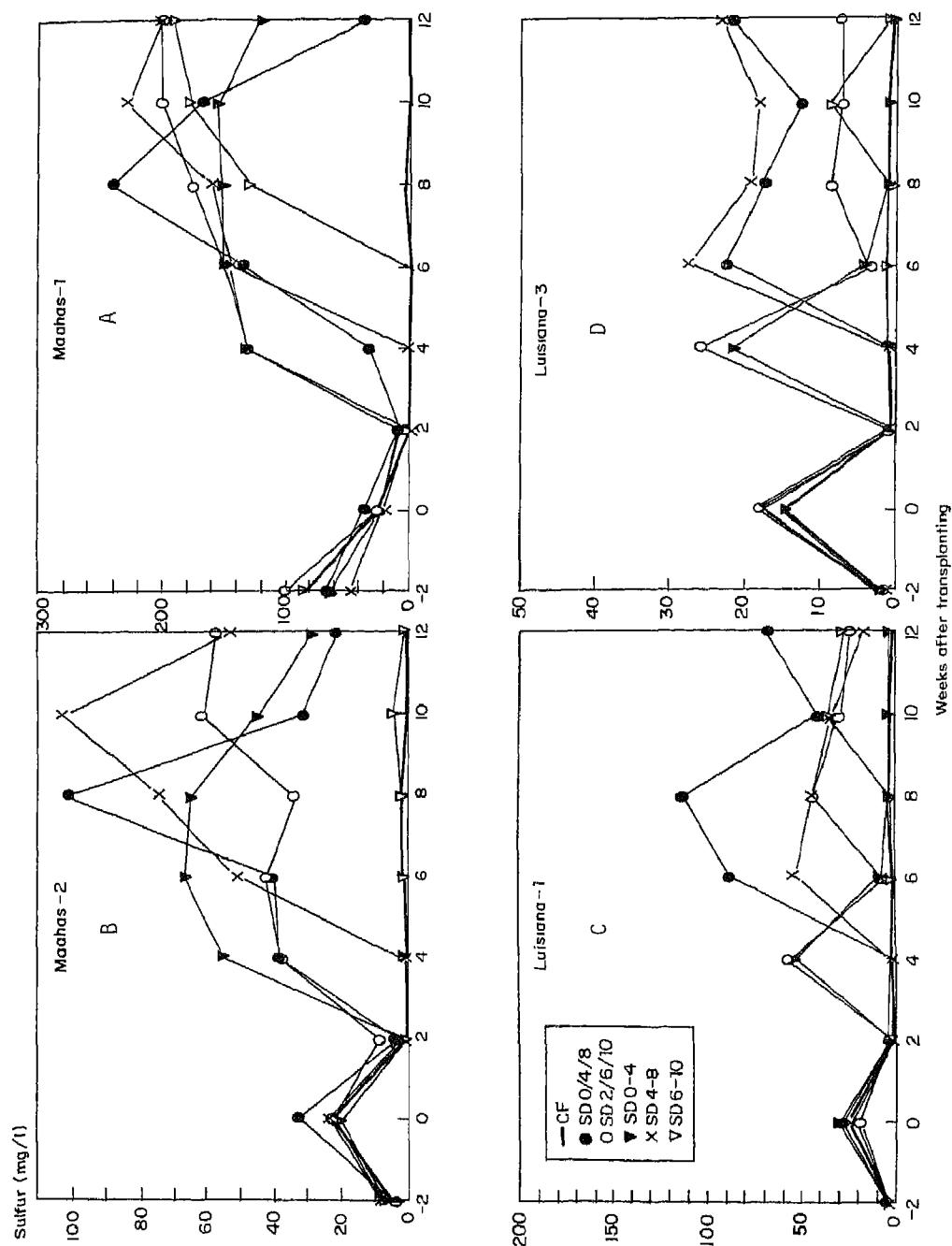


Fig. 63. Influence of six water regimes on the kinetics of water-soluble SO_4 -S in four soils.

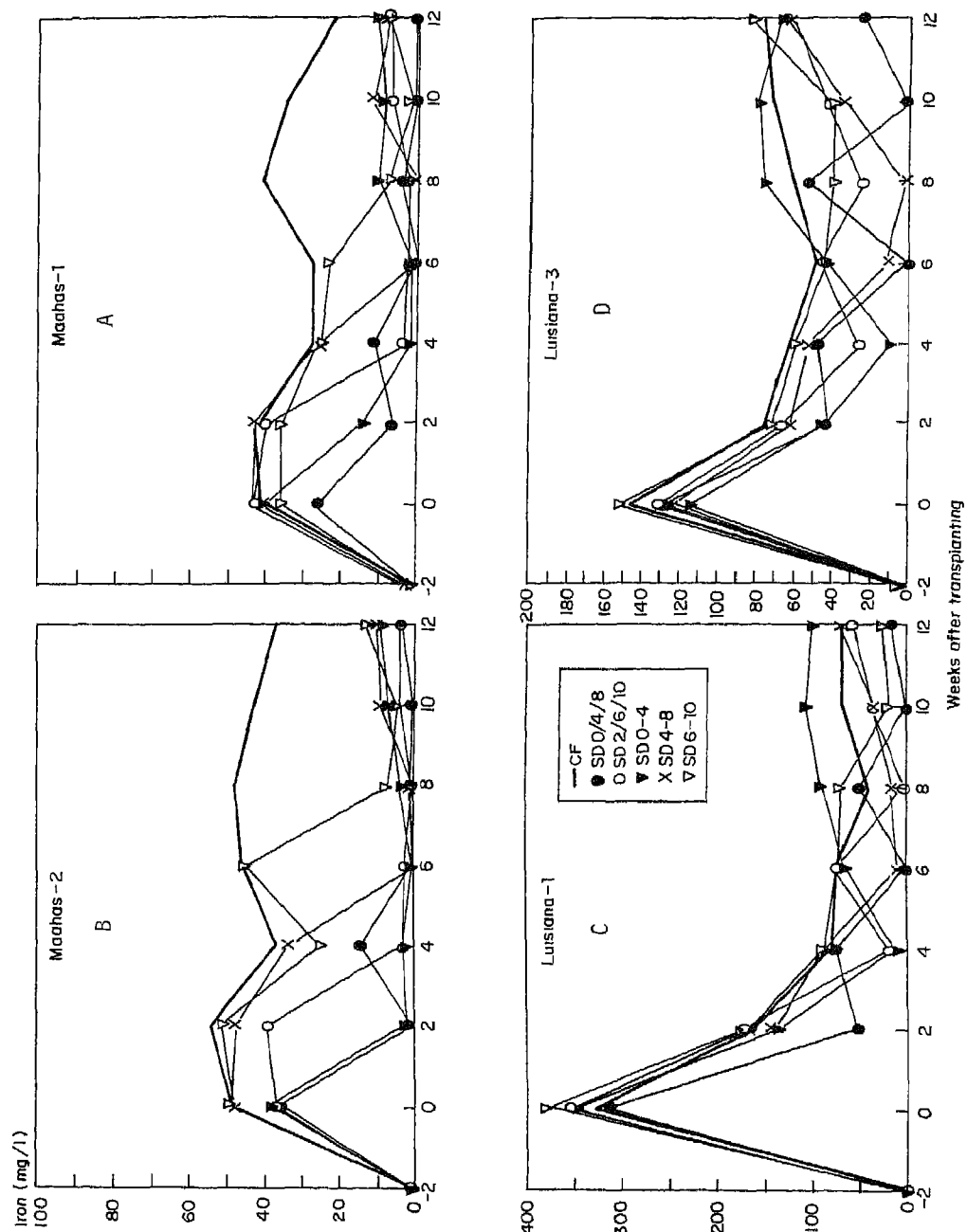


Fig. 64. Influence of six water regimes on the kinetics of water-soluble Fe in four soils

Soil drying for 2 or 4 weeks or three soil drying cycles of 2 weeks each decreased the water soluble Fe^{2+} concentration to very negligible values and reflooding started to raise it. The rise in Fe^{2+} concentration on reflooding was very small in the two Maahas soils (Fig. 64A-B) but was appreciable in the two acid Luisiana soils (Fig. 64C-D).

Manganese (Mn^{2+})

Water soluble Mn^{2+} concentration of soil increased sharply on flooding, came to peak values of different magnitude depending on the type of soils and declined sharply thereafter to come to almost stable values within 6 weeks after flooding (Fig. 65). Soil drying for 2, or 4 weeks or three soil drying cycles of 2 weeks each, decreased the soil solution Mn^{2+} to negligible value but reflooding the dry soil raised it beyond the level in continuously flooded soil.

Zinc (Zn^{2+})

Water soluble Zn^{2+} concentration decreased during the first two weeks after flooding (Fig. 66). In Luisiana-1 soil Zn^{2+} concentration kept on decreasing with time of flooding (Fig. 66C) but in the three other soils the values fluctuated. Because of very low concentration of water soluble Zn^{2+} in these soils it is very difficult to set the absolute trend. However, the influence of soil drying and reflooding was clear and quite consistent. Soil drying and reflooding generally increased the available Zn^{2+} in all the soils.

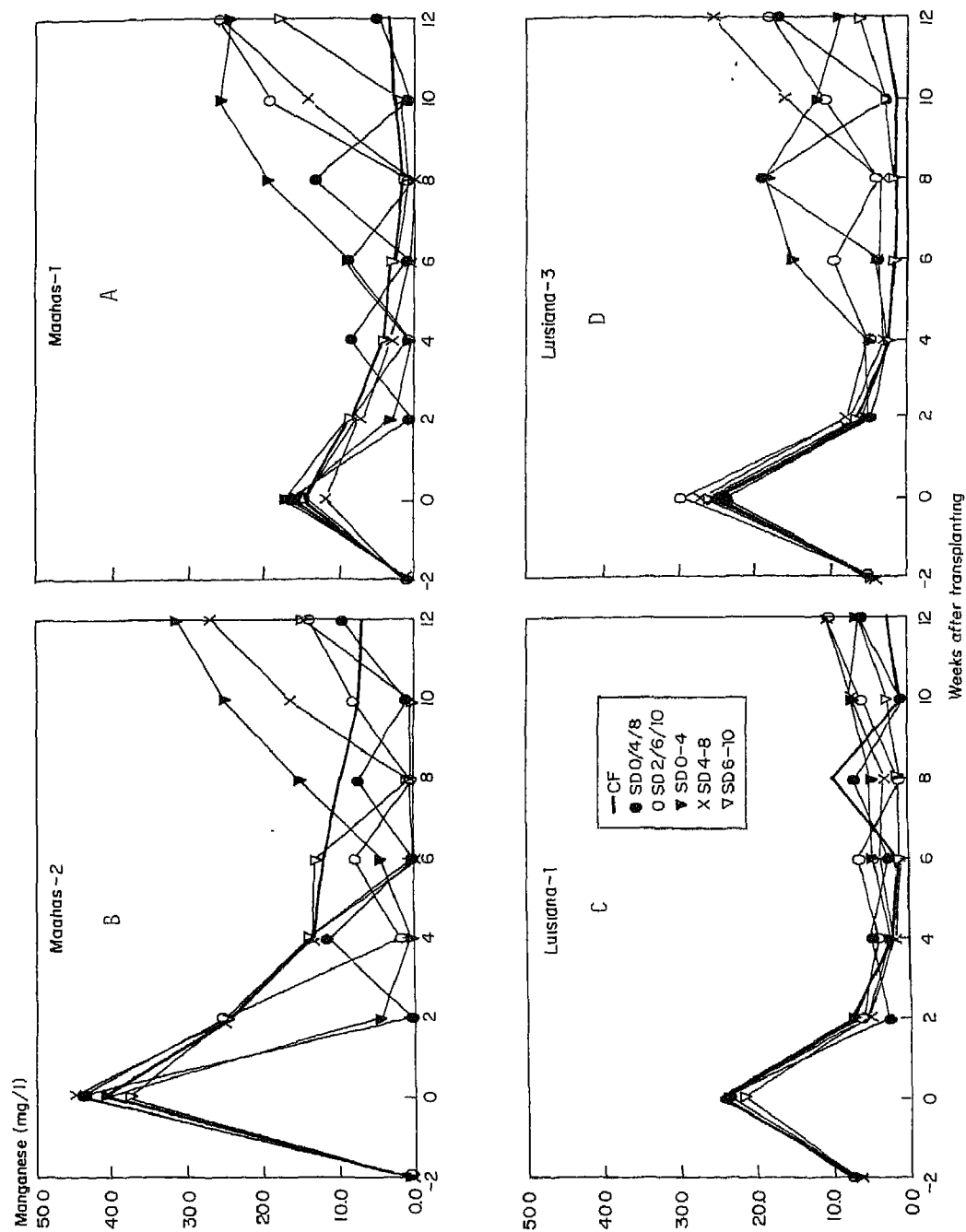


Fig. 65. Influence of six water regimes on the kinetics of water-soluble Mn in four soils.

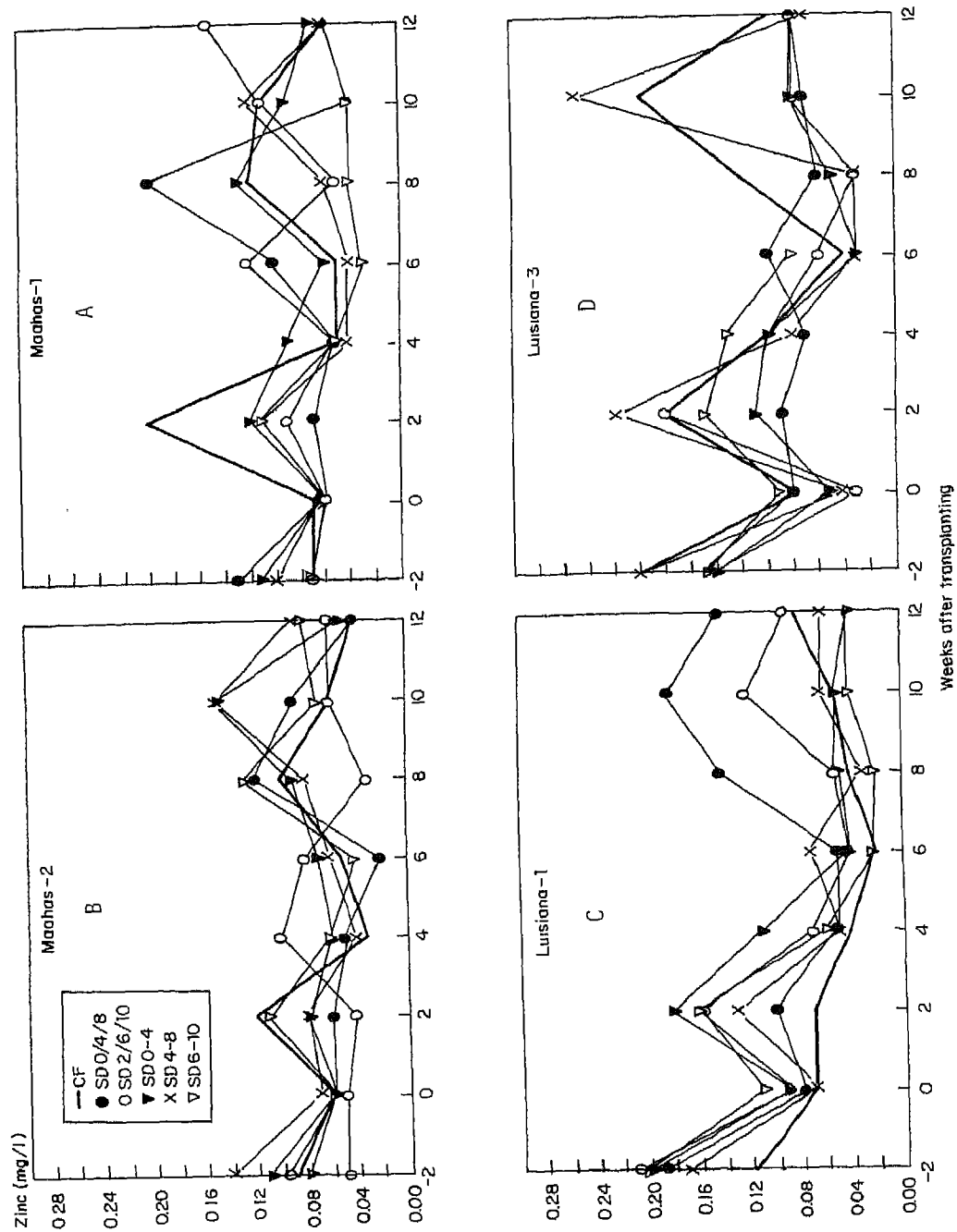


Fig. 66. Influence of six water regimes on the kinetics of water-soluble Zn in four soils.

Silicon (Si)

The water soluble Si concentration of the two Maahas soils increased on flooding while that in the two Luisiana soils decreased (Fig. 67). In the two Maahas soils the gradually increasing trend was observed up to 6 WAT and decreased thereafter (Fig. 67A-B) while in the two Luisiana soils, silica concentration came to a stable value within 2 WAT (Fig. 67C-D). While soil drying decreased the water soluble Si concentration of the two Maahas soils, it had no effect on the two Luisiana soils.

Mineral Nutrition of Rice

Soil and water regimes and their interaction influenced the mineral nutrition of rice plants. The concentrations of mineral nutrients in the 8 weeks old shoots and in the mature straw at harvest are presented. As the yields under different water regimes were different, the concentration of nutrients might be affected due to the dilution of nutrients in higher dry matter yields. Therefore, total uptake of the nutrients by the shoots and by the crop at harvest (straw and grain) were also computed. The results are discussed in the following pages.

