Growth and Nutrient Uptake by Rice Under Controlled Oxidation-Reduction and Ph Conditions in a Flooded Soil.

Aroon Jugsujinda

Louisiana State University and Agricultural & Mechanical College

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The Louisiana State University and
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GROWTH AND NUTRIENT UPTAKE BY RICE UNDER CONTROLLED OXIDATION-REDUCTION AND pH CONDITIONS IN A FLOODED SOIL

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy in The Department of Agronomy

by

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ABSTRACT

Growth and nutrient uptake by rice (Oryza sativa L. cultivar Saturn) under controlled oxidation-reduction and pH conditions in a flooded soil were determined by growing the rice plants under aerobic (oxidized) and anaerobic (reduced) soil suspensions which were maintained at different controlled pH values in the laboratory. The soil used in the investigations was a Mhoon silty clay loam (Typic Fluvaquent; fine-silty, mixed, nonacid, thermic). Four investigations were conducted under both aerobic and anaerobic conditions to determine the effects of soil conditions and pH on the growth and uptake of Fe, Mn, Zn, and P by the rice plants. The influence of ammonium-N, nitrate-N, and urea-N on the recovery of nitrogen by the rice plants were investigated.

Vegetative growth of the rice plants was greater under anaerobic conditions than under aerobic conditions. Dry weights of the plants grown under aerobic conditions uniformly decreased as soil pH was raised from 5.0 to 8.0. Plants grown under aerobic conditions at all pH levels were chlorotic. The chlorosis was attributed to iron deficiency. A decrease was observed in the dry weights of the rice plants grown under anaerobic conditions at pH 5.0 and 8.0. Plants which were grown under anaerobic conditions at pH 6.0 and 7.0 were normal; however, plants grown at pH 5.0 were abnormal, and this was attributed to the high level of Fe in the plant tissue. Plant abnormality was also observed at pH 8.0, and this may have been due to the high soluble sulfide content of the soil.
The uptake of Fe and Mn by rice plants grown under aerobic conditions at pH 5.5 and 7.5 was low and was not affected by pH. The Fe uptake by the rice plants grown under anaerobic conditions was high at low soil pH and low at high soil pH. The Mn uptake was apparently influenced by Fe uptake; Mn uptake was low when Fe uptake was high and vice versa.

The Zn uptake by the rice plants was higher under aerobic than under anaerobic conditions. Under both soil conditions, Zn uptake by the rice plants decreased with each stepwise increase of a pH unit from 5.0 to 8.0. A sharp decrease in Zn uptake by the rice plants occurred when the plants were grown under both soil conditions at the higher pH values. No consistent effect of aerobic and anaerobic conditions on plant uptake of P was observed. The P uptake by the rice plants under both soil conditions consistently decreased as soil pH was raised.

Aerobic and anaerobic soil conditions did not consistently influence recoveries of added labelled ammonium-N, nitrate-N, and urea-N by the rice plants. Three units increase in soil pH from 4.5 to 7.5 decreased recovery of added labelled ammonium-N by the plants under both soil conditions and of added labelled nitrate-N under aerobic conditions.

Aerobic conditions were indicated by a large positive redox potential value of approximately +640 mv at pH 5.0. Anaerobic conditions were indicated by a large negative redox potential value of approximately -280 mv at pH 8.0. An increase or decrease of one pH unit over the experimental range for both soil conditions resulted in
a decrease or increase in redox potential close to the theoretical value of 60 mv. An increase in pH uniformly increased the electrical conductivity of the aerobic soil. Under anaerobic conditions the electrical conductivity increased as the pH value was maintained at lower or higher than the original 6.5 value which was the pH value of the anaerobic soil before pH adjustment.
INTRODUCTION

Oxidation-reduction conditions and pH of a flooded soil have a pronounced effect on solubility of plant nutrients and hence their availability to rice (*Oryza sativa* L.). The physical, biological, and chemical properties of reduced soils are markedly different from those of oxidized soils. Generally, better nutrition and grain yields of rice have been observed when rice is grown under reduced soil conditions than when grown under oxidized conditions. Plants grown under oxidized conditions often suffer from a deficiency of several essential nutrients. Plants grown under highly reduced soil conditions, on the other hand, may suffer from toxicity of reduction products. Too high or too low a soil pH likewise causes deficiency or toxicity of certain essential elements.

Previous workers such as Tanaka and Navasero (1966a, 1966b, 1966c) and Senewiratne and Mikkelsen (1961) have studied several aspects of rice nutrition in culture solutions. Other workers have investigated the chemistry of plant nutrients in flooded soils (Ponnamperuma, 1955, 1965) and their transformations under controlled soil oxidation-reduction conditions (Patrick, 1960, 1964) and also under controlled soil pH and oxidation-reduction conditions (Gotoh and Patrick, 1972, 1974). Effects of flooded and nonflooded soil conditions on the growth and uptake of nutrients by rice have also been reported (Senewiratne and Mikkelsen, 1961). Rice is generally grown under a wide variation of soil oxidation-reduction and pH conditions. Additional study is needed to obtain information on the growth and nutrient uptake by rice grown under various combinations of soil
oxidation-reduction conditions and pH levels in flooded soils. One factor which has hampered such a study is the difficulty of obtaining uniform soil oxidation-reduction conditions due to the heterogeneity of the soil oxidation-reduction potentials along the soil profile or along the oxidized and reduced layers of flooded soils.

A laboratory technique was developed for growing the rice plants in a flooded soil suspension which allowed close control of soil pH and uniform soil oxidation-reduction conditions (both aerobic and anaerobic conditions). The present investigation utilized this technique to carry out experiments with the following objectives:

1. To determine the effect of aerobic and anaerobic conditions and pH on early vegetative growth and physiological disorders of rice in a flooded soil.

2. To determine the effect of aerobic and anaerobic conditions and pH on uptake of native and added labelled Fe and Mn by rice in a flooded soil.

3. To determine the effect of aerobic and anaerobic conditions and pH on uptake of native and added labelled Zn and P by rice in a flooded soil.

4. To determine the effect of aerobic and anaerobic conditions and pH on recovery of added labelled ammonium-N and nitrate-N by rice in a flooded soil.

5. To determine the effect of aerobic and anaerobic conditions and pH on recovery of added labelled ammonium-N and urea-N by rice in a flooded soil.
6. To determine the effect of aerobic and anaerobic conditions and pH on the redox potential, the amounts of acid and alkali added to maintain pH, the electrical conductivity, and the amount of total sulfide-sulfur in a flooded soil.
A. Effect of Flooding on the Changes in Some Soil Properties

1. Changes in Electrochemical Properties

The three most important electrochemical properties of the soil that are affected by flooding are redox potential (Eh or oxidation-reduction potential), pH, and electrical conductivity (Patrick and Mikkelsen, 1971).

a. Redox potential. The redox potential is the most convenient physicochemical measurement that serves to distinguish an oxidized soil from a reduced soil (Rodrigo, 1963; Patrick and Mikkelsen, 1971; and Ponnamperuma, 1972). The redox potential of the soil is determined by the degree of oxidation or reduction of redox systems in the soil. Oxidized or aerobic soils are characterized by highly positive potentials (+800 to +300 mv) while most reduced or anaerobic soils, after a few weeks of submergence, have large negative potentials (+200 to -400 mv). Redman and Patrick (1965) reported redox potential decreased from high values immediately after flooding to very low values after 30 days.

Patrick and Mahapatra (1968) suggested four general ranges of redox potential usually encountered in oxidized and reduced soils. At pH 7, oxidized soils are characterized by a redox potential of greater than +400 mv, moderately reduced soils from +400 to +100 mv, reduced soils from +100 to -100 mv, and highly reduced soils from -100 to -300 mv. Ponnamperuma (1972) reported that the course, rate and magnitude of the decrease in redox potential on submergence depend on
the nature and amount of organic matter, the nature and content of
electron acceptors, temperature and the period of submergence of the
soil.

Patrick and Mahapatra (1968) indicated an approximate redox
potential at which oxidized forms of several inorganic redox systems
became unstable. At pH 7, as the redox potential decreases below about
+320 mv, oxygen disappeared. Nitrate-nitrogen is unstable at a poten-
tial of about +225 mv. Manganic-manganese is reduced at about +200 mv,
ferric iron at about +120 mv, and sulfate is reduced to sulfide at
about -150 mv. According to Pearsall (1938), redox potential values
lower than +320 to +350 mv at pH 5 contained ammonium, ferrous, and
manganous ions, while soils with redox potentials above this range
generally contained nitrate, ferric and manganic ions. Assuming a
redox potential/pH slope of -60 mv/pH unit, this corresponds to a redox
potential range of +200 to +230 mv at pH 7 (E7). He considers this
range as a border line between reduced and oxidized soil conditions.

Results of several investigators indicate that the chemical
changes in soils generally occur in the following sequence as the
redox potential decreases: disappearance of oxygen, reduction of
nitrate, reduction of manganese to divalent form, reduction of iron
to divalent form, and reduction of sulfate to sulfide (Aomine, 1962;

Postgate (1959) demonstrated that the redox potential could be
lowered to -200 mv by the addition of a solution containing 15 ppm of
H₂S. Redman and Patrick (1965) reported that iron compounds in the
soil were active in retarding the decline of redox potential after
submergence. On the other hand, they reported the potential of a
highly reduced soil was increased by the addition of nitrate. The potential did not fall to its previous value until all of the nitrate was reduced.

b. Soil reaction (pH). Redman and Patrick (1965) found that submergence tended to shift the soil pH to values near the neutral point. In general, acid soils increased in pH after submergence and alkaline soils decreased in pH after submergence. Ponnamperuma, Martinez, and Loy (1966) reported that the increase in pH of acid soils was largely due to the reduction of iron and related this quantitatively to the potential of \( \text{Fe(OH)}_3 - \text{Fe}^{++} \) system and to \( \text{Fe}^{2+} \) activity, while the decrease in pH of sodic and calcareous soils was related to the partial pressure of carbon dioxide through the \( \text{Na}_2\text{CO}_3 - \text{H}_2\text{O} - \text{CO}_2 \) and \( \text{CaCO}_3 - \text{H}_2\text{O} - \text{CO}_2 \) equilibrium respectively.

Ponnamperuma (1965) found that for each 0.5 pH unit change there was a 10-fold difference in Fe concentration in the soil solution. He further stated that rice plants may become Fe deficient at pH values higher than 7.5 because of a low concentration of \( \text{Fe}^{++} \) ion in the soil solution, as well as the formation of insoluble \( \text{Fe(OH)}_3 \) in the rice roots.

c. Electrical conductivity. Redman and Patrick (1965) reported that electrical conductivity generally increased upon submerging the soil. Decreases in electrical conductivity after submergence occurred only for soils initially high in nitrate nitrogen. They indicated that organic matter served to increase electrical conductivity.

Mortimer (1941) attributed the increase in conductance to the release of \( \text{Fe}^{2+} \) and \( \text{Mn}^{2+} \) from the insoluble hydrated oxides of \( \text{Fe}^{3+} \)
and Mn$^{4+}$, the accumulation of NH$_4^+$, and in calcareous soil, to the release of Ca$^{++}$ as a result of the solubilization of CaCO$_3$ by CO$_2$.

IRRI (1967) reported that increase in electrical conductivity beyond 4 mmhos/cm makes the conditions unfavorable for the healthy growth of rice.

2. Changes in Chemical Properties

Drastic changes in the chemical properties of a soil occur in flooding. Among the chemical changes that take place when a soil is kept flooded are: a) an accumulation of ammonia, b) an increase in solubility of Mn, c) an increase in solubility of Fe, d) an increase in solubility of P, e) a reduction of sulfate, and f) a decrease in solubility of Zn.

a. Accumulation of ammonia. The mineralization of organic nitrogen in submerged soils stops at the ammonia stage because of the lack of oxygen to carry on ammonium oxidation to nitrite and nitrate. For this reason ammonia accumulates in anaerobic soils.

Tusneem and Patrick (1971) found that the initial rapid increase and subsequent decrease in ammonium accumulation under waterlogged conditions as compared with optimum moisture conditions, were attributed to the low nitrogen requirements of anaerobic metabolism and to subsequent nitrogen loss respectively.

Redman and Patrick (1965) reported that flooding the soil resulted in large increases in ammonia content. Addition of 0.25 percent corn leaves further increased the production of ammonia. All soils reduced nitrate nitrogen under submerged conditions. Added organic matter generally increased the nitrate reduction rate. Patrick and Wyatt (1964) found a considerably higher rate of inorganic nitrogen release
in waterlogged soils than in well-drained soils. In a number of soils, Waring and Bremner (1964) observed a more rapid rate of net mineralization under waterlogged than under aerobic conditions.