Nitrogen

Rice shoots in the two Luisiana soils had higher nitrogen concentration compared to those in the two Maahas soils but the opposite was true in case of N uptake by plants at that stage (Table 46). The higher nitrogen concentration of rice shoots in Luisiana soils were due to higher nitrogen availability as was evident from the kinetics of

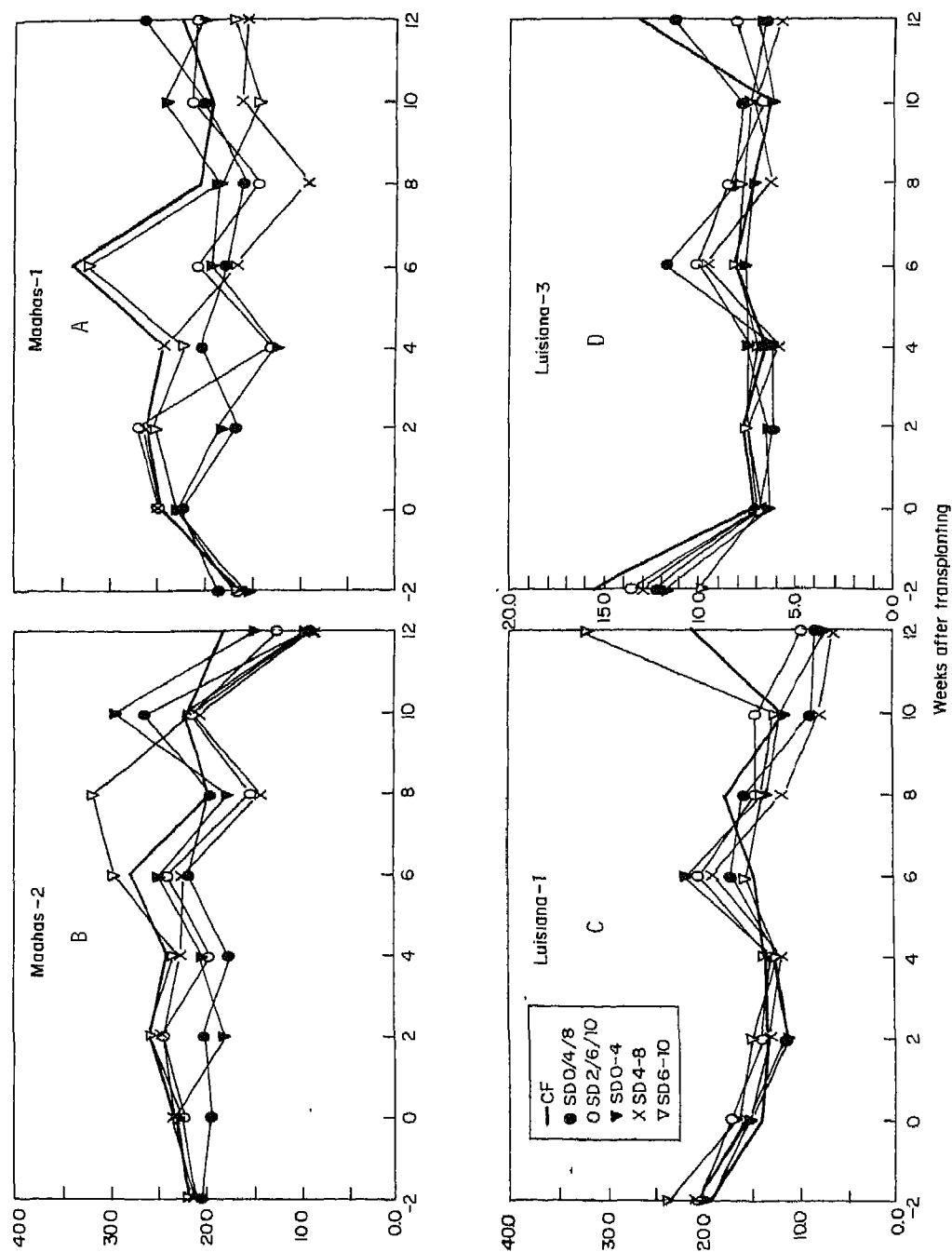


Fig. 67. Influence of six water regimes on the kinetics of water-soluble Si in four soils.

Table 46. Influence of six water regimes on the N concentration and uptake by eight-week-old rice (IR54) shoots in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>% N in rice shoots</u>					
CF	2.42 A	2.24 A	2.87 A	3.15 A	2.67 A	
SD 0-4	2.02 A	1.22 B	3.32 A	3.04 A	2.40 B	
SD 4-8	2.07 A	2.43 A	3.07 A	2.43 B	2.50 AB	
SD 6-10	2.29 A	2.20 A	2.87 AB	2.68 AB	2.51 AB	
SD 0/4/8	2.06 A	2.07 A	3.03 A	3.00 A	2.54 AB	
SD 2/6/10	2.39 A	1.34 B	2.96 A	2.80 AB	2.37 B	
Mean	2.21	1.92	3.02	2.85		
	<u>N uptake (g/pot) by rice shoots</u>					
CF	0.75 A	0.57 A	0.18 B	0.35 A	0.46 A	
SD 0-4	0.17 C	0.18 B	0.42 A	0.22 AB	0.25 B	
SD 4-8	0.26 C	0.58 A	0.22 B	0.12 B	0.29 B	
SD 6-10	0.76 A	0.59 A	0.19 B	0.25 AB	0.45 A	
SD 0/4/8	0.45 A	0.55 A	0.22 B	0.34 A	0.39 A	
SD 2/6/10	0.34 BC	0.22 B	0.34 AB	0.20 AB	0.27 B	
Mean	0.45	0.45	0.26	0.25		
	<u>% N in shoot</u>			<u>N uptake by shoots</u>		
	<u>S</u>	<u>W</u>	<u>SxW</u>	<u>S</u>	<u>W</u>	<u>SxW</u>
SE m±	0.09	0.11	0.22	0.04	0.04	0.09
LSD (0.05)	0.18	0.22	0.45	0.07	0.09	0.18
LSD (0.01)	0.24	0.30	0.60	0.10	0.12	0.24

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

NH_4^+ -N in soil solution (Fig. 58C-D) but the lower uptake was due to less dry matter production. The rice shoots in the two Maahas soils had concentration lower than the critical limit of 2.5%. This can be explained by the soil solution NH_4^+ -N kinetics which showed lower N availability. In both the Maahas soils N uptake by 8 week-old shoot decreased in soil drying and reflooding treatments. This was not because of lower N concentration but because of lower dry matter yield under alternate flooding and drying conditions (Table 46).

Nitrogen concentration in straw and N uptake by grains and straw at harvest were significantly influenced by the type of soil as well as water regimes (Table 47). The interaction of soil and water regime did not influence the N concentration of straw but did influence significantly the total N uptake by the crop at harvest. Three cycles of soil drying of 2 weeks each and reflooding (SD 0/4/8) decreased the N concentration of straw but soil drying for four weeks in the beginning (SD 0-4) increased the N concentration of straw. This increase in the N concentration of straw due to soil drying was not due to higher N availability but due to less total dry matter production in these treatments. Total N uptake at harvest decreased due to soil drying and reflooding cycles (Table 47). However, soil drying for 4 weeks at later stages (from 4 or 6 WAT) (SD 4-8; SD 6-10) did not significantly decrease the total N uptake by the crop at harvest. In spite of lower grain and straw yield in the two Luisiana soils, the total N uptake by rice in these two soils were higher than in the two Maahas soils.

Table 47. Influence of six water regimes on the N concentration of mature straw and N uptake by grain plus straw of rice (IR54) at harvest in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>% N in mature straw</u>					
CF	0.70 A	0.57 A	2.72 A	2.27 CD	1.56 BC	
SD 0-4	1.03 A	0.86 A	2.74 A	3.15 A	1.94 A	
SD 4-8	1.02 A	0.62 A	2.64 A	2.70 A-C	1.74 AB	
SD 6-10	0.97 A	0.70 A	2.74 A	2.64 BC	1.76 AB	
SD 0/4/8	0.66 A	0.58 A	2.56 A	1.97 D	1.44 C	
SD 2/6/10	0.61 A	0.60 A	2.61 A	2.80 AB	1.66 BC	
Mean	0.83	0.65	2.67	2.59		
	<u>N uptake (g/pot) at harvest</u>					
CF	1.36 A	1.13 A	1.67 B	1.63 A	1.45 A	
SD 0-4	0.43 B	0.51 B	1.86 B	1.41 A	1.05 D	
SD 4-8	0.92 AB	1.03 A	2.50 A	1.11 A	1.39 AB	
SD 6-10	1.35 A	1.06 A	1.59 B	1.35 A	1.34 A-C	
SD 0/4/8	0.64 B	0.66 AB	2.10 AB	1.20 A	1.15 B-D	
SD 2/6/10	0.66 B	0.47 B	2.04 AB	1.31 A	1.12 CD	
Mean	0.90	0.81	1.96	1.33		
	<u>% N in straw</u>			<u>N uptake at harvest</u>		
	S	W	SxW	S	W	SxW
SE m±	0.09	0.11	0.22	0.10	0.12	0.24
LSD (0.05)	0.18	0.22	0.44	0.20	0.24	0.48
LSD (0.01)	0.24	0.29	0.59	0.26	0.32	0.64

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Phosphorus

Both, water regimes and type of soils influenced the P concentration in 8 weeks old shoot and its total uptake by shoot and by grains plus straw at maturity (Tables 48 and 49). The interaction between soil and water regime did not significantly influence the P concentration of rice shoot but it significantly influenced the uptake both at vegetative growth stage (8 WAT) and at maturity. The concentration of P in mature straw seemed not to have been influenced by water regime, type of soils or their interaction (Table 49).

Rice plants grown in the two Maahas soils had higher P concentration in shoot and took up more P during vegetative as well as at mature stage compared to those grown in the two Luisiana soils. This is attributed to the lower available P content of both the Luisiana soils.

Plants grown in continuously flooded water regime (CF) in the two Maahas soils had highest concentration of P in shoot and took up highest P at vegetative growth stage as well as at maturity. Soil drying at any stage generally decreased these. However, in the two Luisiana soils soil drying did not affect P uptake by rice plants at 8 WAT stage as well as at maturity.

Potassium

Plants grown in the two Maahas soils had higher K concentration in shoot and straw and also K uptake at 8 weeks stage. Total K uptake by the rice crop at maturity was lowest in Luisiana-3 soil, while that in the other three soils were at par (Tables 50 and 51).

Table 48. Influence of six water regimes on the P concentration and uptake by eight-week-old rice (IR54) shoots in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>% P in rice shoots</u>					
CF	0.229 A	0.292 A	0.182 A	0.153 A	0.214 A	
SD 0-4	0.153 B	0.210 B	0.132 B	0.113 BC	0.152 BC	
SD 4-8	0.145 B	0.206 B	0.143 B	0.082 C	0.144 C	
SD 6-10	0.163 B	0.237 B	0.149 AB	0.101 BC	0.163 B	
SD 0/4/8	0.156 B	0.224 B	0.152 AB	0.121 B	0.163 B	
SD 2/6/10	0.142 B	0.213 B	0.134 B	0.105 BC	0.149 BC	
Mean	0.165	0.231	0.149	0.112		
	<u>P uptake (mg/pot) by rice shoots</u>					
CF	70.9 A	78.7 A	11.0 A	17.2 A	44.5 A	
SD 0-4	13.0 B	30.8 C	17.4 A	8.5 A	17.4 D	
SD 4-8	17.9 B	49.6 BC	10.4 A	4.1 A	20.5 CD	
SD 6-10	55.3 A	63.7 AB	10.2 A	9.6 A	34.7 AB	
SD 0/4/8	33.5 B	60.9 AB	11.9 A	13.7 A	30.0 BC	
SD 2/6/10	20.1 B	34.8 C	15.2 A	7.4 A	19.4 D	
Mean	35.1	53.1	12.7	10.1		
	<u>% P in shoot</u>			<u>P uptake by shoots</u>		
	S	W	SxW	S	W	SxW
SE m±	0.006	0.008	0.016	4.0	4.9	9.8
LSD (0.05)	0.013	0.016	0.032	8.0	9.9	19.7
LSD (0.01)	0.017	0.021	0.042	10.7	13.2	26.3

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 49. Influence of six water regimes on the P concentration of mature straw and P uptake by grain plus straw of rice (IR54) at harvest in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>% P in mature straw</u>					
CF	0.078 BC	0.074 B	0.092 A	0.085 A	0.082 B	
SD 0-4	0.126 A	0.134 A	0.092 A	0.075 A	0.107 A	
SD 4-8	0.111 AB	0.089 B	0.080 A	0.091 A	0.093 AB	
SD 6-10	0.095 A-C	0.078 B	0.116 A	0.085 A	0.094 AB	
SD 0/4/8	0.068 C	0.069 B	0.106 A	0.095 A	0.085 B	
SD 2/6/10	0.065 C	0.080 B	0.095 A	0.086 A	0.082 B	
Mean	0.091	0.087	0.097	0.086		
	<u>P uptake (g/pot) at harvest</u>					
CF	0.22 A	0.24 A	0.07 B	0.08 A	0.15 A	
SD 0-4	0.06 E	0.09 C	0.10 AB	0.05 A	0.08 D	
SD 4-8	0.13 C	0.21 AB	0.11 A	0.06 A	0.13 B	
SD 6-10	0.18 B	0.18 B	0.09 AB	0.06 A	0.13 B	
SD 0/4/8	0.09 DE	0.12 C	0.12 A	0.07 A	0.10 C	
SD 2/6/10	0.12 CD	0.09 C	0.10 AB	0.05 A	0.09 CD	
Mean	0.13	0.16	0.10	0.06		
	<u>% P in straw</u>			<u>P uptake at harvest</u>		
	<u>S</u>	<u>W</u>	<u>SxW</u>	<u>S</u>	<u>W</u>	<u>SxW</u>
SE m±	0.007	0.009	0.018	0.01	0.01	0.02
LSD (0.05)	0.015	0.018	0.036	0.01	0.02	0.04
LSD (0.01)	0.020	0.024	0.048	0.02	0.02	0.05

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 50. Influence of six water regimes on the K concentration and uptake by eight-week-old rice (IR54) shoots in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>% K in rice shoots</u>					
CF	3.71 A	3.96 A	3.42 AB	2.66 B	3.44 B	
SD 0-4	3.21 B	3.42 BC	3.05 B	2.94 AB	3.16 C	
SD 4-8	4.13 A	3.79 AB	3.84 A	3.22 A	3.75 A	
SD 6-10	4.17 A	3.79 AB	3.63 A	3.01 AB	3.65 AB	
SD 0/4/8	3.79 A	3.83 AB	3.71 A	3.15 A	3.62 AB	
SD 2/6/10	3.75 A	3.25 C	3.88 A	3.33 A	3.55 AB	
Mean	3.79	3.67	3.59	3.05		
	<u>K uptake (g/pot) by rice shoots</u>					
CF	1.15 AB	1.08 A	0.21 A	0.30 A	0.68 A	
SD 0-4	0.27 D	0.50 B	0.41 A	0.21 A	0.35 C	
SD 4-8	0.51 CD	0.91 A	0.28 A	0.16 A	0.46 BC	
SD 6-10	1.39 A	1.02 A	0.24 A	0.27 A	0.73 A	
SD 0/4/8	0.84 A	1.04 A	0.28 A	0.36 A	0.63 AB	
SD 2/6/10	0.53 CD	0.53 B	0.45 A	0.23 A	0.43 C	
Mean	0.78	0.85	0.31	0.26		
	<u>% K in shoot</u>			<u>K uptake by shoots</u>		
	S	W	SxW	S	W	SxW
SE m±	0.09	0.11	0.22	0.07	0.08	0.17
LSD (0.05)	0.18	0.22	0.43	0.13	0.17	0.34
LSD (0.01)	0.24	0.29	0.58	0.18	0.22	0.45

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 51. Influence of six water regimes on the K concentration of mature straw and K uptake by grain plus straw of rice (IR54) at harvest in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>% K in mature straw</u>					
CF	3.68 A	3.85 AB	2.07 BC	2.14 AB	2.93 A	
SD 0-4	2.94 B	3.22 C	1.93 C	1.68 B	2.44 B	
SD 4-8	3.57 A	3.81 AB	2.49 AB	2.31 A	3.05 A	
SD 6-10	3.54 A	4.06 A	2.59 A	1.96 AB	3.04 A	
SD 0/4/8	3.43 A	3.29 C	2.77 A	2.21 A	2.92 A	
SD 2/6/10	3.85 A	3.50 BC	2.56 AB	2.10 AB	3.00 A	
Mean	3.50	3.62	2.40	2.07		
	<u>K uptake (g/pot) at harvest</u>					
CF	0.50 A	0.55 A	0.23 B	0.26 A	0.41 A	
SD 0-4	0.16 B	0.18 B	0.35 AB	0.16 A	0.21 D	
SD 4-8	0.29 B	0.47 A	0.42 A	0.15 A	0.33 A	
SD 6-10	0.48 A	0.60 A	0.32 AB	0.20 A	0.40 A	
SD 0/4/8	0.27 B	0.30 B	0.40 A	0.26 A	0.31 BC	
SD 2/6/10	0.30 B	0.23 B	0.32 AB	0.17 A	0.25 CD	
Mean	0.35	0.39	0.34	0.20		
	<u>% K in shoot</u>			<u>K uptake at harvest</u>		
	S	W	SxW	S	W	SxW
SE m±	0.10	0.12	0.23	0.03	0.03	0.07
LSD (0.05)	0.19	0.24	0.47	0.06	0.07	0.14
LSD (0.01)	0.26	0.31	0.63	0.07	0.09	0.18

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

In both the Maahas soils, highest concentration of K in tissue was observed under continuously flooded water regime (CF) while in both the Luisiana soils it was highest when 2 weeks soil drying treatment was imposed at 2 and 6 WAT (SD 2/6/10). In Maahas-1 soil 4 weeks soil drying imposed on the day of transplanting (SD 0-4) decreased the K concentration of shoot while soil drying at other stages did not appreciably decrease it. The same was true in Luisiana-1 soil. In Maahas-2 soil, drying at any stage in general decreased K concentration of shoot but this was appreciable only when 2 weeks drying treatment was imposed two times at 2 and 6 WAT (SD 2/6/10) or soil drying was extended to 4 weeks (SD 0-4) from transplanting. In Luisiana-3 soil however, soil drying in general increased the K concentration of rice shoot (Table 50).