According to Waring and Bremner (1964) and Broadbent and Reyes (1971), inorganic nitrogen is released in large quantities and faster in anaerobic soils than in aerobic soils because less immobilization of nitrogen occurs in anaerobic media. Patrick and Wyatt (1964) observed that nitrogen mineralization under reduced conditions was considerably higher than that under oxidized conditions. The higher rate of mineralization in reduced soil was attributed to the increase in pH of the soils brought on by submergence.

Patrick and Tusneem (1972) reported an appreciable loss of labelled nitrogen occurred in flooded soils exposed to atmospheric oxygen. Nitrogen added as ammonium was apparently nitrified in the aerobic surface layer of soil and then diffused downward into the underlying anaerobic zone when it was denitrified and lost from the system.

The main transformations of nitrogen in submerged soils are accumulation of ammonia, denitrification, and nitrogen fixation. These transformations have an important bearing on the nutrition of rice. Transformations of nitrogen with the emphasis on submerged paddy soils have been extensively reviewed during the past decade (Patrick and Mahapatra, 1968; Ponnampereuma, 1972; Tusneem and Patrick, 1971).

b. Reduction of manganese. Manganese is an essential element that undergoes a marked increase in solubility upon flooding. The release of manganese into the soil solution precedes that of iron
because manganese is more readily reduced and rendered more soluble than iron.

Mandal (1961) showed that manganese entered into the exchangeable complex and also appeared in soluble form much earlier than iron. He pointed out that transformations of manganese in flooded soil is similar to that of iron but the degree and intensity of transformation varies owing to its higher redox potential than iron. Redman and Patrick (1965) reported approximately six times as much manganese was extracted from anaerobic soil after 30 days submergence as under air-dry conditions.

Turner and Patrick (1968) reported that exchangeable manganese in Crowley silt loam increased from about 20 ppm to 280 ppm after 7 days of submergence. They also reported that the conversion of easily reducible manganese to the exchangeable form in an anaerobic soil was greatest when the redox potential decreased to about +200 mv. In an aerobic soil, no exchangeable manganese was present above a pH of 6. In an anaerobic soil, exchangeable manganese was present up to pH 11. They further found that manganese began to be reduced at a redox potential of +400 mv and was essentially completely reduced at a redox potential of +200 mv. Singh (1969) reported that flooding increased the availability of manganese in acid soils to such a high level that it became toxic and caused a bronzing disease to the rice plants.

Manganese transformations in flooded soils as affected by Eh-pH relationships have been examined by various workers (Bohn, 1968, 1970; Collins and Buol, 1970a, 1970b; Ponnamperruma, Loy, and Tianco, 1969; Takai, 1961; Turner and Patrick, 1968). Most of these studies have been theoretical in nature, probably as a result of the difficulty in controlling both Eh and pH in biologically dynamic systems. Gotoh and
Patrick (1972) studied the distribution of different forms of manganese in flooded soil over a wide range of closely controlled Eh-pH conditions and concluded that the Eh and pH of flooded soils provide general control of manganese transformation. They reported that at pH 5 almost all of the soil manganese was converted from reducible to the water-soluble plus exchangeable fraction even at redox potential as high as +500 mv. In sharp contrast, at pH levels between 6 and 8, most of the conversion took place at relatively low redox potentials of +200 to +300 mv.

c. Reduction of iron. The most important chemical change that takes place when a soil is flooded is the reduction of iron and the accompanying increase in its solubility.

It is well established that flooded soils are subject to a succession of iron transformations from the ferric to ferrous state under reducing conditions caused by a wide variety of facultative anaerobic soil bacteria (Starkey and Halvorson, 1927; Allison and Scarseth, 1942; Bromfield and Williams, 1963; Takai and Kamura, 1966; Ottow and Glathe, 1971).

Redman and Patrick (1965) reported that large quantities of iron were released in the ferrous form as a result of submergence. Addition of organic matter usually increased the release of iron. Anaerobic soils and sediments have much more Fe in solution—approximately 50 to 100 parts per million (ppm), compared to less than 1 ppm in aerobic soils (Gotoh and Patrick, 1974).

Turner and Patrick (1968) reported that exchangeable ferrous iron increased from about 5 ppm to 360 ppm in a Sharkey silty clay after 7 days of submergence. According to Ponnampерuma (1965), the reduction
of iron in a waterlogged soil is favored by: 1) the absence of substances at a higher level of oxidation, such as nitrate and manganese dioxide, 2) the presence of readily decomposable organic matter, and 3) a good supply of active iron.

Ferric iron compounds which predominate in well drained soils are reduced to a more soluble ferrous form when a soil is waterlogged (Starkey and Halvorson, 1927; Alexander, 1961; Takai and Kamura, 1966). According to Kamoshita and Iwasa (1959), and Ponnampерuma, Tanco, and Loy (1967), the most commonly occurring iron compounds in flooded soils may be \( \text{Fe}_2\text{O}_3 \) (hematite), and such ferric oxyhydroxides as \( \text{Fe(OH)}_3 \cdot n\text{H}_2\text{O} \) (amorphous ferric oxyhydroxide), \( \alpha\text{-FeOOH} \) (geothite), \( \gamma\text{-FeOOH} \) (lepidocrocite), and \( \text{Fe}_3\text{(OH)}_8 \) (ferrosferric hydroxide) which are likely involved in the redox equilibria.

Patrick (1964) reported extractable iron in flooded soil was largely present in the ferrous form at redox potentials below +200 mv. Ferrous iron increased greatly with a decrease in redox potential below +200 mv. Motomura (1969) reported that the reduction of iron compounds depends on the factors such as the content of easily decomposable organic matter, amount of free iron oxides, redox potential and pH. Temperature below 10°C slowed down the process of reduction, but the same above it enhanced the process. The presence of nitrate-nitrogen retarded the reduction of iron whereas the presence of sugar hastened it.

It has been reported that a decrease in redox potential increases the concentration of ferrous iron and that bacteria play a principal role in iron transformation (Ignatieff, 1941; Bloomfield, 1949; Bradley and Sieling, 1953). Patrick (1964) noted a large release of ferrous iron when redox potential fell below +200 mv. He attributed this
increase in ferrous iron to the reduction of insoluble ferric compounds which were unstable at this reducing potential.

Critical redox potential at which iron is released in flooded soils has been reported. Pearsall and Mortimer (1939), Takai and Kamura (1966), and Gotoh and Yamashita (1966) reported values of +350 mv, +200 mv and +280 mv, respectively. Patrick (1964) found that soluble iron began to increase when the redox potential decreased to about +150 mv and continued to increase with a further decrease in redox potential. Gotoh and Patrick (1974) studied the distribution of different forms of iron in a waterlogged soil over a wide range of closely controlled redox potential and pH conditions. They found that increases in water-soluble and exchangeable iron were favored by a decrease in both redox potential and pH. They reported that the critical redox potentials for iron reduction and consequent dissolution was between +300 mv and +100 mv at pH 6 and 7, and -100 mv at pH 8, while at pH 5 appreciable reduction occurred at +300 mv. They further reported that water-soluble iron accounted for 76% of the water-soluble plus exchangeable fraction under the most acid conditions in combination with the most reduced conditions (pH 5 and Eh -250 mv). At pH 8, the corresponding value was only 4% at a redox potential of -250 mv.

d. Change in phosphate solubility. Most reports in the literature indicate that submergence brings about an increase and subsequent decrease in solubility of phosphorus in the soils. The increase in solubility of phosphate in soil brought on by submergence has usually been attributed to: a) displacement of phosphate from insoluble ferric and aluminum phosphates by organic anions (Bradley and Sieling, 1953), b) the reduction of insoluble ferric phosphate
(Islam and Elahi, 1954; Patrick, 1964), c) hydrolysis of ferric and aluminum phosphates in alkaline soils (Ponnamperuma, 1955; Valencia, 1962), d) exchange of phosphate adsorbed on clay surfaces by organic anions (Russell, 1961), and e) release of occluded phosphate (Chang and Jackson, 1958; Mahapatra, 1966). The subsequent decrease may be caused by a) resorption of phosphate on clay or aluminum hydroxide (Bromfield, 1960), and b) increase in pH.

Submergence of a soil usually results in an increase in extractable soil phosphorus (Beacher, 1952; Ponnamperuma, 1955) and an increase in the utilization of phosphorus by the rice crop (Shapiro, 1958a). Patrick (1964) reported that extractable phosphorus increased over three-fold between redox potentials +200 and -200 mv. The conversion of phosphate to an extractable form was associated with the reduction of ferric compounds in the soil.

Redman and Patrick (1968) reported extractable phosphorus was an average of about 21 percent higher under reduced conditions brought on by submergence than under air-dry conditions in a number of soils. Appreciable phosphate release occurred only in those soils that released large amounts of ferrous iron. Redman and Patrick (1965) reported that in acid soils containing free iron oxide, phosphate also exists in an occluded form, and waterlogging the soil usually causes reduction of hydrated ferric oxide to ferrous hydroxide with the subsequent release of a part of the occluded phosphate.

Patrick (1964) reported a marked increase in extractable phosphorus as a result of lowering the redox potential below +200 mv. Extractable phosphorus increased from 10 to 35 ppm between redox potentials of +200 and -200 mv. The fact that ferric iron began to be reduced to the
ferrous form at these potentials tends to confirm that this increase in extractable phosphorus came from the conversion of ferric phosphate to the more soluble ferrous phosphate.

The increase in pH of acid soils as a result of waterlogging is also considered to aid in the solubility of iron and aluminum phosphates (Mikkelsen and Patrick, 1971). One of the changes brought about by waterlogging a soil that is important to the nutrition of lowland rice is the increase in availability of soil phosphorus (Sapiro, 1958b; Savant and Ellis, 1964; Redman and Patrick, 1965; Patrick and Mahapatra, 1968).

A marked increase in the availability of native and added phosphates in reduced soils as compared to that in oxidized ones has been well documented (Aoki, 1941; Beacher, 1952; Shapiro, 1958a, 1958b; Davide, 1961; Patrick, 1964; Redman and Patrick, 1965). Biddulph (1953) and Humphries (1962) have showed that the uptake of phosphorus was considerably curtailed by the precipitation of the iron deposits in and around roots.

Because of the precipitation of FePO₄ outside the rice roots, the availability of phosphorus should be considerably reduced and the increase in phosphorus availability caused by reduction of the soil virtually nullified.

The availability of native and applied phosphate to rice grown on five waterlogged soils was studied by Valencia (1962). He observed that soon after flooding phosphate increased, apparently through the hydrolysis of AlPO₄ and the reduction of FePO₄. After a long period of waterlogging, however, phosphate became less available, probably due to fixation.
The increased availability of soil phosphorus has usually been attributed to reduction of ferric phosphate to the more soluble ferrous form under chemically reduced conditions brought on by the depletion of oxygen and the production of reduced organic and inorganic substances in the soil (Islam and Elahi, 1954; Ponnampetuma, 1955).

e. Reduction of sulfate. Reduction of sulfate to sulfide takes place in a flooded soil after it has undergone appreciable reduction. This conversion is carried out primarily by a unique group of bacteria known collectively as sulfate-reducers (Starkey, 1950). They are strict anaerobes and their activities are affected by redox potential and pH.

Sulfides in Louisiana soils have been found to vary from a low of 0.2 ppm total sulfide for a short submerged duration (Rodriguez, Jordan, and Hollis, 1965) to a high of 10 to 45 ppm at the end of the growing season. Postgate (1959) proposed that the soil Eh should be about -200 mv in order to stimulate the microbial reduction of sulfate to sulfide.

Connell and Patrick (1969) demonstrated in an incubated soil that the critical redox potential for the inception of sulfate reduction was about -150 millivolts. They also reported that the pH range for sulfide accumulation in a Crowley silt loam to be between 6.0 and 9.5. The maximum sulfide accumulation was found to be at pH 6.8.

Hollis (1967), using theoretical values, showed that free sulfide levels in Louisiana paddy soils may be toxic to the rice plant. He calculated theoretical H₂S concentrations under Louisiana rice field conditions and reported theoretical sulfide concentrations of 100, 16.7, 1.7, 0.17, and 0.017 ppm at pH values of 5.0, 5.5, 6.0, 6.5, and 7.0, respectively.
Sturgis (1936) reported a sulfide content of 29.9 ppm when Sharkey clay loam soil was continuously flooded for three weeks. Connell and Patrick (1969) found as much as 40 ppm total sulfide in a flooded Crowley silt loam paddy soil in Louisiana.