In Maahas-1 soil, 4 weeks soil drying imposed on the day of transplanting (SD 0-4) had lowest K concentration in straw but all other treatments had comparable K concentration in straw. In Maahas-2 soil, 4 weeks soil drying (SD 0-4) and 3 cycles of 2 weeks soil drying (SD 0/4/8) decreased the K concentration of straw but all other treatments were at par. In Luisiana-1 soil, soil drying generally increased the K concentration of straw but this difference was significant only when 4 weeks soil drying was imposed at 6 WAT (SD 6-10) and three soil drying cycles of 2 weeks each were imposed at 0, 4 and 8 WAT (SD 0/4/8). In Luisiana-3 soil, however, water regime did not significantly influence K concentration in straw (Table 51).

In the two Maahas soils, soil drying decreased K uptake both at vegetative growth stage and at maturity while in the two Luisiana soils these were not affected by soil drying.

Calcium

Calcium concentration in shoot was highest in plants grown in Luisiana-1 soil while the lowest Ca was observed in plants grown in Luisiana-3 soil. Rice plants grown in the two Maahas soils had comparable Ca concentration in shoot. Water regime did not significantly influence the Ca concentration of rice shoot in the two Luisiana soils. In Maahas-1 soil four weeks soil drying imposed at 4 WAT (SD 4-8) increased the Ca concentration of the shoot compared to continuously flooded water regime. While 2 soil drying cycles of 2 weeks each imposed at 0 and 4 WAT (SD 0/4/8) increased the Ca concentration of rice shoot, the same treatment imposed at 2 and 6 WAT (SD 2/6/10) decreased the Ca concentration of shoot in Maahas-2 soil (Table 52).

Calcium concentration of straw was higher in the two Luisiana soils compared to that in the two Maahas soils. The lower concentration of Ca in straw in Maahas soils were not due to lower availability of Ca here but because of higher straw yield which diluted the Ca concentration of the straw. In both the Maahas soils soil drying did not significantly influence the Ca concentration of straw. Soil drying decreased the Ca concentration of straw in Luisiana-1 soil but this decrease was appreciable only when 3 soil drying cycles of 2 weeks each were imposed at 0, 4 and 8 WAT (SD 0/4/8). This was due to

Table 52. Influence of six water regimes on the Ca concentration of eight-week-old rice (IR54) shoots and mature straw and Ca uptake by rice shoots in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean																																																												
<u>% Ca in rice shoots</u>																																																																	
CF	0.202 A	0.133 B	0.172 A	0.124 A	0.158 A																																																												
SD 0-4	0.137 B	0.102 B	0.148 A	0.096 A	0.121 B																																																												
SD 4-8	0.183 AB	0.145 B	0.143 A	0.083 A	0.139 AB																																																												
SD 6-10	0.163 AB	0.128 B	0.153 A	0.099 A	0.136 AB																																																												
SD 0/4/8	0.137 B	0.210 A	0.180 A	0.126 A	0.163 A																																																												
SD 2/6/10	0.142 AB	0.083 B	0.140 A	0.105 A	0.118 B																																																												
Mean	0.149	0.134	0.156	0.106																																																													
 <u>% Ca in mature straw</u>																																																																	
CF	0.173 AB	0.128 A	0.314 A	0.368 A	0.245 A																																																												
SD 0-4	0.143 B	0.089 A	0.266 AB	0.236 B	0.183 BC																																																												
SD 4-8	0.197 AB	0.130 A	0.291 A	0.221 B	0.210 B																																																												
SD 6-10	0.215 A	0.123 A	0.255 AB	0.242 B	0.209 B																																																												
SD 0/4/8	0.149 B	0.088 A	0.206 B	0.224 B	0.167 C																																																												
SD 2/6/10	0.167 AB	0.090 A	0.285 A	0.230 B	0.193 BC																																																												
Mean	0.174	0.108	0.270	0.253																																																													
 <u>Ca uptake (mg/pot) by shoots</u>																																																																	
CF	42.0 AB	36.7 B	10.7 A	14.7 A	26.0 A																																																												
SD 0-4	11.7 CD	15.0 C	19.8 A	7.3 A	13.4 B																																																												
SD 4-8	22.8 CD	35.0 B	10.4 A	4.0 A	18.0 B																																																												
SD 6-10	54.2 A	34.6 B	10.1 A	9.3 A	27.1 A																																																												
SD 0/4/8	32.2 BC	55.1 A	13.0 A	14.3 A	28.6 A																																																												
SD 2/6/10	20.1 CD	13.5 C	16.2 A	7.2 A	14.3 B																																																												
Mean	30.5	31.6	13.4	9.5																																																													
<table><tr><td></td><td colspan="3">% Ca in shoot</td><td colspan="3">% Ca in straw</td><td colspan="3">Ca uptake by shoots</td></tr><tr><td></td><td>S</td><td>W</td><td>SxW</td><td>S</td><td>W</td><td>SxW</td><td>S</td><td>W</td><td>SxW</td></tr><tr><td colspan="10"> </td></tr><tr><td>SE m±</td><td>0.012</td><td>0.014</td><td>0.028</td><td>0.012</td><td>0.015</td><td>0.029</td><td>2.9</td><td>3.6</td><td>7.1</td></tr><tr><td>LSD (0.05)</td><td>0.023</td><td>0.029</td><td>0.057</td><td>0.024</td><td>0.029</td><td>0.059</td><td>5.9</td><td>7.2</td><td>14.4</td></tr><tr><td>LSD (0.01)</td><td>0.031</td><td>0.038</td><td>0.076</td><td>0.032</td><td>0.039</td><td>0.078</td><td>7.8</td><td>9.6</td><td>19.2</td></tr></table>							% Ca in shoot			% Ca in straw			Ca uptake by shoots				S	W	SxW	S	W	SxW	S	W	SxW											SE m±	0.012	0.014	0.028	0.012	0.015	0.029	2.9	3.6	7.1	LSD (0.05)	0.023	0.029	0.057	0.024	0.029	0.059	5.9	7.2	14.4	LSD (0.01)	0.031	0.038	0.076	0.032	0.039	0.078	7.8	9.6	19.2
	% Ca in shoot			% Ca in straw			Ca uptake by shoots																																																										
	S	W	SxW	S	W	SxW	S	W	SxW																																																								
SE m±	0.012	0.014	0.028	0.012	0.015	0.029	2.9	3.6	7.1																																																								
LSD (0.05)	0.023	0.029	0.057	0.024	0.029	0.059	5.9	7.2	14.4																																																								
LSD (0.01)	0.031	0.038	0.076	0.032	0.039	0.078	7.8	9.6	19.2																																																								

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

corresponding increase in straw yield on soil drying. In Luisiana-3 soil, soil drying at any stage generally decreased the Ca concentration of straw.

Calcium uptake by 8 week-old rice shoot was higher in the two Maahas soils than in the two Luisiana soils obviously due to higher dry matter yield in the Maahas soils. Water regime had no effect on Ca uptake by rice shoot in both the Luisiana soils. In Maahas-1 soil, soil drying during the early stage (0 to 6 WAT) decreased Ca uptake by plants. In Maahas-2 soil Ca uptake by rice shoots was highest when 2 soil drying cycles of 2 weeks each were imposed at 0 and 4 WAT (SD 0/4/8) but was lowest when these soil drying cycles were imposed at 2 and 6 WAT (SD 2/6/10) (Table 52).

Magnesium

The Mg concentration of shoot in the four soils followed the order Maahas-2 > Maahas-1 > Luisiana-1 > Luisiana-3. In Maahas-1 soil, soil drying for 4 weeks from transplanting (SD 0-4) or 2 soil drying cycles of 2 weeks each, imposed 0 and 4 WAT (SD 0/4/8) or 2 and 6 WAT (SD 2/6/10) decreased Mg concentration of shoot while the other drying treatments had no effect. In Maahas-2 soil, soil drying for 4 weeks from 4 WAT (SD 4-8) increased the Mg concentration of shoot compared to that in continuously flooded water regime (CF) while the same drying treatment imposed on the day of transplanting (SD 0-4) decreased it (Table 53).

Table 53. Influence of six water regimes on the Mg concentration and uptake by eight-week-old rice (IR54) shoots in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>% Mg in rice shoots</u>					
CF	0.304 A	0.305 B	0.259 A	0.225 A	0.273 A	
SD 0-4	0.217 C	0.228 C	0.193 B	0.156 BC	0.198 C	
SD 4-8	0.318 A	0.388 A	0.217 B	0.139 C	0.265 A	
SD 6-10	0.325 A	0.333 B	0.223 B	0.165 BC	0.262 A	
SD 0/4/8	0.250 BC	0.303 B	0.191 B	0.177 B	0.230 B	
SD 2/6/10	0.262 B	0.247 C	0.187 B	0.155 BC	0.213 C	
Mean	0.279	0.301	0.211	0.170		
	<u>Mg uptake (mg/pot) by rice shoots</u>					
CF	94.1 A	79.5 A	15.6 A	26.4 A	53.9 AB	
SD 0-4	18.4 CD	33.5 B	25.2 A	11.7 A	22.2 E	
SD 4-8	39.4 BC	93.3 A	15.7 A	7.0 A	38.9 CD	
SD 6-10	108.9 A	90.0 A	15.4 A	15.4 A	57.4 A	
SD 0/4/8	55.3 B	81.7 A	14.9 A	19.9 A	43.0 BC	
SD 2/6/10	37.0 BC	40.5 B	21.7 A	11.1 A	27.6 DE	
Mean	58.8	69.7	18.1	15.2		
	<u>% Mg in shoot</u>			<u>Mg uptake by shoots</u>		
	<u>S</u>	<u>W</u>	<u>SxW</u>	<u>S</u>	<u>W</u>	<u>SxW</u>
SE m±	0.007	0.008	0.017	4.8	5.9	11.7
LSD (0.05)	0.014	0.017	0.034	9.6	11.8	23.6
LSD (0.01)	0.018	0.023	0.045	12.9	15.7	31.5

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Magnesium concentration in straw was higher in the two Maahas soils. In both the Luisiana soils, soil drying at any stage decreased the Mg concentration of straw. In Maahas-1 soil 4 weeks soil drying imposed on the day of transplanting (SD 0-4) and three soil drying cycles of 2 weeks each imposed at 2, 6 and 10 WAT (SD 2/6/10) decreased the Mg concentration in straw while the other treatments had similar Mg concentration in straw. In Maahas-2 soil, however, three cycles of soil drying cycles of 2 weeks each imposed at 2, 6 and 10 WAT (SD 2/6/10) decreased the Mg concentration of straw (Table 54).

Magnesium uptake by 8 week-old shoot was highest in the two Maahas soils. Soil drying and reflooding decreased the Mg uptake by shoots in both the Maahas soils while it had no effect on the two Luisiana soils (Table 53).

Total Mg uptake at harvest by the rice crop in four soils were of the order Maahas-2 = Maahas-1 > Luisiana-1 > Luisiana-3. In both the Maahas soils, soil drying decreased the total Mg uptake by the crop. In Luisiana-3 soil also soil drying decreased total Mg uptake by the crop. In Luisiana-1 soil however, soil drying for 4 weeks imposed at 4 WAT (SD 4-8) increased the total Mg uptake by the crop at harvest (Table 54).

Iron

In general rice shoots in Luisiana soils had higher Fe concentration compared to the Maahas soils. While soil drying decreased the Fe concentration in shoot in the Luisiana soils, that in the Maahas soils remained unaffected by water regimes (Table 55).

Table 54. Influence of six water regimes on the Mg concentration of mature straw and Mg uptake by grain plus straw of rice (IR54) at harvest in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>% Mg in mature straw</u>					
CF	0.266 A	0.256 AB	0.289 A	0.294 A	0.276 A	
SD 0-4	0.207 B	0.211 BC	0.230 B	0.124 B	0.193 D	
SD 4-8	0.278 A	0.286 A	0.220 B	0.143 B	0.232 B	
SD 6-10	0.301 A	0.274 A	0.183 B	0.125 B	0.221 BC	
SD 0/4/8	0.258 A	0.234 A-C	0.174 B	0.152 B	0.204 CD	
SD 2/6/10	0.206 B	0.195 C	0.202 B	0.132 B	0.184 D	
Mean	0.253	0.242	0.216	0.162		
	<u>Mg uptake (g/pot) at harvest</u>					
CF	0.27 A	0.27 A	0.15 B	0.16 A	0.21 A	
SD 0-4	0.08 C	0.09 C	0.15 B	0.06 B	0.09 D	
SD 4-8	0.18 B	0.29 A	0.23 A	0.06 B	0.19 A	
SD 6-10	0.26 A	0.25 A	0.13 B	0.08 B	0.18 AB	
SD 0/4/8	0.15 BC	0.17 B	0.16 AB	0.10 AB	0.15 BC	
SD 2/6/10	0.14 BC	0.11 BC	0.15 B	0.07 B	0.12 CD	
Mean	0.18	0.20	0.16	0.09		
	<u>% Mg in straw</u>			<u>Mg uptake at harvest</u>		
	<u>S</u>	<u>W</u>	<u>SxW</u>	<u>S</u>	<u>W</u>	<u>SxW</u>
SE m±	0.010	0.013	0.025	0.01	0.02	0.04
LSD (0.05)	0.021	0.026	0.051	0.03	0.04	0.07
LSD (0.01)	0.028	0.034	0.068	0.04	0.05	0.10

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 55. Influence of six water regimes on the Fe concentration and uptake by eight-week-old rice (IR54) shoots in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>ppm Fe in rice shoots</u>					
CF	240 A	240 A	623 A	297 AB	350 A	
SD 0-4	205 A	222 A	373 BC	238 B	260 B	
SD 4-8	225 A	222 A	280 C	220 B	237 B	
SD 6-10	240 A	288 A	446 B	343 A	330 A	
SD 0/4/8	200 A	220 A	303 C	248 AB	243 B	
SD 2/6/10	232 A	218 A	365 BC	257 AB	268 B	
Mean	224	235	399	267		
	<u>Fe uptake (mg/pot) by rice shoots</u>					
CF	7.4 A	6.4 A	3.7 AB	3.5 A	5.3 A	
SD 0-4	1.7 C	3.4 B	4.7 A	1.7 A	2.9 B	
SD 4-8	2.8 BC	5.3 AB	2.1 B	1.1 A	2.8 B	
SD 6-10	8.0 A	7.7 A	3.2 AB	3.2 A	5.5 A	
SD 0/4/8	4.2 B	5.8 AB	2.3 AB	2.8 A	3.8 B	
SD 2/6/10	3.3 BC	3.6 B	4.2 AB	1.8 A	3.2 B	
Mean	4.6	5.4	3.3	2.4		
	<u>ppm Fe in shoots</u>			<u>Fe uptake by shoots</u>		
	S	W	SxW	S	W	SxW
SE m±	19	23	46	0.5	0.6	1.1
LSD (0.05)	38	47	93	0.9	1.1	2.2
LSD (0.01)	51	62	125	1.2	1.5	3.0

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Iron concentration of mature straw was also higher in the Luisiana soils compared to the Maahas soils. In general soil drying decreased the Fe concentration of mature straw on all soils (Table 56). This is consistent with the Fe kinetics data where decreased Fe availability was observed due to soil drying (Fig. 64).

Unlike Fe concentration, total Fe uptake by shoots were higher in the Maahas soils compared to the Luisiana soils. This was due to corresponding higher dry matter yield in the Maahas soils. Soil drying in general decreased Fe uptake by shoots (Table 55).

Total Fe uptake by the crop at harvest was lowest in Luisiana-3 soil while the three other soils had similar uptake values. Soil drying in general decreased the total Fe uptake by rice at harvest (Table 56).

Manganese

Rice plants grown on the two Luisiana soils had higher Mn concentration in 8 week-old shoot as well as in mature straw. Manganese uptake by rice at 8 WAT and at maturity were also higher in the two Luisiana soils (Tables 57 and 58).

Soil drying increased the Mn concentration in 8 week-old shoot. However, in the two Maahas soils Mn concentration of shoots were not influenced by soil drying (Table 57). Soil drying also increased the Mn concentration of mature straw, but this increase was not significant in Maahas-1 soil (Table 58).