Bloomfield (1969) reported that more free \( H_2S \) was generated under alkaline conditions but he added that iron was more immobile under alkaline conditions and that the iron system governed the distribution of sulfide in a reduced soil. Connell and Patrick (1969) likewise reported that in Louisiana soils almost no sulfide existed as \( H_2S \) if excess iron was present.

f. **Changes in zinc solubility.** Zinc shows only a single valence. It is probably not involved in oxidation-reduction reaction in the soil. Ponnamperuma (1972) stated that zinc mobility may be affected by some hydrous oxides of \( Fe^{3+} \) and \( Mn^{4+} \) and the production of organic complexing agents should increase the solubility of zinc. The increase in pH of acid soils and the formation of sulfide as a result of submergence should lower its solubility. The water regime of a soil profoundly affects the zinc nutrition of rice (IRRI, 1970); prolonged submergence reduces zinc availability, soil drying increases it dramatically. The decreases in the solubility of zinc brought on by soil submergence have not been satisfactorily explained.

IRRI (1970) reported that the solubility of zinc in flooded soils appeared to be governed by ionic equilibria involving the zinc phosphate, zinc ammonium phosphate, zinc sulfide, and zinc silicate. They further reported that a high pH, a high content of organic matter, and a high content of available phosphorus depress the availability of zinc in flooded soils, as they do in upland soils. They also reported that as
the available P content of the soil increased the zinc content of the straw decreased and that the interaction between available P and pH influenced the zinc content of the straw. The high P:Zn ratio in the straw of zinc-deficient plants reflects this interaction. They postulated that organic matter either depressed the availability of zinc or hindered its uptake by the rice plant through its effects on soil metabolism.

Little agronomic research has been done on zinc reactions in flooded soils. Soluble zinc is usually present in low concentrations in soil solutions. It has been demonstrated by geologists that zinc readily forms very insoluble sulfide salts when exposed to \( H_2S \) (Krauskopf, 1967). Camp (1945) reported that the critical pH range for Zn availability in soils is between 5.5 and 6.5. He also suggested that in alkaline soils the formation of a negatively charged zincate complex may be a significant factor that contributes to reduced Zn availability. Seatz and Jurinak (1957) reported that Zn availability is at a minimum when the range in the soil pH is between 5.5 and 7.5.

IRRI (1970) reported zinc deficiency was found to be a widespread nutritional disorder of rice on soils with a high pH or a high water table. Incorporation of organic matter depressed the concentration of zinc in the solution of flooded soils and zinc uptake by rice plants. Drying the soil may be as good a remedy for zinc deficiency on permanently wet soils as applying zinc chloride, zinc sulfate, or zinc oxide.

The critical content of Zn in rice plants of 10 ppm in the shoot at tillering for deficiency and 1500 ppm in the straw at maturity for toxicity has been reported by Ishizuka (1971).
B. **Effect of Flooding on Growth and Nutrient Uptake by Rice**

1. **Growth and Nutrient Uptake by Rice Under Flooded and Nonflooded Soil Conditions**

Rice grown under reduced or waterlogged soil condition consistently produces better vegetative growth and higher grain yields than when grown under oxidized soil condition (Lin, 1946; Clark, Nearpass, and Sprecht, 1957; Senewiratne and Mikkelsen, 1961; Chaudhry and McLean, 1963). Lin (1946) attributed such reduced growth of rice grown under oxidized soil condition to low availability of iron.

Clark, Nearpass, and Sprecht (1957) concluded that the better growth of rice in submerged as compared to upland culture in at least some soils was due to greater manganese availability under submerged soil condition. Their plant analyses indicated that rice has a high requirement for an exceptionally high tolerance to manganese.

Senewiratne and Mikkelsen (1961) reported the contrary. On a Stockton clay from California of pH 4.7, poorer growth of rice under upland than flooded conditions was associated with a high content of manganese in the plants. They suggested that differences in growth of rice under flooded and unflooded conditions represented differences in auxin metabolism.

Valoras and Letey (1966) reported that soil-water content had a marked influence on rice growth. They concluded that the better growth of rice cultured under flooded conditions as compared to unflooded conditions was due to differences in soil-water content.

Mandel (1962) observed better growth of rice plants when grown in soils kept under an atmosphere containing only 10 percent oxygen than
when grown in soils exposed to natural air. The better growth was due to greater availability of manganese in soils.

Weeraratna (1969) showed that rice grown in lowland soil absorbed more manganese and produced higher dry matter under flooded than under nonflooded conditions, whereas in upland soil the same were lower under flooded than under nonflooded conditions. Higher soluble iron content in upland soil was found to interfere with the absorption of manganese. Experiments conducted in the Philippines (IRRI, 1964) showed that excellent vegetative growth of rice could be obtained in aerobic soils by supplying extra P and Fe.

Patrick and Mahapatra (1968) reported that soil reduction per se did not appear to be detrimental to rice except possibly at extremely low redox potentials, potentials low enough for sulfide to be formed. Ponnampuruma (1965) suggested that the outstanding beneficial effect of soil submergence is the increase in the availability of iron because the iron requirement of rice is much higher than that of most crop plants. Jeffery (1963) likewise reported that the increase in soluble iron after waterlogging is beneficial to the rice plant.

Chaudhry and McLean (1963) reported that rice plants grown under flooded conditions were healthier, taller, and had more tillers than plants grown under nonflooded conditions. They also reported that plants grown under flooded conditions had significantly higher concentrations of phosphorus and manganese in the tissue.

Sanchez and Briones (1973) reported that in soils of high phosphorus availability no differences in growth and phosphorus uptake were observed when rice was grown under constant flooding (reduced) or partially oxidized conditions. They further reported that in soils of
moderate to low phosphorus availability, partially oxidized conditions produced lower yields and caused lower phosphorus uptake in comparison to constant flooding.

Shapiro (1958a) reported that flooding increased the yield, phosphorus uptake, and nitrogen uptake by rice with both a lowland and an upland variety of japonica rice as compared to the same varieties grown under nonflooded conditions.

In reduced soils, micronutrients are more easily removed than in oxidized soils. Swaine and Mitchell (1960) noted that mobility of Fe, Mn, and Zn increased in poorly-drained soils. They reported in general that improved soil drainage increased the uptake of Zn but decreased the uptake of Fe and Mn.

It appears that there is no single factor which is responsible for the increased vegetative growth and grain yields of rice grown under flooded conditions as compared to rice which is grown under non-flooded conditions.

2. Oxidizing Power of Rice Roots and Its Effect on Some Reduced Substances in a Flooded Soil

a. Plant adaptation. The ability of the rice plant to grow under reducing conditions has been attributed to the unique adaptations of the plant. Van Raalte (1941) reported that the rice plant was able to function in an anaerobic medium because of the development of lysigenous gas spaces in the root which were linked with the air spaces of the shoot system. Through these channels oxygen moved into the roots and diffused out into the soil thereby oxidizing the rhizosphere (Van Raalte, 1944; Mitsui, 1954).
Several workers (Alberda, 1953; Aomine, 1962; Armstrong, 1967) have demonstrated the rice plant ability to ward off some of the toxic products of soil reduction by the secretion of oxygen by the root hairs into the adjacent soil.

The oxidizing power of the rice root can be very important in oxidizing toxic \( \text{H}_2\text{S} \) to a nontoxic form or to render high concentrations of soluble reduced iron and manganese to insoluble ferric and manganic oxides, thus possibly reducing toxic concentrations of the metallic ions.

b. Ferrous-iron and manganous-manganese. Tanaka and Yoshida (1970) indicated that rice roots counteracted a higher level of ferrous iron in the soil solution by their oxidizing power. Ferrous iron is oxidized at the root surface to ferric iron and precipitated as ferric hydroxide or carbonate, resulting in a decreased intake of iron by the plant. Sulfides destroy the oxidizing power of roots and make rice plants more susceptible to iron toxicity (Tanaka, Mulleriyawa, and Yasu, 1968).

Japanese soils high in iron oxides are reported to produce very little free \( \text{H}_2\text{S} \) and the soluble sulfide content is considered insignificant (Takijima, Shiojima, and Konno, 1962). Harter and McLean (1965) found that any free \( \text{H}_2\text{S} \) produced in a flooded soil was precipitated as ferrous sulfide and demonstrated the fact a decrease in the amount of ferrous iron occurred concurrently with an increase in the sulfide content.

Ota and Yamada (1960) reported that addition of iron to strongly reduced soils caused almost all plants to die from severe ferrous iron toxicity. Ponnampерума, Bradfield, and Pech (1955) suggested that the
unthrifty growth of rice in poorly aerated soils was due largely to the accumulation of ferrous iron in the soil solution.

Okuda and Takahashi (1964) indicate that ferrous iron and manganous manganese are readily oxidized by rice roots and become insoluble and deposited on the root surface. As the oxidative power of the rice roots increases more ferrous iron and manganous manganese in solution are deposited on root surfaces as ferric and manganic oxides. Doi (1952) showed lower iron uptake power of the rice plant due to strong oxidative power, which has been considered as the important adaptive physiological function of rice plants, that they can be grown under waterlogged conditions. Some physiological diseases such as Akagare are caused by high iron levels, hydrogen sulfide, organic acid, etc., under reduced conditions (Tanaka and Yoshida, 1970).

Armstrong and Boatman (1967) showed that soluble iron salts behave as sinks for oxygen transported through the stem to the root by rice and other bog plants. Strong support for this hypothesis is provided by a thick sheath of hydrated ferric oxide around roots of bog and swamp plants. This oxidized iron also forms a barrier to entry of sulfide into the roots owing to the precipitation of this ion as highly insoluble ferrous sulfide. They also indicate that under intense reducing conditions iron enters the root to an appreciable degree, but again precipitation occurs and forms a coating on the cell walls bordering the intercellular spaces as well as sometimes completely occluding these spaces. It is conceivable that extensive internal precipitation of iron may eventually inhibit gas exchange within the root.

Rice plants suffered from severe iron deficiency in flooded alkaline soil. This may be due to much iron which is oxidized and
precipitated on or around the roots at pH values of more than 7.0 (Ingebritson, Martin, Vlamis, and Jeter, 1959).

\textit{c. Sulfide-sulfur.} In a study by Vamos (1958), it was shown that H$_2$S at pH 7 affected and could destroy the roots of the rice plant while at pH 8 the plant roots absorbed the SH$^-$ ion which resulted in a browning of the tissue. He also reported H$_2$S to be the causative factor of the disease "bruzone or akiochi," a significant disease of the rice plant in Hungary and Japan.

Mitsui and Kumazawa (1964) in their studies of nutrient uptake by the rice plant, have postulated that the reduced uptake of certain nutrients was associated with the enzymatic reactions affected by H$_2$S toxicity. Several authors (Ponnamperuma, 1955; Ponnamperuma, 1965; Ford, 1965; Harter and McLean, 1965; Connell and Patrick, 1968; Bloomfield, 1969) have postulated that the iron sulfide formation was important in regulating the amounts of toxic H$_2$S in the soil solution.

Hollis (1967), in a comprehensive review of the Japanese literature concerning sulfide toxicity of the rice plant, reported that Mitsui and his co-workers exposed rice roots to a solution containing 0.07 ppm H$_2$S and caused wilting of 42 percent of the leaves at the end of 200 hours. They also demonstrated that the same amount of wilting was evident at the end of 48 hours when the H$_2$S concentration was 2 ppm.

Conditions of high organic matter, high concentrations of sulfate, low concentrations of iron, and intense reduction favor the production of sulfide upon waterlogging a soil (Tanaka, Nojima, and Uemura, 1961). Mitsui (1965) considered it unlikely that toxic levels of hydrogen sulfide would accumulate in most soils due to formation of the relatively insoluble ferrous sulfide.
Goto and Tai (1956) observed an association between resistance to Akiochi disease (a physiological disease associated with hydrogen sulfide toxicity) and the oxidizing capacity of the roots of several Japanese rice varieties.

Armstrong (1969) determined intervarietal differences in oxygen flux from rice roots and reported an association between susceptibility to Akagare (a physiological disease associated with highly reduced soil conditions) and oxygen flux from the roots. The varieties with the greatest oxygen flux were known to have the greatest resistance to Akagare.

Hollis (1967) speculated that the best yielding rice varieties may possess higher root oxidative capacity than lower yielding varieties. He suggested that root oxidative capacity may be a good criterion for the selection and breeding of high yielding rice varieties which are resistant to physiological diseases. Armstrong (1964) was of the opinion that the tolerance of some aquatic plants to toxic H₂S was due to the rapid diffusion of oxygen from the roots and subsequent oxidation of sulfide.