Manganese uptake by 8 week-old shoot increased due to soil drying. However, in the 2 Maahas soils this effect was not appreciable. Total uptake of Mn by rice at maturity also increased due to soil drying, but

Table 56. Influence of six water regimes on the Fe concentration of mature straw and Fe uptake by grain plus straw of rice (IR54) at harvest in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>ppm Fe in mature straw</u>					
CF	208 A	153 A	258 A	352 A	243 A	
SD 0-4	182 AB	163 A	245 AB	267 B	214 B	
SD 4-8	110 C	133 AB	225 A-C	233 BC	175 C	
SD 6-10	138 BC	138 AB	208 BC	187 D	168 C	
SD 0/4/8	148 BC	167 A	193 C	162 D	167 C	
SD 2/6/10	148 BC	98 B	212 BC	203 CD	165 C	
Mean	156	142	224	234		
	<u>Fe uptake (mg/pot) at harvest</u>					
CF	42.7 A	34.5 A	22.6 A	33.7 A	33.4 A	
SD 0-4	13.0 C	18.8 B	29.3 A	18.1 B	19.8 B	
SD 4-8	21.8 BC	35.8 A	34.7 A	15.2 B	26.9 AB	
SD 6-10	30.2 AB	30.1 AB	21.2 A	17.3 B	24.7 B	
SD 0/4/8	23.3 BC	24.3 AB	25.1 A	18.1 B	22.7 B	
SD 2/6/10	25.2 BC	21.2 AB	28.9 A	16.1 B	22.9 B	
Mean	26.0	27.4	27.0	19.8		
	<u>ppm Fe in straw</u>			<u>Fe uptake at harvest</u>		
	<u>S</u>	<u>W</u>	<u>SxW</u>	<u>S</u>	<u>W</u>	<u>SxW</u>
SE m±	8.5	10.4	20.8	2.8	3.5	7.0
LSD (0.05)	17.1	21.0	41.9	5.7	7.0	14.0
LSD (0.01)	22.8	28.0	56.0	7.6	9.4	18.8

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 57. Influence of six water regimes on the Mn concentration and uptake by eight-week-old rice (IR54) shoots in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>ppm Mn in rice shoots</u>					
CF	330 A	483 A	351 C	543 D	426 D	
SD 0-4	471 A	541 A	538 BC	1243 C	698 C	
SD 4-8	255 A	143 A	1901 A	349 A	1446 A	
SD 6-10	336 A	279 A	697 BC	1743 BC	764 C	
SD 0/4/8	515 A	611 A	985 B	1536 C	912 BC	
SD 2/6/10	323 A	250 A	1685 A	2142 AB	1100 B	
Mean	372	384	1083	1782		
	<u>Mn uptake (mg/pot) by rice shoots</u>					
CF	10.2 AB	13.8 AB	2.2 C	6.0 C	8.0 B	
SD 0-4	4.0 AB	8.2 BC	7.1 BC	9.6 BC	7.2 B	
SD 4-8	3.2 B	3.3 C	13.4 AB	17.2 AB	9.3 B	
SD 6-10	11.3 A	7.5 B	4.2 C	15.5 AB	9.6 B	
SD 0/4/8	11.5 A	16.3 A	7.7 BC	17.6 A	13.3 A	
SD 2/6/10	4.6 AB	4.1 C	18.9 A	14.9 AB	10.6 AB	
Mean	7.5	8.9	8.9	13.5		
	<u>ppm Mn in shoots</u>			<u>Mn uptake by shoots</u>		
	<u>S</u>	<u>W</u>	<u>SxW</u>	<u>S</u>	<u>W</u>	<u>SxW</u>
SE m±	108.7	133.1	266.2	1.4	1.7	3.5
LSD (0.05)	218.8	267.9	535.8	2.9	3.5	7.0
LSD (0.01)	292.0	357.6	715.2	3.8	4.7	9.4

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 58. Influence of six water regimes on the Mn concentration of mature straw and Mn uptake by grain plus straw of rice (IR54) at harvest in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>ppm Mn in mature straw</u>					
CF	313 A	396 B	448 C	924 B	520 C	
SD 0-4	6267 A	700 AB	315 C	1019 B	665 C	
SD 4-8	700 A	893 A	739 BC	2009 A	1085 AB	
SD 6-10	438 A	319 B	1628 A	2111 A	1124 AB	
SD 0/4/8	494 A	538 AB	1432 A	2330 A	1198 A	
SD 2/6/10	735 A	714 AB	907 B	1344 B	925 B	
Mean	551	589	911	1622		
	<u>Mn uptake (mg/pot) at harvest</u>					
CF	19.4 A	23.8 B	19.5 D	40.6 C	25.8 B	
SD 0-4	11.7 A	18.9 B	13.3 D	33.3 C	19.3 C	
SD 4-8	29.1 A	51.4 A	40.1 C	62.7 B	45.8 A	
SD 6-10	24.8 A	17.9 B	66.0 B	71.7 B	45.1 A	
SD 0/4/8	15.8 A	20.2 B	88.3 A	90.4 A	53.7 A	
SD 2/6/10	25.6 A	20.6 B	43.6 C	43.4 C	33.3 B	
Mean	21.1	25.5	45.1	57.0		
	<u>ppm Mn in straw</u>			<u>Mn uptake at harvest</u>		
	S	W	SxW	S	W	SxW
SE $\pm$	83.2	101.9	203.7	3.5	4.3	8.5
LSD (0.05)	167.4	205.1	410.1	7.0	8.6	17.1
LSD (0.01)	223.5	273.7	547.5	9.3	11.4	22.9

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

again this effect was not statistically significant in the 2 Maahas soils (Table 58).

Zinc

The Zn concentration of shoot was lowest in Maahas-2 soil while in other three soils Zn concentration of shoots were similar. In general, soil drying increased the Zn concentration in shoot (Table 59). Zinc uptake by rice shoot in the soils followed the order Maahas-1 > Maahas-2 > Luisiana-1 = Luisiana-3. Influence of water regimes on Zn uptake by shoot in the Luisiana soils were not significant. In the Maahas soils also, the effect of water regime on Zn uptake by shoot was not consistent, soil drying sometimes increased Zn uptake (SD 0/4/8) while at other stages decreased Zn uptake (SD 0-4) (Table 59). This was due to difference in shoot dry matter yield in different water regime treatments (Table 65).

Zinc concentration of mature straw and total Zn uptake at harvest were significantly influenced by soil types. While water regimes influenced the total Zn uptake at harvest it did not influence Zn concentration in mature straw. The interaction of soils and water regimes influenced both Zn concentration in straw as well as total Zn uptake by the plants. Zinc concentrations of straw were higher in the Luisiana soils compared to the Maahas soils. Zinc concentration of mature straw was not influenced by water regimes in the Luisiana soils. In Maahas-1 soil, soil drying in general increased Zn concentration in straw. In Maahas-2 soil drying for 4 weeks in the beginning (SD 0-4) and three cycles of soil drying (SD 2/6/10) increased the Zn concentration of straw (Table 60).

Table 59. Influence of six water regimes on the Zn concentration and uptake by eight-week-old rice (IR54) shoots in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>ppm Zn in rice shoots</u>					
CF	31.3 D	35.0 A	44.2 C	44.7 BC	38.8 C	
SD 0-4	43.0 CD	35.7 A	44.0 C	40.8 C	40.9 C	
SD 4-8	75.3 A	38.7 A	74.5 A	59.5 AB	62.0 A	
SD 6-10	53.7 BC	36.8 A	56.0 BC	55.0 A-C	50.4 B	
SD 0/4/8	64.3 AB	41.7 A	64.0 AB	69.3 A	59.8 A	
SD 2/6/10	66.2 AB	32.2 A	61.7 AB	67.0 A	56.8 AB	
Mean	55.6	36.7	57.4	56.1		
	<u>Zn uptake (mg/pot) by rice shoots</u>					
CF	1.0 B	0.9 AB	0.3 A	0.5 A	0.7 BC	
SD 0-4	0.4 C	0.5 B	0.6 A	0.3 A	0.5 C	
SD 4-8	0.9 B	0.9 AB	0.5 A	0.3 A	0.7 BC	
SD 6-10	1.8 A	1.0 AB	0.4 A	0.5 A	0.9 AB	
SD 0/4/8	1.5 A	1.1 A	0.5 A	0.8 A	1.0 A	
SD 2/6/10	0.9 B	0.5 B	0.7 A	0.4 A	0.6 C	
Mean	1.1	0.8	0.5	0.5		
	<u>ppm Zn in shoots</u>			<u>Zn uptake by shoots</u>		
	S	W	SxW	S	W	SxW
SE m±	3.2	3.9	7.8	0.1	0.1	0.2
LSD (0.05)	6.4	7.8	15.6	0.2	0.2	0.5
LSD (0.01)	8.5	10.4	20.9	0.3	0.3	0.7

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 60. Influence of six water regimes on the Zn concentration of mature straw and Zn uptake by grain plus straw of rice (IR54) at harvest in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>ppm Zn in mature straw</u>					
CF	28.7 C	39.2 C	61.5 A	80.3 A	52.4 B	
SD 0-4	38.8 BC	62.3 AB	65.0 A	46.7 B	53.2 AB	
SD 4-8	63.7 A	54.2 A-C	65.5 A	61.9 AB	61.3 AB	
SD 6-10	65.0 A	41.2 BC	69.2 A	69.5 AB	61.2 AB	
SD 0/4/8	57.7 AB	35.7 C	78.5 A	66.0 AB	59.5 AB	
SD 2/6/10	55.5 AB	69.3 A	66.3 A	67.2 AB	64.6 A	
Mean	51.6	50.3	67.7	65.3		
	<u>Zn uptake (mg/pot) at harvest</u>					
CF	4.19 AB	5.08 A	3.64 B	4.74 A	4.41 A	
SD 0-4	1.39 C	2.61 B	3.96 B	2.39 B	2.59 B	
SD 4-8	4.06 AB	5.15 A	5.40 AB	2.54 B	4.29 A	
SD 6-10	5.63 A	4.88 A	3.87 B	3.65 AB	4.51 A	
SD 0/4/8	3.06 BC	2.58 B	6.15 A	3.55 AB	3.83 A	
SD 2/6/10	3.25 B	3.83 AB	4.63 AB	2.89 B	3.65 A	
Mean	3.60	3.86	4.61	3.29		
	<u>ppm Zn in straw</u>			<u>Zn uptake at harvest</u>		
	S	W	SxW	S	W	SxW
SE m±	4.2	5.2	10.4	0.35	0.42	0.85
LSD (0.05)	8.5	10.4	20.9	0.70	0.85	1.70
LSD (0.01)	11.4	13.9	27.8	0.93	1.14	2.27

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Total Zn uptake at harvest was highest in Luisiana-1 soil while that in the three other soils were comparable (Table 60). In Maahas-1 soil, soil drying for 4 weeks at later stage of growth (SD 6-10) increased the total Zn uptake while soil drying at other stages in general, decreased total Zn uptake but this decrease was pronounced when drying was imposed for 4 weeks in the beginning (SD 0-4). In Maahas-2 soil, also soil drying decreased Zn uptake at harvest (Table 60).

Copper

Copper concentration of rice shoot in the four soils followed the order Luisiana-1 = Maahas-1 > Maahas-2 = Luisiana-3. Soil drying in general increased the Cu concentration of rice shoots (Table 61).

Copper concentration of mature straw in the four soils followed the order Maahas-1 = Luisiana-1 > Maahas-2 = Luisiana-3. While water regime did not influence Cu concentration of straw in the two Maahas soils, soil drying increased the Cu concentration of straw in the two Luisiana soils (Table 62).

Copper uptake by rice at 8 WAT as well as at maturity was higher in the two Maahas soils compared to the two Luisiana soils. Influence of soil drying on Cu uptake by rice shoot was not consistent but soil drying generally decreased total Cu uptake by the rice crop at harvest (Table 62).

Table 61. Influence of six water regimes on the Cu concentration and uptake by eight-week-old rice (IR54) shoots in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
<u>ppm Cu in rice shoots</u>						
CF	25.7 C	25.5 B	17.2 C	18.5 C	21.7 D	
SD 0-4	35.7 BC	33.7 AB	29.8 B	24.8 BC	31.0 C	
SD 4-8	42.2 AB	31.2 AB	54.0 A	39.2 A	41.6 A	
SD 6-10	37.2 AB	39.3 A	37.8 B	29.5 A-C	36.0 BC	
SD 0/4/8	47.3 A	38.2 A	50.3 A	36.5 A	43.1 A	
SD 2/6/10	48.5 A	33.3 AB	50.3 A	30.2 AB	40.6 AB	
Mean	39.4	33.5	39.9	29.8		
<u>Cu uptake (mg/pot) by rice shoots</u>						
CF	0.79 BC	0.67 AB	0.11 B	0.21 A	0.45 B	
SD 0-4	0.30 D	0.52 B	0.43 AB	0.19 A	0.36 B	
SD 4-8	0.53 CD	0.75 AB	0.39 AB	0.19 A		
SD 6-10	1.22 A	1.04 A	0.23 AB	0.27 A	0.69 A	
SD 0/4/8	1.05 AB	1.01 A	0.39 AB	0.42 A	0.72 A	
SD 2/6/10	0.69 BC	0.55 B	0.59 A	0.21 A	0.51 B	
Mean	0.76	0.76	0.36	0.25		
<u>ppm Cu in shoots</u>						
	S	W	SxW	<u>Cu uptake by shoots</u>		
				S	W	SxW
SE m±	2.1	2.6	5.2	0.07	0.09	0.18
LSD (0.05)	4.3	5.2	10.5	0.15	0.18	0.36
LSD (0.01)	5.7	7.0	14.0	0.19	0.24	0.47

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 62. Influence of six water regimes on the Cu concentration of mature straw and Cu uptake by grain plus straw of rice (IR54) at harvest in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
<u>ppm Cu in mature straw</u>						
CF	22.8 B	19.3 A	17.3 C	16.3 B	19.0 C	
SD 0-4	27.2 AB	25.0 A	19.8 C	18.5 AB	22.6 B	
SD 4-8	27.8 AB	23.8 A	26.3 B	24.8 A	25.7 AB	
SD 6-10	25.0 AB	21.3 A	32.7 A	23.3 A	25.6 AB	
SD 0/4/8	30.5 A	25.8 A	32.5 A	20.0 AB	27.2 A	
SD 2/6/10	26.3 AB	20.5 A	28.2 AB	18.8 AB	23.5 B	
Mean	26.6	22.6	26.1	20.3		
<u>Cu uptake (mg/pot) at harvest</u>						
CF	5.21 A	4.50 AB	1.88 B	2.84 A	3.61 A	
SD 0-4	1.88 C	2.31 D	3.09 AB	1.59 A	2.22 D	
SD 4-8	2.96 BC	5.41 A	3.83 A	1.56 A	3.44 AB	
SD 6-10	4.17 AB	4.18 BC	2.89 AB	1.90 A	3.29 A-C	
SD 0/4/8	2.83 C	3.06 CD	3.76 A	2.05 A	2.92 BC	
SD 2/6/10	3.09 BC	2.80 D	3.39 A	1.60 A	2.72 CD	
Mean	3.36	3.71	3.14	1.92		
<u>ppm Cu in straw</u>						
<u>Cu uptake at harvest</u>						
	S	W	SxW	S	W	SxW
SE m±	1.2	1.4	2.9	0.24	0.29	0.58
LSD (0.05)	2.4	2.9	5.8	0.48	0.58	1.17
LSD (0.01)	3.2	3.9	7.8	0.64	0.78	1.56

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Silica

The concentration of SiO_2 as well as its uptake by the rice shoots were higher in the two Maahas soils compared to the two Louisiana soils. Water regime did not influence SiO_2 concentration as well as its uptake by rice shoot in the two Louisiana soils. In the two Maahas soils, soil drying for 4 weeks in the beginning (SD 0-4) decreased the SiO_2 concentration of rice shoot. Soil drying decreased the SiO_2 uptake by rice shoots in Maahas-1 soil (Table 63).

In the Louisiana-3 soil, SiO_2 concentration of straw and SiO_2 uptake by rice at harvest were the lowest while that in the three other soils were comparable. Water regimes had no significant influence on SiO_2 concentration of mature straw in the two Louisiana soils. In both the Maahas soils, soil drying for 4 weeks in the beginning (SD 0-4) decreased the SiO_2 concentration of mature straw while that in all other water regimes were similar. In Louisiana-3 soil, water regime did not influence the SiO_2 uptake by rice at harvest. While three soil drying cycles of 2 weeks each significantly decreased SiO_2 uptake by rice at harvest in the two Maahas soils, the same treatments increased SiO_2 uptake in Louisiana-1 soil. Four weeks soil drying in the beginning (SD 0-4) decreased SiO_2 uptake in both the Maahas soils (Table 64).

Table 63. Influence of six water regimes on the SiO_2 concentration and uptake by eight-week-old rice (IR54) shoots in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
<u>% SiO₂ in rice shoots</u>						
CF	12.6 AB	12.9 A	12.1 A	10.9 A	12.1 A	
SD 0-4	10.1 C	10.4 B	11.0 A	10.6 A	10.5 B	
SD 4-8	12.0 B	13.3 A	11.9 A	12.0 A	12.3 A	
SD 6-10	13.8 A	12.6 A	12.0 A	11.4 A	12.4 A	
SD 0/4/8	11.3 BC	13.2 A	11.8 A	11.2 A	11.9 A	
SD 2/6/10	11.7 B	12.3 A	12.2 A	11.6 A	12.0 A	
Mean	11.9	12.4	11.8	11.3		
<u>SiO₂ uptake (g/pot) by rice shoots</u>						
CF	3.91 A	3.50 A	0.76 A	1.24 A	2.35 A	
SD 0-4	0.86 C	1.53 B	1.45 A	0.78 A	1.15 C	
SD 4-8	1.49 BC	3.19 A	0.86 A	0.58 A	1.53 BC	
SD 6-10	4.63 A	3.39 A	0.80 A	1.05 A	2.47 A	
SD 0/4/8	2.50 B	3.55 A	0.92 A	1.26 A	2.06 AB	
SD 2/6/10	1.66 BC	2.01 B	1.39 A	0.83 A	1.47 C	
Mean	2.51	2.86	1.03	0.96		
	<u>% SiO₂ in shoot</u>			<u>SiO₂ uptake by shoots</u>		
	<u>S</u>	<u>W</u>	<u>SxW</u>	<u>S</u>	<u>W</u>	<u>SxW</u>
SE m±	0.3	0.3	0.6	0.22	0.27	0.54
LSD (0.05)	0.5	0.7	1.3	0.44	0.54	1.09
LSD (0.01)	0.7	0.9	1.7	0.59	0.72	1.45

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Table 64. Influence of six water regimes on the SiO_2 concentration of mature straw and SiO_2 uptake by grain plus straw of rice (IR54) at harvest in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
	<u>% SiO₂ in mature straw</u>					
CF	17.6 A	17.1 A	16.1 AB	15.0 AB	16.5 A	
SD 0-4	14.8 B	14.3 B	16.2 AB	13.7 AB	14.8 B	
SD 4-8	16.6 AB	18.8 A	17.5 AB	16.3 A	17.3 A	
SD 6-10	19.1 A	17.6 A	17.5 AB	14.3 AB	17.1 A	
SD 0/4/8	17.7 A	17.2 A	15.6 B	13.2 B	15.9 AB	
SD 2/6/10	18.3 A	17.1 A	18.6 A	14.2 AB	17.0 A	
Mean	17.4	17.0	16.9	14.4		
	<u>SiO₂ uptake (g/pot) at harvest</u>					
CF	13.5 A	11.9 A	8.0 B	7.7 A	10.3 A	
SD 0-4	3.4 C	4.8 C	7.9 B	5.3 A	5.4 C	
SD 4-8	8.4 B	12.0 A	11.7 A	5.7 A	9.5 A	
SD 6-10	12.8 A	11.6 A	8.3 A	6.1 A	9.7 A	
SD 0/4/8	7.1 B	7.9 B	11.2 A	6.3 A	8.1 B	
SD 2/6/10	7.9 B	6.1 BC	10.7 A	5.5 A	7.5 B	
Mean	8.8	9.1	9.6	6.1		
	<u>% SiO₂ in straw</u>			<u>SiO₂ uptake at harvest</u>		
	<u>S</u>	<u>W</u>	<u>SxW</u>	<u>S</u>	<u>W</u>	<u>SxW</u>
SE m±	0.5	0.7	1.3	0.5	0.6	1.2
LSD (0.05)	1.1	1.3	2.6	1.0	1.2	2.4
LSD (0.01)	1.4	1.8	3.5	1.3	1.6	3.1

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Growth and Yield of Rice (IR54)

Height

At the early plant growth stages the height in different water regimes were not much different. After 6 WAT in Maahas-1, Maahas-2 and Luisiana-3 soils plants were tallest under continuously flooded water regime (Fig. 68A,B,D) while in Luisiana-1 soil they were shortest (Fig. 68C). Soil drying and reflooding, in general, decreased plant height in Maahas-1, Maahas-2 and Luisiana-3 soils but increased plant height in Luisiana-1 soil.

Tiller number

Changes in the number of tillers per hill upto 10 WAT are presented in Figure 69. In Maahas-1 soil highest number of tillers were observed under continuously flooded water regime and soil drying at any stage decreased the tiller number (Fig. 69A). Lowest number of tillers was observed in SD 0-4 water regime in Maahas-1 soil. In Maahas-2 soil, 4 weeks soil drying at 4 and 6 WAT (SD 4-8; SD 6-10) slightly increased tiller number compared to continuously flooded water regime but all other drying and reflooding treatments produced lesser tillers than continuously flooded water regime (Fig. 69B). In Luisiana-3 soil SD 0/4/8 produced slightly higher number of tillers than CF but all other drying and reflooding water regimes produced lesser tillers than CF (Fig. 69D). In Luisiana-1 soil, however, number of tillers was lowest in continuously flooded water regime but soil drying during the active tillering stage increased the number of tillers (Fig. 69C). High Fe²⁺

Plant height (cm)

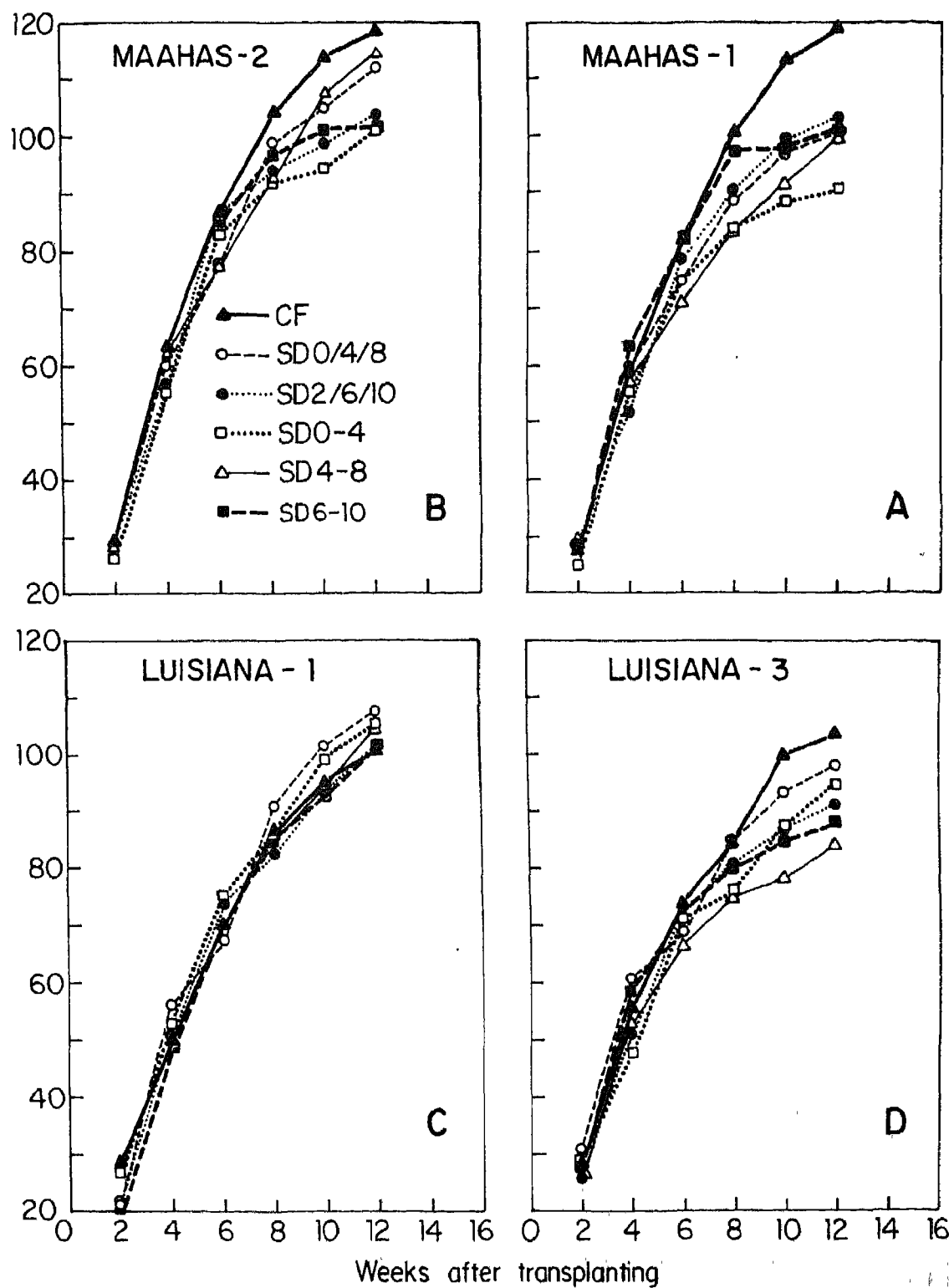


Fig. 68. Influence of six water regimes on the height of rice plants at different growth stages in four soils.

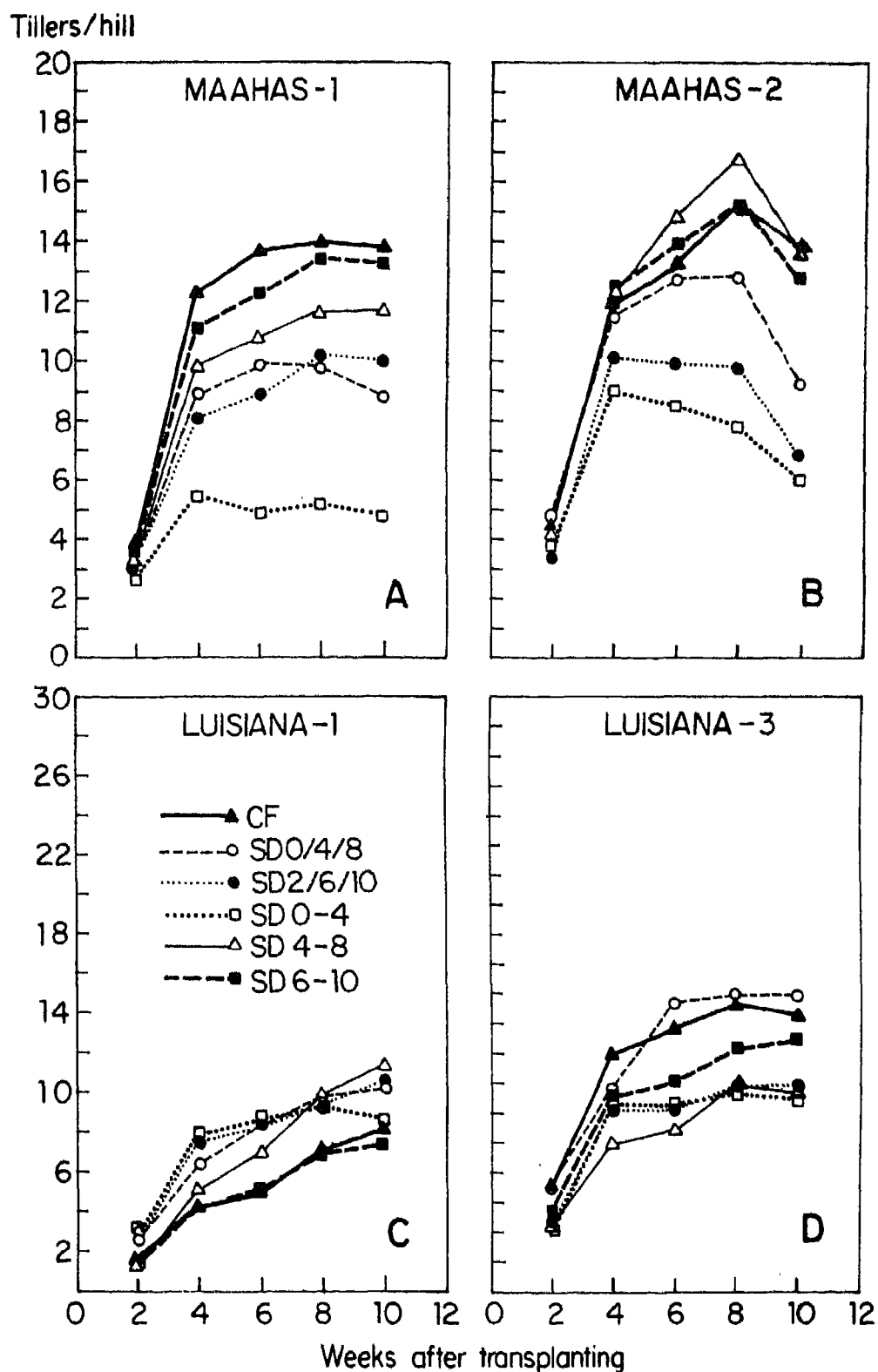


Fig. 69. Influence of six water regimes on the tillering of rice at different growth stages in four soils.

concentration in soil solution in Luisiana-1 soil was probably the reason for low tillering under continuously flooded water regime.

Visual symptoms

In Maahas-1 and Maahas-2 soils, best crop growth was observed under continuously flooded water regime. In the dried and reflooded water regimes the plants showed N and Fe deficiency symptoms, were stunted and had few tillers (Plates 8,9). In both the Luisiana soils plant growth was poor, had fewer tillers than in the Maahas soils. The plants were very green. The plants remained green even when the grains were fully ripe. In Luisiana-1 soil, plant growth suffered due to high Fe^{2+} concentration in soil solution. Soil drying helped to improve the situation. In Luisiana-3 soil, soil drying and reflooding resulted in higher Mn uptake by plants. Although plant tissue analyses did not suggest P deficiency but the appearance of the plants (Plates 10,11) and soil analyses suggest probable P deficiency in both the Luisiana soils.

Dry matter yield of 8-week-old rice shoot

Soil types, water regimes and their interaction significantly influenced the dry matter yield of rice shoots (Table 65). The dry matter yield of shoots were higher in the two Maahas soils compared to the two Luisiana soils (Table 65). While soil drying did not influence the shoot dry matter yield in the two Luisiana soils, it decreased shoot dry matter yields in both the Maahas soils (Table 65).



Plate 8. Influence of water regime on rice (IR54) growth in Maahas-1 soil (AFD1 = SD 0/4/8; AFD2 = SD 2/6/10; AFD3 = SD 0-4; AFD4 = SD 4-8; AFD5 = SD 6-10).

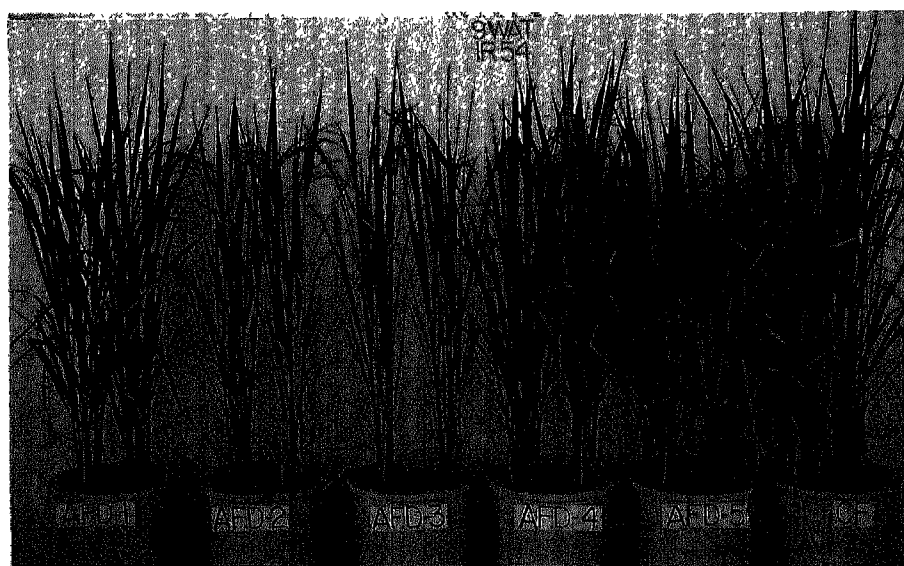


Plate 9. Influence of water regime on rice (IR54) growth in Maahas-2 soil (AFD1 = SD 0/4/8; AFD2 = SD 2/6/10; AFD3 = SD 0-4; AFD4 = SD 4/8; AFD5 = SD 6-10).

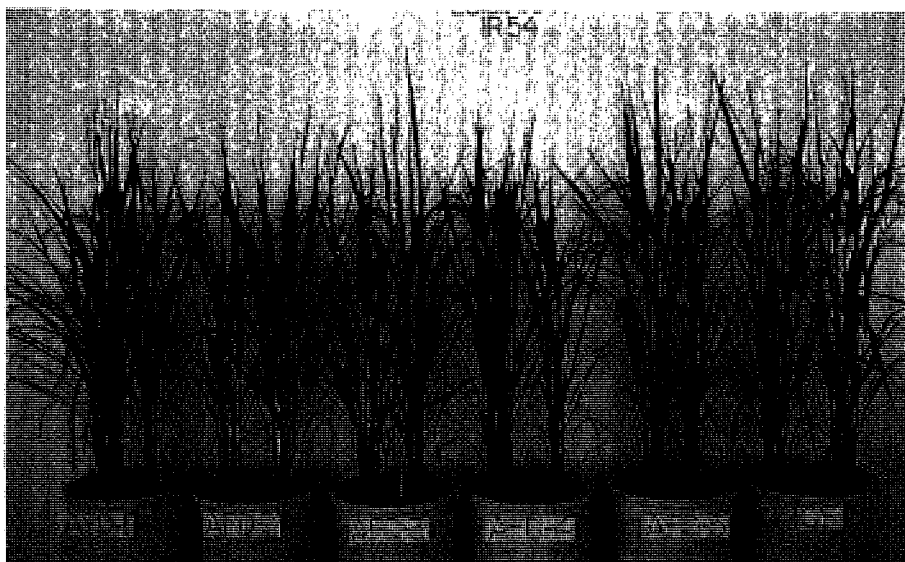


Plate 10. Influence of water regime on rice (IR54) growth in Louisiana-1 soil (AFD1 = SD 0/4/8; AFD2 = SD 2/6/10; AFD3 = SD 0-4; AFD4 = SD 4-8; AFD5 = SD 6-10).



Plate 11. Influence of water regime on rice (IR54) growth in Louisiana-3 soil (AFD1 = SD 0/4/8; AFD2 = SD 2/6/10; AFD3 = SD 0-4; AFD4 = SD 4-8; AFD5 = SD 6-10).

Table 65. Influence of six water regimes on the dry matter yield of eight-week-old shoot and straw at harvest of rice (IR54) in four soils.