Bonnarperuma (1965) indicates that rice roots can oxidize FeS in their immediate vicinity to FeSO₄ and absorb the sulfate ions. Englar and Patrick (1975) worked on the oxidative capacity of rice roots for sulfides. The ³⁵S tagged metal sulfides were mixed with anaerobic soil to which rice was transplanted. The apparent degree of stability and subsequent uptake of ³⁵S was directly related to the solubility of the sulfide salt. Their data suggested that the rice roots oxidized sulfide to sulfate and absorbed the sulfates.
Takai and Okajima (1956a, 1956b) observed that the oxidation of hydrogen sulfide by rice roots in the presence of iron was most active when the pH was around 7.0 and that the intrusion of sulfide sulfur to the base of the shoot was clearly observed at pH less than 6.0, while it could not be detected at pH over 6.0. Similarly, Baba, Inada, and Tajima (1965) showed that the oxidizing activity of roots is impaired and the intrusion of ferrous iron into the roots is facilitated. The influx of \( \text{H}_2\text{S} \) is favored by a soil pH less than 6.5 because a low pH retards the oxidation of \( \text{H}_2\text{S} \) at the roots and increases the permeability of the roots to \( \text{H}_2\text{S} \) and thus creates toxicity to the rice plants. When rice plants are healthy, the oxidizing power of the root is strong, but when nitrogen is limiting, the oxidizing power of roots becomes weak and the plant becomes susceptible to sulfides (Okajima, 1958).

Armstrong (1964) measured the oxygen diffusing from the roots of the rice plant to be \( 1.2 \times 10^{-8} \text{ g} \times \text{O}_2 \) per cm\(^2\) root surface per minute. He suggested that the tolerance of some aquatic plants to toxic \( \text{H}_2\text{S} \) was due to the rapid diffusion of oxygen from the roots and subsequent oxidation of the sulfide.
MATERIALS AND METHODS

For the study of the effects of soil oxidation-reduction (redox) conditions and pH on the growth and nutrient uptake by rice, soil was placed in water in a 2-liter pyrex desiccator base. Soil oxidation-reduction conditions were obtained by continuously bubbling either air or N_2 gas through the soil-water mixture which was kept in suspension by the action of a magnetic stirrer. The aerobic (oxidized) and anaerobic (reduced) soils were maintained at different pH levels during the growth of the rice plants.

The plants were grown in the laboratory at 28 to 30°C under conditions of continuous illumination from 150 watt incandescent lamps which were placed approximately 80 cm above each treatment. The vegetative growth of plants resulting from the various treatments was determined, and the plant tissue was analyzed for concentrations of nonlabelled and labelled iron, manganese, zinc, and phosphorus. In the experiment involving an \(^{15}\)N tracer, the plant tissue and soil organic and inorganic nitrogen fractions were analyzed for \(^{15}\)N/\(^{14}\)N isotope ratio. Redox potential, amounts of acid and alkali used to maintain pH, electrical conductivity, and total sulfide-S of soil suspensions were also determined.

A. Soil Used

Mhoon silty clay loam, a Mississippi floodplain soil, collected from LSU Ben Hur Farm, Baton Rouge, was used in this study. The soil was air-dried, ground and passed through a 20-mesh sieve. The soil was kept in a closed glass container and thoroughly mixed before use. The
soil consisted of 19% sand, 46% silt, and 35% clay, pH (1:1) 5.2, total carbon 1.19%, $\text{NH}_4^+$-N 80 $\mu$g/g, $\text{NO}_3^-$-N 60 $\mu$g/g, CEC 21.0 meq/100 g. Total P, Fe, Mn, and Zn were 540, 2190, 350, and 40 $\mu$g/g, respectively. Extractable P ($0.1 \text{ M HCl} + 0.03 \text{ M NH}_4\text{F}$ 1:20), extractable K, Ca, and Mg ($\text{NH}_4\text{Ac}$ pH 7 1:10), were 96, 208, 2570, 644 $\mu$g/g, respectively. These latter analyses were conducted by the LSU Soil Testing Laboratory according to the procedure of Brupbacher, Bonner, and Sedberry (1968). Extractable Fe, Mn, and Zn (DTPA-TEA pH 7.3), by the method of Lindsay and Norvel (1968) were 108, 40, and 1.56 $\mu$g/g, respectively.

B. Experimental Procedure

1. Soil Incubation Procedure

Duplicate 2-liter round (160 mm ID x 160 mm high) pyrex glass desiccator bases for each treatment were set up as shown in Figure 1. Five-hundred grams of soil were weighed into each of the containers and submerged with 1500 ml distilled water to give a soil to water ratio of 1:3. The soil was kept in suspension by the action of a magnetic stirrer. Arround plexiglass plate containing holes of different sizes around the plate for the purpose of controlling pH and measuring redox potential (Eh) of the soil suspension but without openings for plants (Figure 2b) was placed on top of the desiccator base and sealed with black plastic rubber. The plate and the desiccator base exteriors were painted with aluminum spray to protect the soil suspension from light. Two platinum electrodes were permanently inserted through a rubber stopper on top of the plate to measure Eh. Aerobic or anaerobic soil conditions were obtained by slowly bubbling either air or nitrogen gas through the gas inlet into the incubation vessel. Soil
Figure 1. Soil incubation apparatus for aerobic and anaerobic conditions.
Figure 2. Diagram of growth set up after transplanting rice (a) and a plexiglass plate (b) designed for use in supporting rice seedlings in controlled system.
suspension was normally incubated for a period of 10 days to obtain aerobic and anaerobic conditions.

2. **Measurement of Soil Oxidation-Reduction Potential**

Oxidation-reduction potential (redox potential or Eh) measurements were made by means of bright platinum electrodes which were permanently inserted through holes in the top of the plexiglass plate extending about an inch into the soil suspension. Prior to commencing the experiment, the platinum electrodes were cleaned electrolytically in normal HCl. This was done by connecting the positive pole of a 12-volt wet-cell battery to a carbon electrode and connecting the negative pole of the battery to the platinum electrode and allowing hydrogen to bubble from the platinum electrode for three minutes (Redman and Patrick, 1965). The accuracy of the platinum electrodes was checked in pH buffered quinhydrone solutions. To measure redox potential of the soil suspension, the platinum electrodes were connected to a Beckman Zeromatic pH meter, using a saturated calomel half cell as reference electrode (Patrick and Wyatt, 1964). A complete cell was formed by inserting a salt bridge (glass tube containing gel of saturated KCl and 2% agar) through a serum cap on top of the plate. Redox potential measurements were made daily.

3. **Control of Soil Reaction (pH)**

Ten days after the beginning of soil incubation, but prior to transplanting rice plant seedlings, the pH of each aerobic and anaerobic soil suspension was adjusted to different levels by adding known quantities of either 2 N HCl or 2 N NaOH with a hypodermic syringe through the serum cap. The pH of the soil suspension was adjusted every day and
redox potential was recorded each time the soil pH was adjusted until the end of the experiment.

4. Germination of Rice Seeds

Fungicide treated rice seeds (var. Saturn) were soaked in a petri-
dish containing filter paper moistened with water. The seeds were kept
in the petri-dish at room temperature until germination, which took
place within 48 hours. The sprouted seeds were transferred to shallow
containers filled with 4-cm deep 50 mesh sea sand which was kept
saturated with water. The sprouted seeds were pressed into the
saturated sand with their radicle down in such a way that the plumule
was visible outside. This operation enabled the plumule and radicle to
grow vertically without much curling, which facilitated the seedlings
transference to the plexiglass plate. The shallow container was placed
into a bigger tray containing water. The tray was covered with a
transparent polyethylene sheet to control moisture loss with few small
openings for aeration. The tray was kept near the window of the labora-
tory and maintained at about 30°C under the condition of daily illumina-
tion from 150 watts reflector flood lamps placed approximately 80 cm
above the seed bed.

5. Growing Rice Seedlings in Culture Solution

Five days after seed germination, the sand was washed from the
seedlings with a jet of tap water. Two seedlings of uniform size were
transferred to each of the 10 holes (6 mm diameter) on the plexiglass
plate as shown in Figure 2b. A 2-mm mesh nylon screen was glued onto
the underside of the plate to support the seedlings. The upper side
of the plate was sprayed with aluminum paint. The plexiglass plate
with twenty 5-day old seedlings was then transferred on the top of
the desiccator base filled with nutrient culture solution and kept near the window under the illumination mentioned above. The composition and concentration of culture solution employed were similar to those used by Tanaka and Navasero (1966d), except that a slightly lower pH was used. The culture solution consisted of 40 ppm of N, K, Ca, and Mg; 10 ppm P; 1 ppm Fe; and 0.5 ppm Mn, and was maintained at pH 4.0. Preparation of standard nutrient solution is shown in Table 1. The nutrient culture solution was changed every week until the rice seedlings (20- to 30-day old seedlings) were ready for transplanting. The space around the rice seedlings in each hole was sealed with an inert plastic material (permagum) before transplanting. Dry weight and chemical composition of the young rice seedlings are shown in Table 2.

6. Transplanting Procedure

Ten days after soil incubation, the first plexiglass plate was removed from the top of the desiccator base and the second plexiglass plate similar to the one removed but containing twenty 20- to 30-day old rice seedlings was placed on top of the desiccator base and sealed. After transferring the rice seedlings onto the desiccator base containing the preincubated soil suspension, platinum electrodes, a gas inlet and outlet along with a rubber serum cap and rubber stoppers were installed and used the same way as in the soil incubation procedure. Distilled water was added to fill the 2-liter desiccator base. This gave a soil:water ratio of approximately 1:4. Nitrogen, phosphorus, and potassium were added to the soil suspension at the rate of 75-100, 50, and 30 μg/ml suspension respectively. Distilled water was added whenever the volume fell below 2 liters. The rice plants were allowed
Table 1. Composition of standard nutrient solution for young rice seedlings

<table>
<thead>
<tr>
<th>Chemical Compound</th>
<th>Molecular Weight</th>
<th>Element</th>
<th>Atomic Weight of the Element</th>
<th>Weight of Compound Used to Prepare One Liter of Stock Solution (g)</th>
<th>Concentration of Stock Solution (ppm)</th>
<th>Volume of Stock Solution Used to Prepare One Liter of Final Solution (ml)</th>
<th>Concentration of Final Solution (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaH₂PO₄·H₂O</td>
<td>137.998</td>
<td>P</td>
<td>30.9739</td>
<td>8.9106</td>
<td>2000</td>
<td>5</td>
<td>10.0</td>
</tr>
<tr>
<td>NH₄NO₃</td>
<td>80.048</td>
<td>N</td>
<td>14.0067</td>
<td>22.8599</td>
<td>8000</td>
<td>5</td>
<td>40.0</td>
</tr>
<tr>
<td>KCl</td>
<td>74.560</td>
<td>K</td>
<td>39.1020</td>
<td>15.2545</td>
<td>8000</td>
<td>5</td>
<td>40.0</td>
</tr>
<tr>
<td>CaCl₂·2H₂O</td>
<td>147.030</td>
<td>Ca</td>
<td>40.0800</td>
<td>29.3473</td>
<td>8000</td>
<td>5</td>
<td>40.0</td>
</tr>
<tr>
<td>MgSO₄·7H₂O</td>
<td>246.498</td>
<td>Mg</td>
<td>24.3120</td>
<td>81.1115</td>
<td>8000</td>
<td>5</td>
<td>40.0</td>
</tr>
<tr>
<td>FeSO₄·7H₂O</td>
<td>278.020</td>
<td>Fe</td>
<td>55.8470</td>
<td>0.9956**</td>
<td>200</td>
<td>5</td>
<td>1.0</td>
</tr>
<tr>
<td>MnSO₄·H₂O</td>
<td>169.010</td>
<td>Mn</td>
<td>54.9380</td>
<td>0.3076**</td>
<td>100</td>
<td>5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

1 After Tanaka and Navasero (1966c), modified.

2 Used distilled water to dissolve each compound separately.

*Used tap water to prepare the bulk of final solution, brought initial pH of tap water to 4.0 prior to adding stock solution.

**Adjusted pH of distilled water to 3.0 with 2 N HCl prior to dissolving the compound.

Note: The final solution (pH 3.7-4.0) should have EC x 10⁻³ = approximately 1.4 mmhos/cm.
Table 2. Vegetative yield and chemical composition at different ages of young rice seedlings.