	Maahas-1	Maahas-2	Luisiana-1	Luisiana-3	Mean	
<u>Dry matter yield of shoots (g/pot)</u>						
CF	31.0 A	27.0 A	6.2 A	11.4 A	18.9 A	
SD 0-4	8.5 C	14.7 C	13.1 A	7.3 A	10.9 B	
SD 4-8	12.4 C	24.0 AB	7.3 A	5.0 A	12.2 B	
SD 6-10	33.3 A	27.0 A	6.7 A	9.2 A	19.1 A	
SD 0/4/8	21.5 B	26.7 A	7.7 A	11.3 A	16.8 A	
SD 2/6/10	14.1 BC	16.5 BC	11.5 A	7.1 A	12.3 B	
Mean	20.1	22.7	8.7	8.5		
<u>Straw yield at harvest (g/pot)</u>						
CF	52.6 A	51.6 A	37.4 B	39.8 A	45.4 A	
SD 0-4	17.5 C	24.6 B	34.9 B	29.6 A	26.7 D	
SD 4-8	37.2 B	49.5 A	49.7 A	29.1 A	41.4 AB	
SD 6-10	50.9 A	45.8 A	37.4 B	33.1 A	41.8 AB	
SD 0/4/8	28.9 BC	34.2 B	54.4 A	36.5 A	38.5 BC	
SD 2/6/10	30.7 B	25.8 B	44.1 AB	30.9 A	32.9 C	
Mean	36.3	38.6	43.0	33.2		
	Shoot			Straw yield		
	S	W	SxW	S	W	SxW
SE m±	1.6	1.9	3.9	2.4	2.9	5.8
LSD (0.05)	3.2	3.9	7.8	4.7	5.8	11.6
LSD (0.01)	4.3	5.2	10.5	6.3	7.8	15.5

*In a column treatment means having a common letter are not significantly different by DMRT at alpha 5%.

Grain yield

Soil types, water regimes and their interaction influenced the grain yields significantly (Table 66). Grain yields in the four soils followed the order Maahas-2 = Maahas-1 > Luisiana-1 > Luisiana-3 (Table 66). Soil drying at any stage decreased rice grain yield in Maahas-1 soil. This yield reduction ranged from 34.0% in SD 6-10 to as high as 78.5% in SD 0-4 (Table 66). In Maahas-2 soil also, soil drying decreased rice grain yields to different extents depending upon the time and duration of drying and here the yield reduction ranged from 19.4% to 66.4% (Table 66). In the Luisiana-3, soil drying decreased rice grain yield ranging from 20.8% to 55.1%. In Luisiana-1 soil, soil drying increased grain yield instead of decreasing it. The grain yield increase due to soil drying ranged from 33.5% to as high as 76.3% (Table 66). This increase in grain yield appears to be related to decrease in water soluble Fe^{2+} due to soil drying in this soil (Fig. 64C).

In experiment 3, compared to the continuously flooded water regime, soil drying and reflooding increased rice grain yield in S and Zn deficient Maahas-2 soil, but when these elements were added to the soil, alternate soil drying and reflooding water regime significantly decreased rice grain yield.

Table 66. Influence of six water regimes on the grain yield and Δ GY* of rice (IR54) grown in four soils.

	Maahas-1		Maahas-2		Luisiana-1		Luisiana-3		Mean grain yield (g/pot)
	Grain yield (g/pot)	Δ GY (%)	Grain yield (g/pot)	Δ GY (%)	Grain yield (g/pot)	Δ GY (%)	Grain yield (g/pot)	Δ GY (%)	
	69.4 A	-	64.3 A	-	24.5 B	-	30.3 A	-	47.1 A
0-4	14.9 D	-78.5	21.6 D	-66.4	35.5 AB	+44.9	18.4 AB	-39.3	22.6 D
4-8	32.1 C	-53.7	51.8 B	-19.4	43.2 A	+76.3	13.6 B	-55.1	35.2 AB
5-10	45.8 B	-34.0	50.4 B	-21.6	23.5 B	-4.1	20.3 AB	-33.0	35.0 B
0/4/8	37.6 BC	-45.8	26.5 CD	-58.8	34.1 AB	+39.2	16.4 B	-45.9	30.4 BC
2/6/10	29.6 C	-57.3	35.2 C	-45.2	32.7 AB	+33.5	24.0 B	-20.8	28.6 C
m	38.2	-53.9	41.6	-42.3	32.3	+38.0	20.5	-38.8	
	S	W	SxW						
m±	2.3	2.8	5.7						
1 (0.05)	4.6	5.7	11.4						
1 (0.01)	6.2	7.6	15.2						

*a column treatment means having a common letter are not significantly different by T at alpha 5%.

$$\Delta \text{GY} = \frac{[(\text{Yield in a treatment}) - (\text{Yield in CF})]}{\text{Yield in CF}} \times 100$$

Straw yield

Soil type, water regime and their interaction significantly influenced the straw yield of rice (Table 65). Highest straw yield was obtained in Luisiana-1 soil while the lowest was obtained in Luisiana-3 soil. Soil drying decreased straw yields in both the Maahas soils while it increased straw yield in Luisiana-1 soil. In Luisiana-3 soil, however, soil drying had no significant effect on rice straw yields (Table 65).

Experiment 6

Influence of Six Water Regimes and Three Nitrogen Application
Methods on Growth and Mineral Nutrition of
Rice Under Field Conditions

Influence of different water regimes on the chemical kinetics of several soils in relation to growth and mineral nutrition of rice were studied in detail in the greenhouse. In order to see the effect of variable water regimes under field condition an experiment was conducted in the IRRI farm during the 1986 dry season. In this experiment three methods of nitrogen fertilizer application were also tested.

MATERIALS AND METHODS

The experiment was conducted in Block M14 of the IRRI farm, the collection site of the Maahas-1 soil for the greenhouse experiments. This experiment was conducted during the dry season (1986) to achieve better control of water management. Some characteristics of the soil are presented in Table 2.

Experiment set up

The experiment was laid out in a 6 x 3 factorial randomized complete block design with four replications.

a. Water regimes

- i. Continuously flooded (CF)
- ii. Four weeks soil drying imposed on the day of transplanting and reflooding (SD 0-4)
- iii. Four weeks soil drying imposed at 4 WAT and reflooding (SD 4-8)

- iv. Four weeks soil drying imposed at 6 WAT and reflooding (SD 6-10)
- v. Alternate soil drying and reflooding for 2 weeks imposed on the day of transplanting, 4 and 8 WAT (SD 0/4/8)
- vi. Alternate soil drying and reflooding for 2 weeks imposed at 2, 6 and 10 WAT (SD 2/6/10)
- b. Nitrogen application method. Three methods of nitrogen fertilizer application were tested.
 - i. 90 kg N/ha (as urea) applied in two splits, $\frac{1}{2}$ as basal and $\frac{1}{2}$ at 45 days after transplanting (DT) (N1)
 - ii. 90 kg N/ha (as urea) applied in three splits, $\frac{1}{3}$ as basal, $\frac{1}{3}$ at 2 WAT and $\frac{1}{3}$ at 45 DT (N2)
 - iii. 90 kg N/ha (as urea) applied in four splits, $\frac{1}{4}$ as basal, $\frac{1}{4}$ at 2 WAT, $\frac{1}{4}$ at 4 WAT and $\frac{1}{4}$ at 6 WAT (N3)

Land preparation

The entire field (90 m x 25 m) was plowed and kept submerged for 2 weeks. Thereafter, the field was plowed again, harrowed and levelled. Rectangular plots of 6.5 m x 3.5 m were constructed. All the plots were surrounded by 0.50 m wide bunds to minimize seepage of water into the adjacent plots (Fig. 70). Nitrogen (as urea) at the specified rates, and P and K at the rate of 25 and 50 kg/ha in the form of single superphosphate (16% P_2O_5) and muriate of potash (50% K_2O) respectively were applied evenly to each plot and mixed thoroughly with the soil using a power weeder one day before transplanting of rice seedlings.

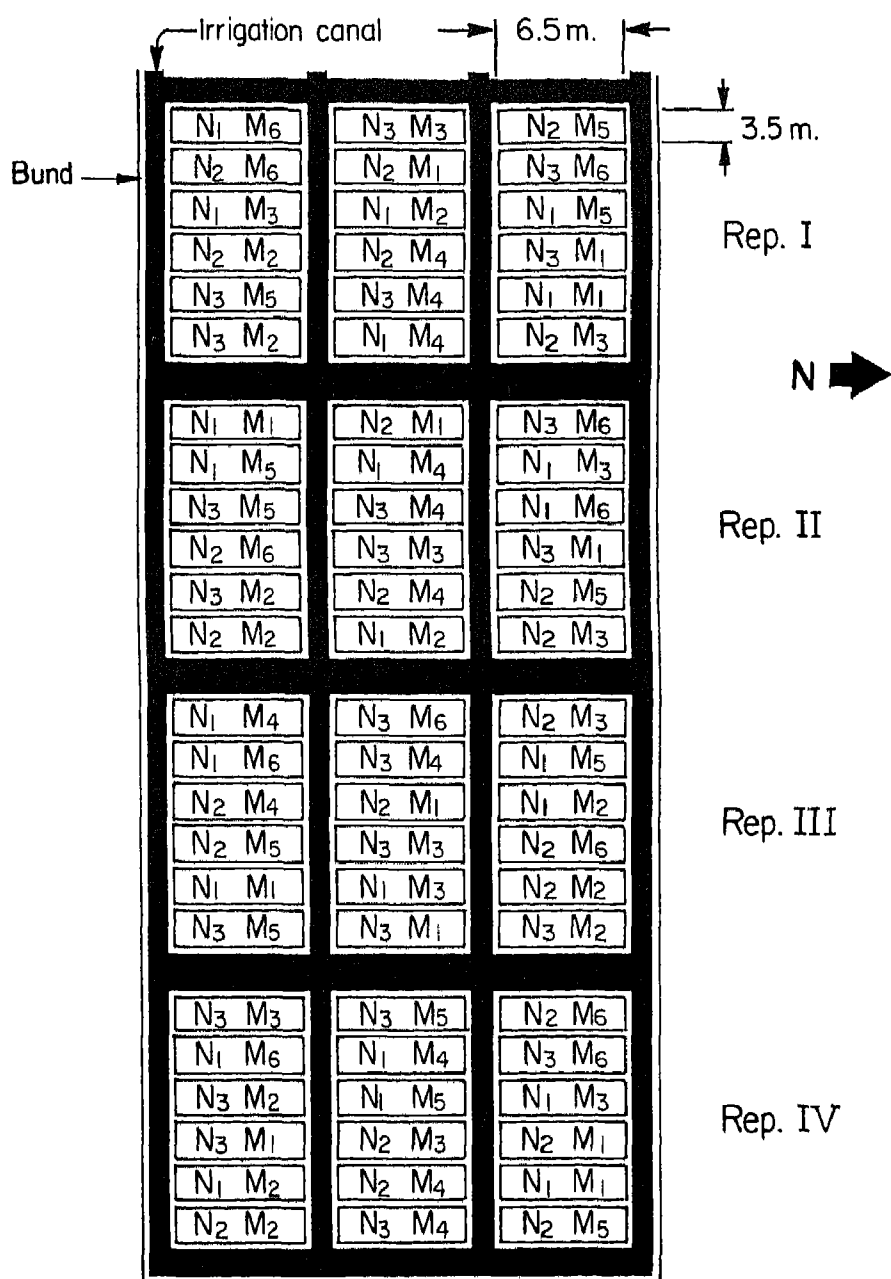


Fig. 70. Lay-out of the experimental plots in the field, Block M-14, IRRRI Farm.

(M₁ = CF; M₂ = SD 0-4;
 M₃ = SD 4-8; M₄ = SD 6-10;
 M₅ = SD 0/4/8; M₆ = SD 2/6/10)

Transplanting

Seedlings of IR64 were raised in wet seedbed and healthy 21-day-old seedlings were transplanted at 20 cm x 20 cm spacing. The seedlings were given a "root-dip" in 2% ZnO suspension before transplanting to prevent Zn deficiency.

Weeding

Granular herbicide formulations Saturn and Lambast at the rate of 10 kg and 5 kg/ha respectively were applied to the plots at 1 WAT to control weed emergence. All the plots were kept weed free by regular handweeding.

Pesticide application

A granular broad-spectrum insecticide (Furadan) at the rate of 60 kg/ha was applied to the field during land preparation. Two sprayings of 'Azodrin' was done at the recommended dose.

Water regime maintainance

To ensure that 3-5 cm standing water was always maintained on the flooded plots, the plots were irrigated thrice a week. In plots receiving drying treatments, irrigation was applied on the appropriate date and maintained for specified period. During the drying period irrigation to saturate was given when cracks started developing in the plots.

Sampling of plants

Four hills of plants from each plot were harvested at 4, 6, 8 and 10 WAT from four sides of the plots. These samples were taken outside the inner 5 m² area marked for final harvesting for grain yield determination.

Harvesting

At maturity, panicles of 150 hills from the 5 m² area were harvested for grain yield determination. Another 25 hills of plants from 1 m² area were harvested for straw yield determinations. After threshing, the grains from the total 6 m² area were mixed. The straw and grains were dried in an open drier and then weighed. Grain yields were corrected to 14% moisture content and expressed in kg/ha.

Measurement of yield components

At harvest, 10 hills from each plot were randomly harvested. These were used to measure plant height, number of panicles and percent unfilled grains. The straw of these plants were combined, washed thoroughly and kept for analysis.

Plant analyses

The plant samples collected at 4, 6, 8 and 10 WAT and straw at harvest were washed thoroughly, dried, cut into small pieces and ground following the procedures described in experiment 1. All these samples were analyzed for different nutrient concentration following methods described in the earlier experiments.

RESULTS AND DISCUSSION

Mineral Nutrition of Rice at Different Stages of Growth

Nitrogen

Water regime did not significantly affect the N concentration of 4 week-old rice shoot but higher basal dose of N application (N₁) resulted in significantly higher N in shoot at this stage (Table 67).

At 6 WAT stage, rice shoots in all the treatments had less than critical limit of 2.5% N for N deficiency at this stage (Yoshida et al., 1976) (Table 68). Soil drying for 2 weeks (SD 2/6/10; SD 4-8) or 4 weeks (SD 0-4) did not show consistent influence on N concentration of shoot. While shoot N concentration under SD 2/6/10 was significantly lower than that in CF, the N concentration of shoot in SD 0-4 and SD 4-8 were comparable to that in CF (Table 68). However, soil drying for 2 weeks at 2 WAT (SD 2/6/10) and reflooding significantly decreased the N concentration of 6 week-old shoot. At 6 WAT, N concentration of shoot under 3 (N₂) and 4 split (N₃) application of N were higher compared to that under 2 split (N₁) applications (Table 68).

At 8 WAT also, the plants were deficient in N in all the treatments (Table 69) and N concentration of shoot under flooded and dried water regimes were comparable to that in continuously flooded water regime. At this stage when the full dose of 90 kg N/ha was applied in 2, 3 or 4 splits (N₁, N₂, N₃), the N concentration of shoot was significantly higher for 2 and 3 splits (N₁ and N₂) compared to 4 splits (N₃).

At 10 WAT also the plants in all the treatments were deficient in nitrogen and water regime did not significantly influence N concentrations (Table 70). At this stage, unlike at 8 WAT, the N

Table 67. Influence of six water regimes and three N application methods on the mineral nutrient concentration of four-week-old rice shoots in Maahas-1 soil.

	N	P	K	Ca	Mg	SiO ₂	Mn	Zn	Cu
	%				ppm				
	<u>Water regimes (W)^a</u>								
CF	3.37 A	0.257 AB	2.88 A	0.095 B	0.201 AB	13.2 B	325.8 A	18.8 A	9.4 C
SD 0-4	3.32 A	0.267 A	2.64 BC	0.114 AB	0.199 AB	14.8 A	317.9 A	19.9 A	11.8 A
SD 4-8	3.36 A	0.250 B	2.72 A-C	0.110 AB	0.218 A	13.9 B	341.5 A	20.3 A	10.7 A-C
SD 6-10	3.28 A	0.249 B	2.67 A-C	0.095 B	0.187 B	13.6 B	336.3 A	18.3 A	10.4 A-C
SD 0/4/8	3.20 A	0.259 AB	2.81 AB	0.120 A	0.217 A	13.9 B	336.7 A	19.8 A	11.3 AB
SD 2/6/10	3.37 A	0.264 A	2.53 C	0.112 AB	0.213 AB	15.1 A	335.4 A	19.4 A	12.0 A
	<u>N application methods (N)^b</u>								
N1	3.49 A	0.261 A	2.79 A	0.109 A	0.215 A	14.4 A	327.6 A	21.3 A	11.8 A
N2	3.24 B	0.257 A	2.77 A	0.102 A	0.196 A	14.1 AB	332.1 A	18.9 B	10.8 B
N3	3.23 B	0.256 A	2.56 B	0.112 A	0.207 A	13.8 B	337.1 A	18.0 B	10.1 B
LSD (0.05)									
For W means	ns	0.011	0.19	0.019	ns	0.8	ns	ns	1.2
For N means	0.14	ns	0.14	ns	ns	ns	ns	1.7	0.9

^aThe values are mean of three N application methods with four replications each.

^bThe values are mean of six water regimes with four replications each.

In a column W (or N) means having a common letter are not significantly different by DMRT at alpha 5%.

Table 68. Influence of six water regimes and three N application methods on the mineral nutrient concentration of six-week-old rice shoots in Maahas-1 soil.

	N	P	K	Ca	Mg	SiO ₂	Mn	Zn	Cu
	<u>Water regimes (W)^a</u>								
CF	2.32 B	0.224 A	1.74 BC	0.072 C	0.240 C	13.4 B	253.7 C	20.3 B	9.4 B
SD 0-4	2.29 BC	0.210 B	1.87 B	0.072 C	0.232 C	13.7 B	292.9 AB	23.4 AB	9.6 B
SD 4-8	2.35 AB	0.219 AB	1.74 BC	0.087 A	0.261 A	16.1 A	283.3 A-C	28.8 A	11.4 A
SD 6-10	2.24 BC	0.222 A	1.66 C	0.076 BC	0.245 BC	13.8 B	270.0 BC	22.6 AB	9.6 B
SD 0/4/8	2.45 A	0.219 AB	2.18 A	0.082 AB	0.256 AB	16.0 A	310.4 A	20.8 B	10.9 A
SD 2/6/10	2.20 C	0.213 B	2.12 A	0.074 C	0.240 C	14.6 B	272.9 BC	25.3 AB	8.3 C
	<u>N application methods (N)^b</u>								
N1	2.15 B	0.202 B	1.69 C	0.083 A	0.245 A	14.9 A	276.7 AB	24.1 A	9.3 B
N2	2.42 A	0.222 A	2.07 A	0.072 C	0.245 A	14.7 A	295.2 A	24.8 A	10.6 A
N3	2.36 A	0.227 A	1.89 B	0.077 B	0.247 A	14.2 A	269.8 B	21.6 A	9.7 B
LSD (0.05)									
For W means	0.12	0.009	0.14	0.007	0.014	1.3	28.5	5.9	0.7
For N means	0.08	0.006	0.10	0.005	ns	ns	20.1	ns	0.5

^aThe values are mean of three N application methods with four replications each.

^bThe values are mean of six water regimes with four replications each.

In a column W (or N) means having a common letter are not significantly different by DMRT at alpha 5%.

Table 69. Influence of six water regimes and three N application methods on the mineral nutrient concentration of eight-week-old rice shoots in Maahas-1 soil.

	N	P	K	Ca	Mg	SiO ₂	Mn	Zn	Cu
	%								
	ppm								
	<u>Water regimes (W)^a</u>								
CF	1.95 AB	0.266 A	3.01 A	0.095 A	0.261 A	11.6 C	375.4 AB	30.4 BC	14.4 C
SD 0-4	1.89 B	0.259 AB	3.01 A	0.098 A	0.240 B	12.0 C	352.5 A-C	46.8 A	15.1 C
SD 4-8	2.02 A	0.248 BC	2.94 A	0.103 A	0.255 AB	13.6 AB	319.6 BC	26.5 C	18.9 A
SD 6-10	1.92 AB	0.237 C	2.88 A	0.107 A	0.261 A	14.0 A	301.7 C	23.2 C	15.4 BC
SD 0/4/8	1.88 B	0.251 B	2.89 A	0.093 A	0.240 B	13.1 B	398.4 A	27.5 BC	17.2 AB
SD 2/6/10	1.92 AB	0.252 B	3.00 A	0.106 A	0.259 A	13.4 AB	314.2 C	35.7 B	16.3 BC
	<u>N application methods (N)^b</u>								
N1	2.03 A	0.260 A	2.93 AB	0.098 A	0.264 A	13.2 A	341.0 A	36.3 A	16.0 AB
N2	1.95 A	0.247 B	3.05 A	0.096 A	0.249 B	13.0 A	347.7 A	27.1 B	17.1 A
N3	1.81 B	0.249 B	2.88 B	0.107 A	0.246 B	12.7 A	342.1 A	31.6 AB	15.5 B
LSD (0.05)									
For W means	ns	0.012	ns	ns	0.016	0.8	54.2	8.3	1.9
For N means	0.08	0.009	0.12	ns	0.011	ns	ns	5.8	1.4

^aThe values are mean of three N application methods with four replications each.

^bThe values are mean of six water regimes with four replications each.

In a column W (or N) means having a common letter are not significantly different by DMRT at alpha 5%.

Table 70. Influence of six water regimes and three N application methods on the mineral nutrient concentration of ten-week-old rice shoots in Maahas-1 soil.

	N	P	K	Ca	Mg	SiO ₂	Mn	Zn	Cu
	%								
	ppm								

concentration of shoot was significantly higher in N_3 compared to N_1 and N_2 .

The N concentration of straw at maturity was significantly influenced by water regimes as well as N application methods. Nitrogen concentrations of mature straw, in general, were lower in dried and reflooded treatments compared to continuously flooded water regime and the N concentration of straw was highest when N was applied in four splits (N_3) (Table 71).

The same soil was used in greenhouse experiment (Experiment 5) with similar treatments. The values of N concentration in 8 week-old shoot and mature straw were generally higher in the greenhouse. This was due to higher N application rates in the greenhouse (100 mg N/kg soil in the greenhouse compared to 45 mg N/kg soil in the field).

Phosphorus

At 4 WAT stage, the P concentration of shoot in continuously flooded water regime was similar to that under alternately flooded and dried water regimes (SD 0-4; SD 0/4/8 and SD 2/6/10) (Table 67). Nitrogen application methods also did not significantly influence the P concentration of shoot at this stage.

At 6 WAT rice shoots under soil drying and reflooding treatments (SD 0-4; SD 2/6/10) had significantly lower P than under continuously flooded water regime (Table 68). Three and 4 split application of N (N_2 and N_3) resulted in higher P concentration in tissue as compared to 2 splits (N_1). Decreased availability of phosphorus due to soil drying and reflooding was observed in the earlier experiments conducted

Table 71. Influence of six water regimes and three N application methods on the mineral nutrient concentration of straw at maturity in Maahas-1 soil.

	N	P	K	Ca	Mg	SiO ₂	Na	Zn	Cu
	%								
	ppm								
	<u>Water regimes (%)^a</u>								
CF	0.75 A	0.102 AB	2.49 A-C	0.094 A	0.200 A	16.8 B	194.6 C	26.0 B	13.2 B
SD 0-4	0.73 AB	0.104 A	2.55 A-C	0.081 B	0.190 A	16.7 B	261.3 C	26.2 B	13.9 B
SD 4-8	0.65 C	0.086 BC	2.61 AB	0.091 A	0.182 A	19.5 A	463.3 AF	31.8 AB	16.3 A
SD 6-10	0.67 BC	0.094 A-C	2.69 A	0.089 AF	0.189 A	19.6 A	499.6 A	34.6 A	17.1 A
SD 0/4/8	0.63 C	0.088 A-C	2.40 C	0.091 A	0.164 BC	18.4 A	328.3 FC	29.9 AB	13.8 B
SD 2/6/10	0.63 C	0.083 C	2.45 BC	0.089 AB	0.162 C	19.5 A	458.3 AB	31.9 AB	15.5 AB
	<u>N application methods (N)^b</u>								
N1	0.65 B	0.089 A	2.53 A	0.090 A	0.167 B	18.9 A	356.3 A	27.6 B	15.7 A
N2	0.67 AB	0.097 A	2.54 A	0.088 A	0.162 B	18.4 A	365.6 A	29.1 B	14.9 A
N3	0.71 A	0.093 A	2.52 A	0.090 A	0.214 A	18.0 A	380.8 A	33.4 A	14.2 A
LSD (0.05)									
For W means	0.06	0.015	0.18	0.008	0.019	1.4	133.0	5.9	2.2
For N means	0.04	ns	ns	ns	0.013	ns	ns	4.2	ns

^aThe values are mean of three N application methods with four replications each.

^bThe values are mean of six water regimes with four replications each.

In a column W (or N) means having a common letter are not significantly different by DMRT at alpha 5%.

in the greenhouse. So, here also, the lower P concentration in shoot was due to lower P availability under alternately flooded and dried conditions. The higher P concentration, in shoot in N_2 and N_3 were probably associated with higher N status of the plant.

At 8 WAT stage the P concentration of shoots were significantly lower under alternate flooding and drying conditions (SD 4-8; SD 6-10; SD 0/4/8 and SD 2/6/10) compared to continuously flooding water regime (CF) (Table 69). These observations are in conformity with those in the greenhouse with the same soil (Experiment 5). At this stage when the full dose of 90 kg N/ha was applied, plants grown with N application in 2 splits (N_1) had significantly higher P compared to 3 or 4 splits (N_2 and N_3). It is worth mentioning that the P concentrations in shoots at 8 WAT were higher in the field compared to those in the greenhouse.

At 10 WAT stage however, the P concentration of shoots under different water regimes were comparable (Table 70). Here again like that of N the P concentration of shoots were higher in N_3 and N_2 compared to N_1 (Table 70).

The P concentration of straw at maturity (except in SD 0-4) was generally lower under drying and reflooding water regime conditions. However, this difference was significant only in SD 2/6/10 (Table 71). This, again, is in conformity with the results of the greenhouse experiment (experiment 5) using the same soil. Nitrogen application method did not significantly influence the P concentration of straw at maturity (Table 71).

Potassium

At 4 WAT stage, the K concentration of shoot was highest under continuously flooded water regime (CF) and soil drying for 2 weeks in the beginning (SD 0/4/8) did not significantly decrease it (Table 67). However, soil drying for 4 weeks in the beginning (SD 0-4) or for 2 weeks at 2 WAT (SD 2/6/10) significantly decreased the K concentration of rice shoot. The K concentration of shoot was lowest where N was applied in 4 splits (N_3) compared to 2 and 3 split applications (N_1 and N_2) (Table 67).

At 6 WAT stage, 2 weeks soil drying and reflooding at 2 WAT (SD 2/6/10) and 2 soil drying and reflooding cycles of 2 weeks each (SD 0/4/8) significantly increased the K concentration of shoot compared to that under continuously flooded water regime (Table 68). The K concentration of shoot under other water regime treatments were comparable. The K concentration of shoot was lowest in N_1 among the 3 N application methods (Table 68).

At 8 WAT stage, the K concentrations of shoots under different treatments were not significantly different (Table 69). Comparison of the concentration of K in shoot at this stage under greenhouse (experiment 5) and field with the same soil reveals generally lower concentration of K under field condition. It should be noted however, that the rice variety used in greenhouse was IR54 while that in the field was IR64.

At 10 WAT stage K concentration of shoot was lowest under continuously flooded water regime (CF) and drying for 2 or 4 weeks in general increased this (Table 70). However, this difference was

statistically significant only in SD 2/6/10 water regime. Like P, the K concentration of shoot at this stage was highest in N_3 followed by N_2 and N_1 (Table 70).

At maturity, K concentrations of straw under different water regimes were comparable and N application methods did not significantly influence this (Table 71). Here again, its worth mentioning that the K concentration of straw in the field experiment was generally lower than that in the greenhouse experiment using the same soil.

Calcium

At 4 WAT stage, the Ca concentration of shoot was lowest under continuously flooded water regime and 2 weeks soil drying from the day of transplanting and reflooding (SD 0/4/8) significantly increased it (Table 67). Nitrogen application methods did not significantly influence the Ca concentration of shoot at this stage.

At 6 WAT stage, Ca concentration of shoot under SD 4-8 water regime was higher compared to continuously flooded water regime (Table 68). Under other water regime treatments, the Ca concentration of shoots were comparable to that under continuously flooded water regime. The Ca concentration of shoot was highest in N_1 followed by N_3 and N_2 (Table 68). Its interesting to note that highest concentration of Ca in shoot was associated with lowest concentration of K and vice-versa suggesting a K-Ca antagonism in plant uptake.

At 8 WAT stage, neither water regime nor N application method significantly influenced the Ca concentration of shoot (Table 69). In contrast to the field results, the Ca concentration of shoot at this

stage in the greenhouse experiment decreased due to soil drying (Tables 52 and 69). At this stage also the antagonistic relationship between K and Ca was evident. The Ca concentration of shoot at this stage, was much higher in the greenhouse conditions than under field conditions.

At 10 WAT stage neither water regime nor N application method significantly influenced the Ca concentration of shoot (Table 70).

At maturity, in all the treatments, Ca concentration of straw were below the critical level of 0.15% (Yoshida et al., 1976) indicating possible Ca deficiency (Table 71). Drying for 4 weeks from transplanting (SD 0-4) decreased it further and aggravated the problem. Nitrogen application method did not significantly influence the Ca concentration of straw. In the greenhouse experiment however, the Ca concentration of straw at maturity was higher than the critical limit of 0.15% under continuously flooded condition which decreased to marginally deficient range under 4 weeks soil drying treatment imposed at the start (SD 0-4) (Table 71).

Magnesium

Neither water regime nor N application methods influence the Mg concentration of 4 week-old rice shoots.

At 6 WAT stage Mg concentration of shoot was highest in SD 4-8 water regime (Table 68). Magnesium concentration of shoot under SD 0/4/8 was comparable to that under SD 4-8. In all other treatments Mg concentrations of shoots were comparable. Nitrogen application methods did not significantly influence the Mg concentration of shoot at this stage.

At 8 WAT stage, Mg concentration of shoot was lowest when soil drying was imposed for 4 weeks in the beginning (SD 0-4) or 2 weeks soil drying cycles were imposed (SD 0/4/8) (Table 69). The Mg concentrations of shoots in all other treatments were comparable. Highest Mg concentration in shoot was observed under N_1 (Table 69).

At 10 WAT stage, the Mg concentration of shoot was not influenced by water regimes (Table 70). The Mg concentration of shoot was highest in N_3 followed by N_1 and N_2 (Table 70).

At maturity, Mg concentration of straw was highest under continuously flooded water regime and 3 cycles of soil drying and reflooding (SD 0/4/8; SD 2/6/10) significantly decreased it (Table 71). At this stage again the Mg concentration was highest with 4 split applications of N (N_3) (Table 71).

Magnesium concentration in 8 week-old shoot and were generally lower in the field compared to that in the greenhouse (Tables 53,54,71).

Manganese

At 4 WAT stage neither water regime nor N application methods significantly influenced the Mn concentration of shoot (Table 67).

At 6 WAT, the Mn concentration in shoot was lowest under continuously flooded water regime (Table 68). Soil drying for 2 weeks did not increase it but 4 weeks of cumulative soil drying (SD 0-4; SD 0/4/8) significantly increased the Mn concentration of shoot (Table 68). Higher rates of N application (as in N_3 , 3/4 of the total dose of 90 kg N/ha) was applied before this stage) was found to reduce Mn concentration in shoot (Table 68).

At 8 WAT, 2 weeks soil drying from 6 WAT (SD 6-10; SD 2/6/10) had lowest Mn concentration in shoot but in other treatments Mn concentrations were comparable (Table 69). Nitrogen application method had no influence on Mn concentration of shoot at this stage. The Mn concentration of shoot at this stage under the greenhouse and field conditions were comparable (Tables 57, 69).

At 10 WAT the Mn concentration of shoot under continuously flooded water regime was comparable to that under SD 0-4 and SD 0/4/8 while other soil drying treatments significantly increased the Mn concentration of shoot (Table 70). Nitrogen application methods, however, did not influence Mn concentration of shoot at this stage.

At maturity, the Mn concentration of straw increased under soil drying and reflooding conditions compared to continuously flooded water regime but N application methods had no effect on it (Table 71).

The Mn concentration in straw at maturity was comparatively lower under field conditions than under greenhouse conditions (Tables 58, 71).

Zinc

At 4 WAT stage, the Zn concentration of shoot in all treatments were quite low (Table 67). Water regimes did not significantly influence the Zn status of shoot at this stage. Higher basal dose of N application favored Zn uptake by plants as was evident from the highest Zn concentration of shoot under N_1 treatment.

At 6 WAT stage, the Zn concentration of shoot under continuously flooded water regime was marginal (critical limit 19 ppm, Rattan and Shukla, 1984) and soil drying and reflooding slightly improved the Zn

status of shoots (Table 68). Nitrogen application method had no significant influence on Zn concentration of shoot at this stage.

At 8 WAT stage, the Zn concentration of shoot increased well above the critical level of 19 ppm (Table 69). At this stage the Zn concentrations of shoots were above the deficiency range. Soil drying for 4 weeks in the beginning (SD 0-4) significantly increased Zn concentration of shoot but soil drying for 2 weeks just prior to sampling (SD 4-8; SD 6-10; SD 0/4/8; SD 2/6/10) did not significantly increase Zn concentration of shoots (Table 69).

At 10 WAT stage Zn concentration of shoot was highest in SD 6-10 but in all other water regimes Zn concentration was comparable (Table 70).

At maturity, soil drying and reflooding generally improved the Zn status of straw (Table 71). Zinc concentration of mature straw was highest in N_3 followed by N_2 and N_1 (Table 71). The Zn concentration of rice straw at maturity was much higher under greenhouse conditions than in the field conditions (Tables 59,60,69,71). Root-dip method was probably not very effective in correcting Zn deficiency in the field but it was effective in the greenhouse.

Copper

At 4 WAT stage, compared to that under continuously flooded water regime, the Cu concentrations of shoots were higher in soil drying and reflooding water regimes (SD 0-4; SD 2/6/10) (Table 67). Lower basal dose of N decreased Cu uptake by plant at this stage as was evident from the lower Cu concentration of shoot under N_2 and N_3 treatments (Table 67).

At 6 WAT stage, 2 weeks soil drying at 4 WAT (SD 4-8; SD 0/4/8) increased the Cu concentration of shoot compared to that under continuously flooded water regime while 2 weeks soil drying at 2 WAT (SD 2/6/10) significantly decreased Cu concentration in shoot (Table 68). In the other treatments Cu concentrations of shoots were comparable.

At 8 WAT stage Cu concentration of shoots increased by soil drying and reflooding (Table 69). Of the 3 N application methods, the Cu concentration of shoot was higher in N_2 followed by N_1 and N_3 (Table 69).

At 10 WAT stage, however, neither water regime nor N application methods significantly influenced the Cu concentration of shoot (Table 70).

At maturity, the Cu concentration of straw was lowest under continuously flooded water regime and soil drying and reflooding generally increased the Cu concentration of straw (Table 71). Nitrogen application methods, however, did not significantly influence Cu concentration of straw (Table 71).