<table>
<thead>
<tr>
<th>Age of Seedlings* (day)</th>
<th>Dry Matter Wt. of 20 Plants</th>
<th>Nutrient Contents in Shoots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shoots (g)</td>
<td>Roots (g)</td>
</tr>
<tr>
<td>20</td>
<td>0.784</td>
<td>0.169</td>
</tr>
<tr>
<td>25</td>
<td>1.218</td>
<td>0.345</td>
</tr>
<tr>
<td>30</td>
<td>3.660</td>
<td>0.750</td>
</tr>
</tbody>
</table>

*Rice seedlings had been grown in nutrient solution

*Nutrient contents in shoots and roots combined
to grow for 14 to 20 days in the laboratory with conditions maintained at about 30°C under continuous illumination from 150 watt reflector flood lamps which were placed approximately 60 cm above the plants. Light intensity at the plants tops was approximately 500 foot candles.

7. **Electrical Conductivity Measurement**

Electrical conductivity of soil suspensions was measured by means of conductivity bridge employing a cell with a constant of approximately 2 reciprocal centimeters. The electrode was inserted directly into the soil suspension. The electrical conductivity was calculated based on the resistance value read from the relation: \( \text{EC}_t = k/R_t \), where \( \text{EC}_t \) was the electrical conductivity of the soil suspension at temperature \( t \), \( k \) was the cell constant, and \( R_t \) was the recorded resistance of the soil suspension at temperature \( t \).

C. **Rice Variety Used**

Saturn, a rice variety commonly grown in Louisiana, was used. Rice seeds were obtained from the Seed Testing Laboratory, Louisiana State University, Baton Rouge, Louisiana.

D. **NPK Fertilizer Used**

Basically nitrogen was added as \((\text{NH}_4)_2\text{SO}_4\) and followed by the second increment as \(\text{NH}_4\text{Cl}\). Different other sources of nitrogen were used in the tracer \(^{15}\text{N}\) studies. Phosphorus and potassium were added as \(\text{NaH}_2\text{PO}_4 \cdot \text{H}_2\text{O}\) and \(\text{KCl}\), respectively.

E. **Nitrogen-\(^{15}\text{N}\) Sources Used**

In the \(^{15}\text{N}\) tracer experiments, the following sources of nitrogen were used:
1) Ammonium sulfate containing 10.8414 atom percent $^{15}$N excess.
2) Sodium nitrate containing 10.0812 atom percent $^{15}$N excess.
3) Urea containing 9.9038 atom percent $^{15}$N excess.

F. Radioactive Isotopes Used

In the experiments utilizing $^{54}$Mn, $^{59}$Fe, $^{65}$Zn, and $^{32}$P studies, the following radioactive compounds were used:
1) Carrier-free $^{54}$MnCl$_2$ in 0.5 M HCl.
2) FeCl$_3$ tagged with $^{59}$Fe in 1.0 N HCl. The radioactive compound had a specific activity of 40.5 mCi/mg FeCl$_3$.
3) Carrier-free $^{65}$ZnCl$_2$ in 0.5 N HCl.
4) Carrier-free H$_3$PO$_4$ in 0.02 N HCl.

G. Description of Experiments

1. Effect of Aerobic and Anaerobic Conditions and pH on Soil Redox Potential and Growth and Uptake of Fe and Mn by Rice in a Flooded Soil

This experiment was designed (1) to study the effect of aerobic and anaerobic conditions and soil pH on redox potential of soil suspensions in which rice was grown, (2) to determine the amounts of acid and alkali required to maintain soil pH levels under aerobic and anaerobic conditions, and (3) to determine the growth of rice and the uptake of both native and added labelled Fe and Mn by the rice plants grown under these soil oxidation-reduction and pH conditions. The treatments were duplicated and are listed below:
(a) Aerobic pH 5.5 + labelled Mn
(b) Aerobic pH 5.5 + labelled Fe
(c) Aerobic pH 7.5 + labelled Mn
(d) Aerobic pH 7.5 + labelled Fe
(e) Anaerobic pH 5.5 + labelled Mn
(f) Anaerobic pH 5.5 + labelled Fe
(g) Anaerobic pH 7.5 + labelled Mn
(h) Anaerobic pH 7.5 + labelled Fe

The soil suspensions were incubated to obtain aerobic and anaerobic conditions as described under soil incubation procedure. Ten days after the beginning of soil incubation, the pH of aerobic and anaerobic soil suspensions was adjusted to 5.5 and 7.5 with measured amount of acid or alkali. Twenty-five-day old rice seedlings which had been grown in culture solution were transferred onto the aerobic and anaerobic soil suspensions as described under growing rice seedlings in culture solution and under transplanting procedure. N P K fertilizers were added at the rate of 50, 50, and 50 µg/ml respectively. A nitrification inhibitor, 2-Chloro-6-(trichloromethyl) pyridine (N-Serve) was used at the rate of 6 µg/g in all treatments to prevent formation of nitrate under aerobic conditions. Thus, the ammonium form of nitrogen was maintained both under aerobic and anaerobic conditions. Specific activity of radioactive isotopes added to respective treatments was 0.01 µCi/g for $^{54}$Mn and 0.02 µCi/g for $^{59}$Fe. A second increment of N as ammonium chloride was added at 25 µg/ml five days after transplanting. Plant height was measured at 7-day intervals until harvest. At harvest the soil suspension under anaerobic conditions was sampled to determine total sulfide-S.
At the end of the experimental period, which consisted of 14 days after transplanting, the shoots and roots of the rice plants were harvested and dried separately in a forced draft oven. After drying, the weights of shoots and roots were recorded, the shoots were wet ashed and analyzed to determine the concentration of native Fe and Mn and specific activity of added $^{59}\text{Fe}$ and $^{54}\text{Mn}$ taken up by the rice plants.

2. **Effect of Aerobic and Anaerobic Conditions and pH on Soil Redox Potential and Electrical Conductivity and Growth and Uptake of Zn and P by Rice in a Flooded Soil**

The purposes of this study were to determine (1) the effect of aerobic and anaerobic conditions and pH levels on redox potential, amount of acid and alkali added to maintain soil pH levels, and electrical conductivity of flooded soil suspensions which were used to grow rice, (2) the effect of these soil oxidation-reduction and pH conditions on growth, chemical composition, and uptake of native and added labelled Zn and P by the rice plants, and (3) recovery of added labelled Zn and P in the plant as affected by these experimental conditions.

Two identical experiments were conducted. Each experiment had the following treatments in duplicate:

(a) Aerobic pH 5
(b) Aerobic pH 6
(c) Aerobic pH 7
(d) Aerobic pH 8
(e) Anaerobic pH 5
(f) Anaerobic pH 6
(g) Anaerobic pH 7
(h) Anaerobic pH 8
The soil suspensions were incubated to obtain aerobic and anaerobic conditions as described in the section on soil incubation procedure. Fourteen days after the beginning of soil incubation, the pH of aerobic and anaerobic soil suspensions was adjusted to pH 5, 6, 7, and 8 with measured amounts of acid or alkali. Twenty-day old rice seedlings which had been grown in culture solutions were transferred to the aerobic and anaerobic soil suspensions as described above for growing rice seedlings in culture solution and under transplanting procedures. N P K fertilizers were added at the rates of 50, 50, and 50 μg/ml respectively. The nitrification inhibitor described above was added at the rate of 6 μg/g in all treatments to prevent nitrification of ammonium under aerobic conditions. In one experiment, carrier-free ZnCl₂ tagged with ⁶⁵Zn was added to all treatments at 0.1 μCi of ⁶⁵Zn/g of soil. In another experiment, all treatments received carrier-free H₃PO₄ tagged with ³²P at the rate of 0.08 μCi of ³²P/g of soil. A second increment of N as ammonium sulfate was added in both experiments at 25 μg/ml 14 days after transplanting. Redox potential was measured every day following the adjustment of soil pH. Electrical conductivity of aerobic and anaerobic soil suspensions and total sulfide-sulfur of soil suspension of anaerobic soil was determined at the end of the experimental period.

At the conclusion of each experimental period, which consisted of 20 days after transplanting, the shoot and root of the rice plants were harvested and dried separately in a forced draft oven. After drying, the weights of shoot and root were recorded, the shoot was wet ashed and analyzed to determine the mineral constituents and specific activity of ⁶⁵Zn and ³²P in the rice plant tissue.
3. Effect of Aerobic and Anaerobic Conditions and pH on Soil Redox Potential, Electrical Conductivity, Growth and Recoveries of Added Labelled Ammonium-N and Nitrate-N by Rice in a Flooded Soil

This experiment was designed to examine the effect of aerobic and anaerobic conditions and soil pH on the uptake of ammonium nitrogen and nitrate nitrogen by rice. Ammonium sulfate and sodium nitrate each enriched with $^{15}$N were used in this experiment. The specific objectives were to determine recovery of labelled N from ammonium sulfate and from sodium nitrate in different soil fractions and in the rice plants grown under aerobic and under anaerobic conditions controlled at pH 4.5, 6.0, and 7.5. An attempt was also made to study the effect of these soil oxidation-reduction and pH conditions on redox potential, amount of acid and alkali added to maintain pH, electrical conductivity, and distribution of applied N into different soil nitrogen fractions. The treatments were duplicate and as follows:

(a) Aerobic pH 4.5 + ($^{15}$NH$_4$)$_2$SO$_4$
(b) Aerobic pH 6.0 + ($^{15}$NH$_4$)$_2$SO$_4$
(c) Aerobic pH 7.5 + ($^{15}$NH$_4$)$_2$SO$_4$
(d) Aerobic pH 4.5 + Na$^{15}$NO$_3$
(e) Aerobic pH 6.0 + Na$^{15}$NO$_3$
(f) Aerobic pH 7.5 + Na$^{15}$NO$_3$
(g) Anaerobic pH 4.5 + ($^{15}$NH$_4$)$_2$SO$_4$
(h) Anaerobic pH 6.0 + ($^{15}$NH$_4$)$_2$SO$_4$
(i) Anaerobic pH 7.5 + ($^{15}$NH$_4$)$_2$SO$_4$
Soil incubation to obtain aerobic and anaerobic conditions was the same as described for the soil incubation procedure. Eight days after the beginning of the soil incubation, the pH of aerobic and anaerobic soil suspensions was adjusted to 4.5, 6.0, and 7.5 with measured amounts of acid or alkali. Thirty-day old rice seedlings which had been grown in culture solution were transferred onto the aerobic and anaerobic soil suspensions as described for the transplanting procedure. Nitrogen, phosphorus and potassium were added to the soil suspension at the rates of 100, 50, and 50 μg/ml, respectively. Nitrogen sources as either \((^{15}\text{NH}_4)\text{SO}_4\) with 10.8414 atom % \(^{15}\text{N}\), or \(\text{Na}^{15}\text{NO}_3\) with 10.0812 atom % \(^{15}\text{N}\) were added according to treatment. Phosphorus and potassium were added to all treatments as \(\text{NaH}_2\text{PO}_4 \cdot \text{H}_2\text{O}\) and \(\text{KCl}\), respectively. The nitrification inhibitor described above was added at the rate of 6 μg/g in all treatments to prevent nitrification of ammonium under aerobic conditions. Thus, the utilization of ammonium nitrogen and nitrate nitrogen applied under aerobic soil conditions can effectively be compared. Redox potential was measured every day following the adjustment of soil pH. Electrical conductivity of aerobic and anaerobic soil suspensions was measured at the end of the experiment.

At the end of the experimental period, which consisted of 14 days after transplanting, the shoot and root of the rice plants were harvested and dried separately in a forced draft oven. After drying, the weights of shoot and root were recorded and then mixed and finely ground. A portion of the plant sample from each treatment was digested and distilled for total nitrogen and for \(^{15}\text{N}\) isotope ratio analysis. A sample of the soil suspension from each treatment was removed for
determination of inorganic N (\(\text{NH}_4^+ - N + \text{NO}_3^- - N\)) and organic N and for \(^{15}N\) isotope ratio analysis.