Silica (SiO_2)

At 4 WAT stage, SiO_2 concentration of shoot was lowest under continuously flooded water regime and soil drying for 2 weeks at 2 WAT and reflooding (SD 0-4; SD 2/6/10) increased it (Table 67). Nitrogen application method did not significantly influence the SiO_2 concentration of shoot.

At 6 WAT stage, SiO_2 concentration in shoot was lowest under continuously flooded water regime and 2 weeks soil drying from 4 WAT and reflooding (SD 4-8; SD 0/4/8) significantly increased it. Silica concentration of shoot under other drying treatments were comparable to that under continuously flooded water regime. Nitrogen application method did not significantly influence the SiO_2 concentration of shoot at this stage (Table 68).

At 8 and 10 WAT stages, the SiO_2 concentration of shoot were lowest under continuously flooded water regime. Soil drying and reflooding in general increased the SiO_2 concentration of shoot at both these stages. Nitrogen application methods, however, did not significantly influence the SiO_2 concentration of shoots at both the stages (Tables 69, 70).

At maturity, the SiO_2 concentration of straw was lowest under continuously flooded water regime and soil drying for 2 or 4 weeks (except SD 0-4) generally increased the SiO_2 concentration of straw. Nitrogen application methods did not significantly influence the SiO_2 concentration of straw (Table 71).

Summary of Mineral Nutrition of Rice Under Different
Water Regimes and With Different N
application methods

Analyses of plant samples at different stages of growth revealed the following:

1. N deficiency under all the water regime treatments and soil drying and reflooding aggravated the problem. In this soil, 90 kg N/ha was not sufficient for good crop growth.

- ii. Among the three N application methods tested, N application in 3 splits was in general most efficient.
- iii. Soil drying and reflooding particularly between 2 and 8 WAT decreased P availability to plants.
- iv. K nutrition was probably not a problem under alternate flooding and drying conditions.
- v. Plant analyses suggested Ca deficiency under alternate flooding and drying conditions and was probably one of the growth limiting factors.
- vi. Mg nutrition was not a problem under alternate flooding and drying water regimes.
- vii. Mn concentration in plant increased due to soil drying and reflooding but values were below the critical limit of Mn toxicity.
- viii. In spite of dipping the roots in 2% ZnO suspension before transplanting, the Zn concentration in shoots were marginal in continuously flooded water regime. Soil drying and reflooded helped to increase Zn concentration in plant tissues.
- ix. Concentration of Cu in tissues probably were not limiting under continuously flooded water regime

Growth and Yield of Rice

Visual symptoms

Under continuously flooded water regime the plants grew vigorously during the early vegetative growth period but 6 WAT onwards the plants showed symptoms of N deficiency. Application of N in three splits

(N₂) slightly improved plant growth in all the water regimes. The 90 kg N/ha rate was not sufficient for good crop growth in this soil.

Plant height

Height of the plants at maturity are presented in Table 72. Water regime did not significantly influence the plant height. Among the N application methods, plants were tallest in N₂.

Panicle number

Number of panicles per hill was not significantly influenced by N application methods (Table 72). Soil drying and reflooding, in general, increased the number of panicles but these were smaller with more unfilled grained than under continuously flooded water regime.

Percent unfilled spikelets

Nitrogen application methods did not significantly affect the percent sterility of spikelets. Lowest amount of sterile grains were observed under continuously flooded water regime. Percent unfilled spikelets in SD 0-4 and SD 2/6/10 were also comparable to that in CF. Soil drying and reflooding at the later stages (SD 4-8; SD 6-10 and SD 0/4/8) resulted in higher percentage of unfilled spikelets (Table 72).

Grain yield

The rice yield under continuously flooded condition was quite low (Table 73). Nitrogen deficiency and low Zn in plants were probably the main reasons for low yield level in continuously flooded water regime.

Table 72. Influence of six water regimes and three N application methods on the plant height (at harvest), panicle number and percentage of unfilled spikelets of rice (TR54) in Maahas-1 soil.

	CF	SD 0-4	SD 4-8	SD 6-10	SD 0/4/8	SD 2/6/10	Mean		
<u>Plant height (cm) at harvest</u>									
N1	76.9 A	75.1 A	76.9 A	73.9 A	75.0 A	76.2 A	75.6 b		
N2	78.1 A	77.5 A	77.2 A	75.8 A	76.5 A	78.5 A	77.3 a		
N3	76.9 A	75.6 A	76.0 A	75.2 A	74.9 A	76.0 A	75.8 b		
Mean	77.3 A	76.1 AB	76.7 AB	75.0 B	75.4 AB	76.9 AB			
<u>Number of panicles per hill</u>									
N1	15.2 BC	15.0 C	18.3 A	17.5 AB	16.9 A-C	17.0 A-C	16.7 a		
N2	15.7 A	15.7 A	17.5 A	17.5 A	16.8 A	16.4 A	16.6 a		
N3	15.1 A	15.8 A	17.3 A	17.1 A	15.2 A	16.8 A	16.2 a		
Mean	15.3 D	15.5 CD	17.7 A	17.4 AB	16.3 B-D	16.7 A-C			
<u>% Unfilled spikelets</u>									
N1	13.5 A	13.1 A	14.9 A	13.6 A	15.3 A	14.5 A	14.1 a		
N2	12.0 B	13.1 A	14.1 AB	14.9 AB	16.2 A	11.7 B	13.7 a		
N3	13.7 A	13.9 A	15.4 A	14.2 A	15.2 A	12.4 A	14.1 a		
Mean	13.1 B	13.4 B	14.8 AB	14.2 AB	15.6 A	12.9 B			
	Height			Panicles			% Unfilled spikelets		
	W	N	WxN	W	N	WxN	W	N	WxN
SE m±	0.9	0.6	1.5	0.6	0.4	1.1	1.0	0.7	1.7
LSD (0.05)	1.7	1.2	3.0	1.3	0.9	2.2	2.0	1.4	3.4

In a column N means having a common small letter and in a row W means having a common capital letter, are not significantly different by DMRT at alpha 5%.

Table 73. Influence of six water regimes and three N application methods on the grain and straw yield of rice (IR54) in Maahas-1 soil.

	CF	SD 0-4	SD 4-8	SD 6-10	SD 0/4/8	SD 2/6/10	Mean
<u>Grain yield (kg/ha)</u>							
N1	4622 A	4262 A	4772 A	4871 A	4240 A	4729 A	4583 a
N2	4908 A	4644 A	5109 A	5002 A	4528 A	4818 A	4835 a
N3	4789 A-C	4215 C	5057 AB	5111 A	4425 BC	4782 A-C	4730 a
Mean	4773 A	4374 B	4979 A	4995 A	4398 B	4776 A	
<u>Straw yield (kg/ha)</u>							
N1	5345 A	4310 A	5387 A	4972 A	4342 A	4712 A	4845 a
N2	4962 A	4962 A	5167 A	5027 A	5035 A	4877 A	5005 a
N3	4707 A	4437 A	4810 A	4992 A	4542 A	4465 A	4659 a
Mean	5005 A	4570 A	5121 A	4997 A	4640 A	4685 A	
<u>Grain yield</u>				<u>Straw yield</u>			
	W	N	WxN	W	N	WxN	
SEm±	173	123	300	277	196	479	
LSD (0.05)	348	246	603	556	393	963	

In a column N means having a common small letter and in a row W means having a common capital letter, are not significantly different by DMRT at alpha 5%.

Soil drying and reflooding resulted in N loss and thus aggravated the N deficiency problem under intermittently dried and reflooded water regimes. However, N application methods did not significantly influence rice grain yield. Soil drying for 4 weeks in the beginning (SD 0-4) and 3 soil drying cycles of 2 weeks each (SD 0/4/8) significantly decreased rice grain yield. Grain yield in the other water regimes were comparable.

Straw yield

Water regimes did not significantly influence the straw yield of rice. Similarly, the straw yields under the 3 N application methods were also not significantly different.

SUMMARY AND CONCLUSIONS

Rice yields in intermittently dried and reflooded lowlands are generally lower compared to that in continuously flooded lowlands. Poor yields of these soils are most commonly attributed to water stress and weed and pest and disease problems. Under intermittent dried and reflooded water regimes however, the solubility and availability of several mineral nutrients may be low or high. As a result plants may suffer from deficiency of some nutrients and toxicity of few others. Similarly, accumulation of reducing substances may inhibit rice growth and yield in continuously flooded soil, and drainage of the flooded soil might help to overcome this problem. Greenhouse and field experiments were therefore carried out to study the influence of different water regimes on chemical kinetics and rice growth in different Philippine rice soils.

In order to identify the unfavorable chemical factors under inadequate water supply, the chemical kinetics of a fertile Tropaequalf of pH 6.4 was studied under 18 different water regimes (Experiment 1). Results of the soil solution chemical kinetics study and plant analyses indicated lower availability of N, P, Fe and Si in dried and reflooded soils. The availability of K, Ca, Mg, Mn, Zn and Cu also decreased during the dry periods, but on reflooding, their availability increased. However, depending on the time and duration of drying, the availability of these elements could also become limiting under alternately dried and reflooded soils. As a result of these changes, grain yield of IR54 also decreased depending on the time and duration of soil drying. The grain yield reduction due to 2 weeks soil drying and reflooding at different

rice growing stages ranged from 7% to 56%, while that due to 4 weeks soil drying and reflooding ranged from 32% to 76%. Cycles of soil drying and reflooding resulted in grain yield decrease ranging from 51% to 63%. Drainage of 5 to 10 mm/day decreased grain yield by 7% instead of increasing it, while continuously saturated condition produced 19% less grains. These yield reductions in alternately dried and reflooded water regimes however, could not be attributed solely to the unfavorable soil chemical factors. It is possible that during the drying periods, the crop might have also suffered from water stress resulting in grain yield reduction.

In experiment 2, the influence of drainage and intermittent soil drying and reflooding on chemical kinetics of a potentially iron-toxic acid Tropudult in relation to mineral nutrition, growth and yield of rice (IR54) was studied. In addition to drainage and soil drying treatments, continuously saturated water regime was also included in these studies. Under continuously flooded condition, this soil was highly reduced. Water soluble oxidizable matter and Fe^{2+} were very high under continuously flooded water regime. Soil solution kinetics data showed lower concentration of NH_4^+-N , K^+ , Ca^{2+} , Mg^{2+} , and Fe^{2+} in soil solution under alternately dried and reflooded water regimes compared to that under continuously flooded water regime. But unlike in near neutral fertile Maahas-1 soil (experiment 1) the grain yield and total uptake of mineral nutrients were higher under dried and reflooded water regimes in this soil. Drainage of 5-10 mm/day and keeping the soil saturated, significantly increased grain yield and nutrient uptake. It is possible that in this soil, high reducing conditions under

continuously flooded water regime, could be a reason for the poor rice growth and lower rice yield under continuously flooded water regime.

In experiment 3, influence of soil drying and reflooding on the chemical kinetics of two Zn- and S-deficient soils and an acid Louisiana-2 soil (a Tropudult with comparatively less active iron than the Louisiana-1 soil) was studied in relation to mineral nutrition, and growth and yield of rice (IR54). The results of this study showed that influence of water regime on rice growth and yield is soil specific. In S- and Zn-deficient Maahas-2 soil, soil drying and reflooding increased the S uptake by plants, decreased the N:S ratio in shoot and straw at maturity, and increased grain yield. In Louisiana-2 soil, grain yield was highest under continuously flooded water regime, and soil drying and reflooding decreased grain yield. In San Manuel soil, the plants suffered from S deficiency under continuously flooded water regime while under alternately dried and reflooded water regime they suffered from N deficiency. Thus, the yields were not significantly different under the different water regimes.

Experiment 4 was conducted to further verify the effect of soil drying on rice growth and yield on six S- and Zn-deficient soils. In order to see whether soil drying and reflooding result in the improvement of S status of plants, an additional treatment with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ as S-source was included. Application of S to flooded soil increased both the S concentration in plant, and grain yield. Without S-addition, these parameters were lowest under continuously flooded water regime. Soil drying for 2 weeks at 4 and 8 WAT improved S nutrition of plants and significantly increased grain yield. Cutting

down the water availability from continuous submergence to continuous saturation, and soil drying for 2 weeks at 2 WAT and reflooding, did not significantly increase grain yield.

In experiment 5, in addition to N, P and K, S and Zn were also applied to the soils and influence of six water regimes on the chemical kinetics in relation to growth and yield of rice (IR54) in S- and Zn-deficient Maahas-2 soil was studied. In addition to Maahas-2 soil, a near neutral fertile soil (Maahas-1), a potentially Fe-toxic acid (Luisiana-1) and another acid soil collected from a lowland rice field (Luisiana-3, Paleaquult) were also used. In all the treatments, soils were treated with 0.25% (w/w) chopped rice straw to study if straw application would minimize chemical problems associated with high Eh in intermittent dried and reflooded water regimes. After addition of straw the soils were kept flooded for 2 weeks before transplanting of rice. Soil solution kinetics data showed increased soil reduction under continuously flooded water regime. Under continuously flooded water regime, water soluble SO_4^{2-} -S concentration decreased to almost negligible values in all soils while the concentration of water soluble Fe^{2+} went up to very high values only in Luisiana-1 soil. In spite of very low water soluble SO_4^{2-} -S in continuously flooded soils, the plants did not show S deficiency and the plants grew well in the S- and Zn-deficient Maahas-2 soil. Under continuously flooded water regime in Luisiana-1 soil, plant growth was poor and it improved on soil drying and reflooding. In the other three soils, plant growth was best under continuously flooded water regime, and soil drying and reflooding, resulted in poor plant growth. Soil drying and reflooding in Maahas-2

soil, resulted in grain yield loss ranging from 22% to 67% depending on the time and duration of soil drying, while in Louisiana-1 soil, soil drying and reflooding increased grain yield to the extent of 33% to 76%. Rice grain yields under intermittent drying and reflooding water regimes in Maahas-1, Maahas-2 and Louisiana-3 were lower than continuously flooded water regime and application of rice straw did not decrease this yield loss.

To see the effect of variable water regimes on mineral nutrition, growth and yield of rice (IR64) under field condition, experiment 6 was conducted in the IRRI farm during the 1986 dry season. Three methods of N application were also tested in this experiment. Plant analyses at different stages of rice growth suggested N deficiency in all the water regime treatments but N application methods did not improve N nutrition of rice. It appeared that the N rate of 90 kg/ha was not sufficient for good rice growth in this soil. Soil drying and reflooding resulted in lower availability of N, P and Ca but improved availability of Zn. In spite of dipping the roots of the seedlings in 2% ZnO suspension, rice plants under continuously flooded water regime were marginal in total Zn. This suggested the ineffectiveness of root-dipping method for correction of Zn deficiency in this soil. Despite the observed differences in the mineral nutrition of the plants under the different water regimes, only soil drying and reflooding at the early stage of growth (between 0 and 6 WAT) decreased grain yield compared with continuously flooded water regime. From the foregoing discussions the following conclusions can be made:

1. Influence of water regime on chemical kinetics and rice growth is soil specific and thus the influence of interaction between water regimes and soil is more important and meaningful than that of water regime alone.
2. As compared to continuously flooded water regime, soil drying and reflooding results in:
 - ° lower availability of N, P, K, Ca, Mg, S, Fe, Mn, Zn and Si in all soils during the dry spell;
 - ° lower availability of N, P and Fe in all soils after reflooding
 - ° relatively higher availability of K, Ca, and Mg in neutral soils but lower availability in acid soils, after reflooding
 - ° higher availability of S in all soils after reflooding
 - ° higher availability of Zn in neutral and acid soils but lower availability in high pH soils after reflooding
 - ° higher availability of Si in acid soils but lower availability in neutral and high pH soils after reflooding
3. In neutral fertile soils, rice grows best and produces highest grain yield under continuously flooded condition. Soil drying for 2 or 4 weeks between 0 and 12 WAT and reflooding decreased grain yields by 7% to 76% depending on the time and duration of drying. Highest yield reduction (75.8%) was seen when 4 weeks soil drying was imposed at 4 WAT. The specific adverse chemical factors associated with poor performance of rice

under intermittently dried and reflooded water regimes were found to be the lower availability of N, P, Fe and Si.

4. In potentially iron toxic acid soil, poorest crop growth and lowest grain yield were seen under continuously flooded condition. Soil drying for 2 or 4 weeks and reflooding improved rice growth and increased grain yield by 41% to 52% depending on time and duration of soil drying. Highest yield increase of 51.6% was obtained when the flooded soil was dried for 2 weeks starting 4 WAT. High reducing condition and high water soluble Fe^{2+} were found to be the main reasons for poor rice yield under continuously flooded water regime.
5. In acid soils where Fe-toxicity is not a problem, rice growth was best and grain yield was highest under continuously flooded water regime. Soil drying and reflooding during the vegetative growth stages decreased grain yield. Grain yield reduction under intermittently dried and reflooded water regime was associated with lower availability of Ca and Mg.
6. In S- and Zn- deficient soils, plant growth and grain yields were poorest under continuously flooded water regimes. Soil drying for 2 or 4 weeks during vegetative growth stages improved plant growth and increased grain yield. But when both S and Zn were applied to these soils crop growth improved and highest grain yield was obtained under continuously flooded water regime.

7. In spite of application of straw, the redox condition of dried and reflooded soils did not become favorable to crop growth and thus the grain yields of dried and reflooded soils remained lower than under continuously flooded water regime.
8. Drainage of 5-10 mm/day did not significantly influence rice growth and grain yield in neutral soil but improved plant growth and increased grain yields in Fe-toxic acid soils.
9. Continuously saturated water regime did not significantly decrease grain yield in neutral soil but improved plant growth and increased grain yield in Fe toxic acid soil.

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