4. **Effect of Aerobic and Anaerobic Conditions and pH on Soil Redox Potential, Electrical Conductivity, Growth and Recoveries of Added Labelled Amonium-N and Urea-N by Rice in a Flooded Soil.**

This experiment was designed to examine the effect of aerobic and anaerobic conditions and pH levels on recovery of applied \(^{15}N\) labelled ammonium sulfate and \(^{15}N\) labelled urea by rice plants in flooded soil. The specific objectives of this study were to determine: (1) the effect of aerobic and anaerobic conditions and pH levels on the nitrogen uptake of added labelled ammonium sulfate and urea by the rice plant grown in flooded soil, (2) the recovery of added labelled nitrogen in soil organic and inorganic nitrogen fractions as affected by the soil oxidation-reduction and pH conditions, and (3) the effect of these experimental conditions on soil redox potential, amount of acid and alkali required to maintain soil pH levels, electrical conductivity and the total recovery of applied nitrogen sources in the soils. The treatments were in duplicate and as follows:

(a) Aerobic  
\(\text{pH} 5.5 + \left(\text{^{15}NH}_4\right)_2\text{SO}_4\)

(b) Aerobic  
\(\text{pH} 5.5 + \left(\text{^{15}NH}_2\right)_2\text{CO}\)

(c) Aerobic  
\(\text{pH} 7.5 + \left(\text{^{15}NH}_4\right)_2\text{SO}_4\)

(d) Aerobic  
\(\text{pH} 7.5 + \left(\text{^{15}NH}_2\right)_2\text{CO}\)

(e) Anaerobic  
\(\text{pH} 5.5 + \left(\text{^{15}NH}_4\right)_2\text{SO}_4\)

(f) Anaerobic  
\(\text{pH} 5.5 + \left(\text{^{15}NH}_2\right)_2\text{CO}\)

(g) Anaerobic  
\(\text{pH} 7.5 + \left(\text{^{15}NH}_4\right)_2\text{SO}_4\)

(h) Anaerobic  
\(\text{pH} 7.5 + \left(\text{^{15}NH}_2\right)_2\text{CO}\)
Soil incubation to obtain aerobic and anaerobic conditions was the same as described under soil incubation procedure. Ten days after the beginning of the soil incubation, the pH of the aerobic and anaerobic soil suspension was adjusted to 5.5 and 7.5 with measured amounts of either acid or alkali. Twenty-five-day old rice seedlings which had been grown in culture solution were transferred to the aerobic and anaerobic soil suspensions as described under the transplanting procedure. Nitrogen, phosphorus and potassium were added to the soil suspension at the rates of 100, 50, and 50 ppm respectively. Nitrogen sources as either \((^{15}\text{NH}_4)_2\text{SO}_4\) with 10.8414 atom % \(^{15}\text{N}\) or \((^{15}\text{NH}_2)_2\text{CO}\) with 9.9038 atom % \(^{15}\text{N}\) were added according to the treatment listed above. Phosphorus and potassium were added to all treatments as \(\text{NaH}_2\text{PO}_4 \cdot \text{H}_2\text{O}\) and \(\text{KCl}\) respectively. No N-Serve, nitrification inhibitor was added. Redox potential was measured every day following the adjustment of soil pH. Electrical conductivity of aerobic and anaerobic soil suspensions was measured at the end of the experiment.

At the conclusion of the experiment, which was 14 days after transplanting, the shoots and roots of the rice plants were harvested and dried separately in a forced draft oven. After drying, the weights of shoots and roots were recorded and then mixed and finely ground. The plant samples were analyzed for \(^{15}\text{N}\) isotope ratio. Soil suspension from each treatment was taken at 0, 5, 10, and 15 days after transplanting for determination of \(\text{NH}_4^+\)-N and \(\text{NO}_3^-\)-N. Five ml of 1\% \(\text{HgCl}_2\) solution was added to the soil sample to stop biologically nitrogen transformation. The samples were stored in the refrigerator at 0°C until analysis. The \(^{15}\text{N}\) isotope ratio analysis was made for inorganic
(NH$_4^+$-15N + NO$_3^-$-15N) fraction and organic-15N fraction in soil suspension taken at the end of the experiment.

H. **Analytical Methods**

1. **Soil Analysis**

   a. **Determination of inorganic nitrogen.**

      (1) **Extraction.** Inorganic nitrogen (ammonium + nitrate) was extracted from the soil suspension by adding 10 grams of KCl into 100 ml of soil suspension and shaking for one hour. The samples were then filtered, using a Buchner funnel. The extracts were acidified by adding a drop of concentrated H$_2$SO$_4$ and stored in the refrigerator at 0°C until analyzed.

      (2) **Determination of ammonium-N.** The ammonium-N in the extract was determined by micro-Kjeldahl distillation with MgO (Bremner, 1965b). The distillate was collected in standard 0.1 N H$_2$SO$_4$ and analyzed colorimetrically following addition of Nessler's reagent.

      (3) **Determination of nitrate-N.** The nitrate-N in the extract was determined by micro-Kjeldahl distillation in the presence of Devarda's alloy (Bremner, 1965b) after the distillation of ammonium-N was completed. The distillate was collected in standard 0.1 N H$_2$SO$_4$ and analyzed colorimetrically following addition of Nessler's reagent.

      (4) **Determination of total inorganic-N.** The total inorganic nitrogen (ammonium + nitrate) in the extract was determined by macro-Kjeldahl distillation with MgO and Devarda's alloy added immediately before distillation (Bremner, 1965a). The distillate was collected in standard 0.1 N H$_2$SO$_4$ and titrated with standard 0.1 N NaOH using methyl red indicator. The titrated solution was further prepared for 15N analysis.
b. Determination of organic nitrogen. The soil remaining in the Buchner funnel after the extraction of inorganic nitrogen was oven-dried and analyzed for organic nitrogen by a modified Kjeldahl procedure employed by Tusneem and Patrick (1971). Five grams of soil sample, oven-dry basis, was placed in 650-ml Kjeldahl digestion flask. About 10 ml of distilled deionized water was added to the soil and allowed to stand for 20 minutes. The flask was then swirled carefully and 6 grams of digestion mixture (10 parts K$_2$SO$_4$, 1 part FeSO$_4$, 1/2 part of CuSO$_4$) were added. Then 15 ml of concentrated H$_2$SO$_4$ was added and the contents were mixed by swirling the flask. The digestion was then commenced and continued for two hours after the solution had cleared. The digested material was allowed to cool, diluted to 200 ml with distilled water, and distilled after adding 50 ml of 50% NaOH. The ammonia released by distillation was collected in standard 0.1 N H$_2$SO$_4$ and determined by titration with standard 0.1 N NaOH. The titrated solution was further prepared for $^{15}$N analysis.

c. Determination of total sulfide-S. The method used for the determination of total sulfide-sulfur was an iodometric method presented in Standard Methods for the Examination of Water and Waste-water (Farber, 1960) which was modified and used by Engler (1972).

2. Plant Analysis

a. Determination of mineral constituents. After harvesting, the plant tissue was dried in a forced draft oven at 65°C for 24 hours. After drying, the aerial portion of plants resulting from the various treatments was weighed and chopped by hand to a moderate degree of fineness. Duplicate 0.5 gram samples of plant tissue were wet-ashed with a 10:1:4 mixture of HNO$_3$-H$_2$SO$_4$-HClO$_4$ as described by Jackson (1958).
The solution remaining after digestion was brought up to volume in a 25 ml volumetric flask.

The concentration of iron, manganese, and zinc were measured without further dilution of the solution by means of a Perkin-Elmer 107 Atomic Absorption Spectrophotometer. Remaining solutions were used for radioassay of their respective tracers.

Phosphorus was determined colorimetrically on an aliquot of the solution by an ascorbic methods described by Watanabe and Olsen (1965). The optical density of the solution was measured with a Bausch and Lomb Spectronic 20 Spectrophotometer. Aliquot was saved for radioactive $^{32}$P assay.

b. **Determination of total nitrogen.** In the experiment dealing with tracer $^{15}$N, after harvesting the plant tissue was dried in a forced draft oven at 65°C for 24 hours. After drying, the shoots and roots of the rice plants resulting from various treatments were weighed and ground to moderate fineness. Total nitrogen in the plant tissue was analyzed by a modified Kjeldahl procedure similar to the one used for the determinations of soil organic nitrogen. The titrated solution was further prepared for $^{15}$N analysis.

3. **$^{15}$N Techniques**

The titrated samples containing nitrogen in the form of ammonium sulfate were concentrated so that about 3 ml of the final solution contained at least 1 mg N per ml. The $^{15}$N analysis was carried out using a DuPont Model 21-614 mass spectrometer according to the method of Rittenberg (1948) as described by Bremner (1965c).

Further calculation for atom-percent $^{15}$N excess and labelled N recovered was made after Jansson (1958).
4. **Radioassay Techniques**

**a. Assay of beta-emitting samples.** Radioassay of plant samples obtained from the experiment utilizing $^{32}$P (a beta-emitting) was made by liquid scintillation counting. Aliquots (5 ml) of wet-ashed plant samples described in the section on determination of mineral constituents were mixed with 10 ml of "Aquasol" (New England Nuclear, Boston, Mass.) and then counted for 10 minutes in a Beckman L.S.-250 Liquid Scintillation Spectrometer using the wide $^{32}$P discriminator (isoset). All samples, including standards, were assayed in an identical manner. Counting efficiency was calculated from the net counts (cpm) after subtraction of background activity and the absolute activity of the standards (in dpm). Appropriate decay corrections were also applied. Counting efficiency was then determined as follows:

$$\% \text{ efficiency} = \frac{\text{net cpm}}{\text{dpm}}$$

The counting efficiency obtained from the above relation was then used to convert the data to specific activity (where 1 $\mu$Ci = 2.22 x $10^6$ dpm) in $\mu$Ci/g of plant tissue, and to total activity in $\mu$Ci/pot. The percent of $^{32}$P recovered in the plants was also calculated from the total activity in the plant samples and the initial total activity added to the soil after appropriate decay corrections were made.

**b. Assay of gamma-emitting samples.** Plant samples obtained from the experiments dealing with the gamma-emitting radiotracers $^{59}$Fe, $^{54}$Mn, and $^{65}$Zn were assayed in a deep-well NaI (TI) counter. The size of the crystal was 2 x 2 inches right cylinder. Wet-ashed plant samples described in the section on determination of mineral constituents were used for radioassay. A 5 ml aliquot containing a single
label of either $^{59}$Fe or $^{54}$Mn or $^{65}$Zn was placed in a test tube and counted for 10 minutes. Best operating voltage was determined for each isotope separately by plotting the square of sample count rate $R_s^2$ over the background count rate $R_{bk}$ versus applied voltage. The "figure of merit" was at a maximum on the curve and this was the best operating voltage. These voltages, for each isotope ($^{54}$Mn: 950 v, $^{59}$Fe: 900 v, and $^{65}$Zn: 900 v) were also verified by the integral spectrum method for well-counters as described by Chase and Rabinowitz (1967). All of the samples and standards were assayed after the completion of each study. The samples as well as the dosing standards were derived from the same source of each radiotracer. The counting efficiency and the radioactivity of each radiotracer taken up by the plants were calculated in the same fashion as described under assay of beta-emitting samples.
RESULTS AND DISCUSSION

A. Effect of Aerobic and Anaerobic Conditions and pH on Soil Redox Potential and Growth and Uptake of Fe and Mn by Rice in a Flooded Soil

A laboratory study was conducted to evaluate the effect of aerobic and anaerobic conditions on soil redox potential and growth and Fe and Mn utilization by rice at controlled pH values of 5.5 and 7.5 in flooded soil suspension. The utilization of both added labelled and native soil Fe and Mn by rice plants was followed in this study.

1. Effect of Aerobic and Anaerobic Conditions and pH on Soil Redox Potential

Eight days after the beginning of soil incubation and before different pH levels were controlled, the redox potential under aerobic and anaerobic soil conditions differed markedly. The redox potential of the aerobic soil was as high as +683 mv at pH 4.6, while that of anaerobic soil was as low as approximately -64 mv at pH 5.7. A redox potential value of +300 mv at pH 5.0 is ordinarily considered to be a boundary between oxidized and reduced conditions (Aomine, 1962; Gotoh and Patrick, 1974).

When pH levels were controlled, the redox potential under aerobic and anaerobic soil conditions was shifted to more or less constant values at each pH level. Redox potential values of aerobic and anaerobic soil conditions controlled at pH 5.5 and 7.5 during the 14 days after transplanting are shown in Figure 3.
Figure 3. Effect of aerobic and anaerobic conditions on redox potential of the soil maintained at pH 5.5 and 7.5 after transplanting rice.

Figure 4. Effect of aerobic and anaerobic conditions on the amounts of acid and alkali required to maintain soil pH at 5.5 and 7.5.
Redox potential was constant at about +550 mv and +430 mv at pH 5.5 and 7.5, respectively, under aerobic soil conditions. Under anaerobic conditions, in contrast, the redox potentials were constant at about -160 mv and -280 mv at pH 5.5 and 7.5 respectively. The results showed the difference in the potential values between pH 5.5 and 7.5 (2 pH units) was about 120 mv or about 60 mv/pH unit under both conditions. This was close to the theoretical value (60 mv) used to correct Eh data to pH 7.0. Consequently, correcting Eh to pH 7.0 ($E_7$) for aerobic and anaerobic conditions gave +461 mv and -250 mv respectively.

Redox potential has a marked effect on manganese and iron behavior. Redox potential values ($E_7$) below +200 mv and +120 mv have been reported to be favorable for manganese reduction and iron reduction, respectively (Patrick, 1964; Turner and Patrick, 1968). In subsequent studies on transformation of manganese and iron in waterlogged soil at controlled pH, Gotoh and Patrick (1972, 1974) reported that at pH 5 appreciable reductions of manganese and iron occurred at redox potential as high as +500 mv and +300 mv, respectively.

2. Effect of Aerobic and Anaerobic Conditions and pH on the Amounts of Acid and Alkali Required to Maintain pH

During the incubation period of the soil, the pH decreased from its initial value of 5.2 to 4.6 under aerobic conditions and increased to 5.7 under anaerobic conditions. The total amounts of acid or alkali required to control the pH under the two soil oxidation-reduction conditions are shown in Figure 4.

Under anaerobic conditions, total amount of HCl required to control pH at 5.5 was 10.0 meq/100 g whereas 8.2 meq/100 g NaOH was required to
control pH at 7.5. No HCl was required under aerobic conditions, but approximately 2.8 and 6.9 meq/100 g NaOH were added to control soil pH at 5.5 and 7.5 respectively.

Fe and Mn reductions were probably responsible for HCl being required to maintain soil at pH 5.5 under anaerobic conditions. Reduction reactions of Fe and Mn under anaerobic conditions have been reported by many workers (i.e. Patrick, 1964; Ponnampерuma, 1972; Gotoh and Patrick, 1972, 1974). All of these reported reduction reactions involve the consumption of H⁺ ions. Calculations based on 1 meq of H⁺ ion reacting with approximately 0.5 meq of Fe³⁺ yield 2792 ppm of Fe²⁺ released under anaerobic conditions at pH 5.5. This amount represents the maximum amount of combined Fe²⁺ (and Mn²⁺ equivalent) released.

3. Effect of Aerobic and Anaerobic Conditions and pH on Plant Height and Dry Matter Weight

The heights of the rice plants which were grown under aerobic and anaerobic conditions controlled at pH 5.5 and 7.5 measured at different growth stages are shown in Figure 5.

Under the different soil oxidation-reduction and pH conditions the plants grew slowly during the first week after transplanting and did not show any appreciable differences among treatments. Two weeks after transplanting, however, the plants had grown considerably and showed marked differences among treatments. Plants grown under anaerobic conditions were taller than plants grown under aerobic conditions at both pH levels. Under both soil oxidation-reduction conditions, the plants grown at pH 5.5 were taller than the plants grown at pH 7.5. The differences in the heights of the plants grown under these
Figure 5. Effect of aerobic and anaerobic conditions on plant height measured at different periods of growth at pH 5.5 and 7.5.

Figure 6. Effect of aerobic and anaerobic conditions on dry matter weights of shoots and roots of the rice plants at pH 5.5 and 7.5.
oxidation-reduction conditions and pH treatments indicate that differences in soil oxidation-reduction conditions and pH have nutritional and physiological effects on the rice plants.

The effect of aerobic and anaerobic conditions on the dry matter weight of shoots and roots of the rice plants grown at pH 5.5 and pH 7.5 is shown in Figure 6.

Plants grown under anaerobic conditions produced greater dry weight of shoots and roots than plants grown under aerobic conditions at all pH levels. There was no appreciable effect of the two soil pH levels on the weight of shoots and roots of the plants grown under aerobic conditions. The dry weight of shoots and roots of the plants grown under anaerobic conditions, on the other hand, was markedly affected by the two soil pH levels. The dry weight of shoots of the plants grown under anaerobic conditions was greater at pH 5.5 than at pH 7.5. The greater dry weight of the shoots of the plants grown at pH 5.5 as compared to that grown at pH 7.5 may be due to greater solubility and subsequent availability of certain plant nutrients at low pH as compared to those at high pH under reducing conditions. Among these nutrients are Fe and Mn (Gotoh and Patrick, 1972, 1974). It is interesting to note that plants grown under anaerobic conditions produced greater shoot weight but lower root weight at pH 5.5 than at pH 7.5. Greater dry matter weight of roots and lower weight of shoots of the plants grown under anaerobic conditions at pH 7.5 compared to pH 5.5 might be due to lower redox potential of the soil under anaerobic conditions. These results suggest either better ability of rice roots to proliferate under greater reducing conditions or the need for a more extensive root system. No such
relationship in the shoot and the root weight was observed in the plants grown under aerobic conditions.

Young leaves of the plants grown under aerobic conditions were chlorotic at all pH levels. This symptom was observed during the first week after transplanting and appeared to be similar to iron deficiency symptoms. Other physiological disorders were also observed in the rice plants which were grown under anaerobic conditions. Rice which was grown under anaerobic conditions at pH 5.5 showed iron toxicity symptoms and at pH 7.5 rice plants showed symptomless toxicant disease (Hollis, 1967) apparently due to soluble sulfide. Analysis of soil under anaerobic conditions at the end of the experiment revealed that total sulfide-sulfur was 2.2 ppm at pH 5.5 and 19.4 ppm at pH 7.5. Examination of rice roots at the conclusion of the experiment also revealed that the roots of rice plants grown under anaerobic conditions had a slightly orange-brown coating at pH 5.5 and were blackened and apparently unhealthy at pH 7.5. The soil under latter conditions smelled strongly of H₂S. The roots under aerobic conditions were creamish-white and apparently healthier at pH 5.5 than at pH 7.5.

4. Effect of Aerobic and Anaerobic Conditions and pH on Concentrations of Native and Added Labelled Fe and Mn in the Rice Plants

The effect of aerobic and anaerobic conditions on concentrations of native soil Fe and Mn in the rice plants at controlled pH 5.5 and 7.5 is shown in Figure 7.

Both soil oxidation-reduction conditions and pH had marked effects on concentrations of native soil Fe and Mn in the rice plants. At pH 5.5, the concentrations of native soil Fe in the plants under anaerobic
Figure 7. Effect of aerobic and anaerobic conditions on concentrations of native soil Fe and Mn in the rice plants at pH 5.5 and 7.5.

Figure 8. Effect of aerobic and anaerobic conditions on concentrations (specific activity) of added labelled Fe and Mn in the rice plants at pH 5.5 and 7.5.
conditions was about five times higher than for any other soil oxidation-reduction and pH conditions. The high concentration of native soil Fe in the plant under anaerobic conditions at pH 5.5 was probably due to the presence of large amounts of ferrous iron and manganous manganese (Gotoh and Patrick, 1972, 1974). The low concentration of native soil Fe in the plants under aerobic conditions was due to the fact that iron was not mobile under oxidized conditions and that the minimum pH value used in this experiment was not low enough to effect its mobility.

High concentration of Fe in the plants grown under anaerobic conditions is in agreement with the findings of Ponnamperuma, Bradfield, and Peech (1955), but is contrary to the findings of Chaudhry and McLean (1963).

The concentration of native soil Mn in the plant under anaerobic conditions was about three times higher than under aerobic conditions at pH 5.5 and about four times higher at pH 7.5. However, similar to the concentration of native soil Fe in the plant under aerobic conditions, no appreciable difference was observed in the concentration of native soil Mn in the plants under aerobic conditions at both controlled pH levels. This is due to the fact that manganese, too, was not especially mobile under oxidized conditions. The higher native soil Mn content in the plants which were grown under anaerobic conditions than native Mn content in the plants which were grown under aerobic conditions at all pH levels found in this experiment is in agreement with the findings of Clark, Nearpass, and Sprecht (1957), but is contrary to the findings of Senewiratne and Mikkelsen (1961).
The results suggest that as the pH level of the soil under aerobic conditions increased, the concentration of native soil Fe in the plants decreased. In contrast, as the pH levels increased, the concentration of native soil Mn in the plants increased. It appears that these two elements at least partially regulate the absorption of one another. This finding is in agreement with the results of Tanaka and Navasero (1966b) which was explained as an antagonism between these nutrients. The ratio of native soil Fe and Mn concentration in the plant under different soil oxidation-reduction conditions and pH treatments are noteworthy. Plants grown under aerobic conditions controlled at pH 5.5 and 7.5 had Fe/Mn ratios of 0.92 and 1.23 respectively and were chlorotic. Plants grown under anaerobic conditions at pH 5.5 had Fe/Mn ratio of 1.75 and had slight chlorosis. Plants grown under anaerobic conditions at pH 7.5 had the lowest Fe/Mn ratio of 0.3 but were not chlorotic. Chlorosis in the plant grown under aerobic conditions was apparently due to low contents of both iron and manganese. Tanaka and Navasero (1966c) reported that a low content of iron and high content of phosphorus, calcium, manganese or organic acids accompanied chlorosis. Bronzing in the plants grown under anaerobic conditions at pH 5.5 was probably due to iron toxicity since the level of Fe shown in the plant tissue represented a toxic level for the rice plants. Iron content above 300 ppm in the leaf blade has been reported to be toxic to the rice plants (Tanaka, Loe, and Navasero, 1966; IRRI, 1969).

The effect of aerobic and anaerobic conditions on the concentration or specific activity of labelled Fe and Mn in the rice plants at controlled pH 5.5 and pH 7.5 is shown in Figure 8.
Relatively similar trends were observed with the concentration of labelled Fe (Figure 8) as with the concentrations of native soil Fe (Figure 7) in the plants as affected by both soil oxidation-reduction conditions and pH. These results suggest a uniformly label of all added $^{59}$Fe with native soil Fe fractions which were available to plants. The results with labelled Mn were not consistent with the results for native soil Mn. The concentration of labelled Mn in the plant tissue under aerobic conditions was almost equal to or higher than under anaerobic conditions. The different trends in the absorption of labelled Mn and native soil Mn by the plants under anaerobic conditions suggest that labelled Mn added to the soil two days prior to transplanting did not uniformly label all of the native soil Mn. To insures uniformly labelled native soil Mn after mixing labelled Mn, Gotoh and Patrick (1972) kept the soil submerged for three weeks at 30°C and then held 1/3 bar moisture percentage for another three weeks. However, the results with the high absorption of labelled Mn by the plants under aerobic conditions indicated further that if manganese is not a limiting factor in the soil solution, absorption of this nutrient would also be affected by pH and increased as the pH of the soil solution increased. The increased concentrations of labelled Mn in the plants under both aerobic and anaerobic conditions as the pH increased was marked.

5. **Effect of Aerobic and Anaerobic Conditions and pH on Total Uptake of Native and Added Labelled Fe and Mn by the Rice Plants**

The effect of aerobic and anaerobic conditions on the uptake of native soil Fe and Mn by the rice plants at controlled pH 5.5 and pH 7.5 is shown in Figure 9. Nutrient uptake by plants involves dry
Figure 9. Effect of aerobic and anaerobic conditions on the uptake of native soil Fe and Mn by the rice plants at pH 5.5 and 7.5.

Figure 10. Effect of aerobic and anaerobic conditions on the uptake (total activity) of added labelled Fe and Mn by the rice plants at pH 5.5 and 7.5.
matter weight and the concentration of nutrients in the plant tissue. Nutrient uptake may be a better criterion for evaluating treatments than concentration of nutrients in the plant tissue.

There were marked differences in the uptake of native soil Fe and Mn in the rice plants as affected by soil oxidation-reduction conditions and pH. At pH 5.5, approximately five to seven times more soil Fe was taken up by the plants under anaerobic conditions than under any other soil oxidation-reduction and pH conditions. The higher uptake of this nutrient by the plant was due to both higher concentrations of native soil Fe in the plant tissue and relatively higher dry matter weight.

The uptake of native soil Mn by the plant followed the same pattern as the concentration of this nutrient in the plant tissue. The uptake of native soil Mn by the plants under anaerobic conditions was about four times higher than under aerobic conditions at pH 5.5 and about five times higher at pH 7.5. The greater uptake of this nutrient was also due to both higher concentrations of native soil Mn in the plant tissue and higher dry matter weight.

It is interesting to note that the two soil pHs had no effect on the uptake of both native soil Fe and Mn by the plant under aerobic conditions. The slightly higher native soil Fe uptake by the plants under anaerobic conditions at pH 7.5 was due to slightly higher dry matter weight.

The increase in native soil Mn uptake by the plants as the pH increased under anaerobic conditions was marked. In spite of the decreased dry matter weight as the pH increased, higher uptake of this element occurred as a result of higher concentrations of native soil Mn in the plant tissue.
The effect of aerobic and anaerobic conditions on the uptake (or total activity) of labelled Fe and Mn by the rice plants at controlled pH 5.5 and pH 7.5 is shown in Figure 10.

The uptake of labelled Fe and Mn by the rice plants differed appreciably for different soil oxidation-reduction and pH conditions and followed the same pattern as already discussed above except in the case of the uptake of labelled Mn by the plant under anaerobic conditions at pH 5.5. The increased labelled Mn concentration in the plants for this treatment was due to increased dry matter weight.

6. Effect of Aerobic and Anaerobic Conditions and pH on Recoveries of Added Labelled Fe and Mn by the Rice Plants

The effect of aerobic and anaerobic conditions on the recoveries of added labelled Fe and Mn by the rice plant under controlled pH 5.5 and pH 7.5 is shown in Figure 11.

Recovery of labelled Fe was as high as 0.24% in the plants grown under anaerobic conditions at pH 5.5 followed by 0.03, 0.03, 0.03, and 0.02% in the plants grown under the same conditions at pH 7.5, and in the plants grown under aerobic conditions at pH 5.5 and pH 7.5 respectively. The higher recovery percentage of labelled Fe in the plants grown under anaerobic conditions at pH 5.5 than under any other soil oxidation-reduction condition and pH treatments reflects the higher concentration of this labelled element in the soil.

Percent recovery of labelled Mn in the plants was higher under anaerobic than under aerobic conditions and increased slightly as the pH increased under both conditions. As the pH increased from 5.5 to 7.5, the amount of labelled Mn recovered increased from 0.60 to 0.74% under aerobic conditions, and from 0.82 to 0.89% under anaerobic
Figure 11. Effect of aerobic and anaerobic conditions on recoveries of added labelled Fe and Mn by the rice plants at pH 5.5 and 7.5.
conditions. Higher recovery of labelled Fe at low pH than at high pH and the lower recovery of labelled Mn at low pH than at high pH in the plants grown under both soil conditions again suggest that Mn uptake is partially governed by Fe uptake, and Mn uptake is low when Fe uptake is high and vice versa.

It is interesting to note, in general, that the recovery of both labelled Fe and Mn in the plants for all treatments is less than 1%. The low recovery percentage of these labelled elements was probably due to either dilution of these labelled elements in the soil solution or short duration of the experiment. Higher recovery of $^{54}$Mn than $^{59}$Fe was due to higher requirements of manganese than iron by rice plants. High manganese requirement by rice plants have been reported by several workers (i.e. Tanaka and Navasero, 1966a).

B. Effect of Aerobic and Anaerobic Conditions and pH on Soil Redox Potential and Electrical Conductivity and Uptake of Zn and P by Rice in a Flooded Soil

Two laboratory experiments were conducted to determine the effect of aerobic and anaerobic conditions and pH on soil redox potential, electrical conductivity, vegetative yield, chemical composition, and nutrient uptake by rice. Either labelled Zn or P was added and followed in these experiments. Soil pH was controlled at pH 5, 6, 7, and 8 under both aerobic and anaerobic conditions. The rice plants were allowed to grow under controlled conditions for 20 days after transplanting 20-day old seedlings. The results shown represent averages of the values obtained for each treatment from both experiments.
1. Effect of Aerobic and Anaerobic Conditions and pH on Soil Redox Potential

The results obtained from redox potential measurements made in the aerobic and anaerobic soil suspensions which had been maintained at different pH levels for 20 days after transplanting rice are shown in Figure 12.

The Eh values of aerobic and anaerobic soil conditions which were controlled at pH 5, 6, 7, and 8 remained more or less constant during the 20 days after transplanting rice. An increase of one unit in pH for the aerobic soil resulted in a decrease of approximately 66 mv. This value was close to the value of 59 mv per unit pH change which is often used to correct Eh data to pH 7.

Under anaerobic conditions at pH 5, soil biological activity is affected by the acidity and soil reduction is not as intense as for soil maintained at pH 6, 7, or 8. This accounts for the 140 mv difference between pH 5 and pH 6 rather than the theoretical 60 mv change.

2. Effect of Aerobic and Anaerobic Conditions and pH on the Amounts of Acid and Alkali Required to Maintain pH

The total amount of acid or alkali required to control pH of aerobic and anaerobic soil conditions to pH 5, 6, 7, and 8 is shown in Figures 13a and 13b.

Under aerobic conditions, the total amount of NaOH required steadily increased as the pH increased (Figure 13a). Little or no HCl was required to maintain pH 5 under aerobic conditions. The tendency for soils to increase in acidity under aerobic conditions is
Figure 12. Effect of aerobic and anaerobic conditions on redox potential of the soil maintained at pH 5, 6, 7, and 8 after transplanting rice.
Figure 13. Effect of aerobic (a) and anaerobic (b) conditions on soil electrical conductivity and the amounts of acid and alkali required to maintain pH 5, 6, 7, and 8.

Figure 14. Effect of aerobic (a) and anaerobic (b) conditions on soil redox potential and total sulfide-sulfur in soil maintained at pH 5, 6, 7, and 8.
demonstrated in the increased amount of alkali added to maintain higher pH values. Under anaerobic conditions, on the other hand, the substances produced as a result of soil reduction tended to shift the soil pH to values near the neutral point (Redman and Patrick, 1965). Obviously either acid or alkali were needed to control pH levels below or above this point. As shown in Figure 13b, the amounts of either HCl or NaOH steadily increased as pH levels decreased or increased from approximately pH 6.5 which was the pH value of the anaerobic soil before adjustment.

3. Effect of Aerobic and Anaerobic Conditions and pH on Soil Electrical Conductivity

Electrical conductivity values of aerobic and anaerobic soil suspensions which were controlled at pH 5, 6, 7, and 8 are shown in Figures 13a and 13b.

Increase in pH levels steadily increased the electrical conductivity of aerobic soil suspension (Figure 13a). The increase in electrical conductivity as the pH increased was closely related to the increase in the amount of NaOH added. Under anaerobic conditions, electrical conductivity steadily increased as pH decreased or increased from the near neutral point (Figure 13b). This trend was closely related to the amount of acid or alkali added.

4. Effect of Aerobic and Anaerobic Conditions and pH on Total Soil Sulfide Content

The effect of aerobic and anaerobic conditions and pH on total sulfide content in flooded soils controlled at pH 5, 6, 7, and 8 is shown in Figures 14a and 14b.
No sulfide was detected under aerobic conditions at any pH levels. This was due to very high redox potential of soil under this condition (Figure 14a). It has been reported by Connell and Patrick (1968) that little or no sulfide accumulated with a redox potential above -150 mV, or outside a pH range of 6.5 to 8.5. Redox potential values measured under aerobic conditions were +635, +575, +501, and +437 mV for pH values 5, 6, 7, and 8, respectively. Under anaerobic conditions, on the other hand, approximately 9.8, 25.3, and 25.2 μg/g of total sulfide was detected at pH 6, 7, and 8, respectively. No sulfide was detected at pH 5. Sulfide was either not produced at pH 5, as suggested by Connell and Patrick, or that which was produced but escaped as H₂S under the slightly acid conditions. Redox potential values of the soil under this condition were -55, -195, -240, and -279 mV at pH 5, 6, 7, and 8, respectively (Figure 14b).

5. **Effect of Aerobic and Anaerobic Conditions and pH on Weight of the Rice Plants**

The effect of aerobic and anaerobic conditions on the dry matter weight of shoots and roots and the shoot/root ratio of the rice plants grown at controlled pH 5, 6, 7, and 8 is shown in Figures 15a and 15b.

Dry matter weight of shoots of the plants grown under aerobic conditions steadily decreased as soil pH increased. The weight of shoots of the plants grown under anaerobic conditions, on the other hand, steadily decreased as the pH decreased or increased from pH 6 (Figure 15a). Yields were inversely related to electrical conductivity. Apparently the increased soluble salts which resulted from increased electrical conductivity of soil contributed to decreased growth of the plants.
Figure 15. Effect of aerobic and anaerobic conditions on weights of shoots and roots (a) and the shoot/root ratio (b) of the rice plants at pH 5, 6, 7, and 8.
The difference in weight of shoots between aerobic and anaerobic conditions at pH 5 was marked. No appreciable difference was observed above pH 6. In contrast, no appreciable difference existed in dry matter weight of roots between these two redox conditions at pH 5, but the difference above pH 6 was marked. These results suggest either the better ability of rice roots to proliferate under anaerobic conditions or the need for a more extensive root system. The greater root growth under anaerobic conditions is reflected in the shoot/root ratio (Figure 15b).

Physiological disorders of the plants were observed in these experiments. Plants grown under aerobic conditions were chlorotic at all pH levels. Plants grown under anaerobic conditions were normal at pH 6 and 7 which corresponded to redox potential values of -194 and -240 mv. Outside this pH range, plants showed toxicity symptoms typical of iron toxicity (Tanaka and Navasero, 1966c; Ponnamperuma, Bradfield, and Peech, 1955) at pH 5 (-55 mv) and typical of toxicant disease apparently caused by soluble sulfide (Hollis, 1967) at pH 8 (-289 mv). Photos 1 and 2 illustrate the growth performance of the plants grown under these soil oxidation-reduction and pH conditions.

6. Effect of Aerobic and Anaerobic Conditions and pH on Concentrations of Nonlabelled and Labelled Zn and P in the Rice Plants

The effect of aerobic and anaerobic conditions on the concentrations of nonlabelled and specific activity of labelled Zn and P in the plant tissue grown at pH 5, 6, 7, and 8 is shown in Figures 16a, 16b, 17a, and 17b.
Photo 1. Growth performance of the rice plants under aerobic (oxidized) conditions at different controlled pH levels.

Photo 2. Growth performance of the rice plants under anaerobic (reduced) conditions at different controlled pH levels.
Figure 16. Effect of aerobic and anaerobic conditions on concentration of native Zn (a) and on specific activity of $^{65}\text{Zn}$ (b) in the rice plants at pH 5, 6, 7, and 8.

Figure 17. Effect of aerobic and anaerobic conditions on concentration of native and added nonlabelled P (a) and on specific activity of added $^{32}\text{P}$ (b) in the rice plants at pH 5, 6, 7, and 8.
As shown in Figure 16a, both soil oxidation-reduction conditions and pH had marked effects on concentration of native Zn in the plant tissue. Plants which were grown under aerobic conditions had higher Zn content than plants which were grown under anaerobic conditions. The Zn content in the plants grown under both conditions progressively decreased as pH increased. There was a sharp decrease in Zn content in the plants which were grown under aerobic conditions at pH 7 to 8 range. Consequently, at pH 8, Zn content in the plants grown under both soil conditions showed only a slight difference as compared to any other pH level.

Lower Zn content in the plants grown under anaerobic conditions as compared to Zn content in the plants grown under aerobic conditions was apparently due to the formation of sulfide and possibly production of organic complexing agents brought on by soil reduction under anaerobic conditions (Figure 14b). It has been reported that soil reduction depressed the concentration of Zn in the solutions of flooded soils and Zn uptake by rice plants (IRRI, 1970).

A possible explanation for the decreased Zn content in the plants grown under both soil conditions as pH increased is that solubility and stability of Zn are pH dependent with high solubility at low pH and low solubility at high pH. Data shown by Verloo (1974) indicated a sharp drop of solubility and stability of Zn and Zn humate as pH increased above approximately pH 6. Further, it has been reported that solubility and availability of Zn to rice plants and upland crops are depressed by high pH (IRRI, 1970; Sedberry et al., 1971).

Figure 16b depicts the effect of soil oxidation-reduction conditions and pH on concentration of labelled Zn in the plant tissue.
Carrier-free ZnCl₂ tagged with ⁶⁵Zn was added to aerobic and anaerobic soil suspensions at time of transplanting. Concentration of labelled Zn in the plant tissue was reported as specific activity of ⁶⁵Zn in microcurie per gram of plant tissue. Almost identical relationships between absorption of Zn by plants and soil pH-redox conditions were obtained when ⁶⁵Zn activity was considered instead of native Zn concentration in the plant tissue. These results suggest a uniformly labelling of native Zn with ⁶⁵Zn in the soil solution.

Data in Figure 17a show the effect of soil oxidation-reduction conditions and pH on concentration of P in the plant tissue. Each container received an initial application of 200 µg/g of P added at transplanting time. The concentration of P in the plant tissue of aerobic and anaerobic treatments did not differ appreciably. This may be due to the plants having access to a relatively large amount of P in soil solution under both conditions. The data shown by Patrick and Khalid (1974) indicated an equal amount of P was released in solution after adding approximately 200 µg/g of P to oxidized and reduced suspensions of Mhoon soil. In general, lowland rice shows considerably less response to P than do upland crops grown on the same soil. Results from many experiments have shown that response to added P was similar for rice grown under flooded and nonflooded soils.

A marked effect of soil pH on the P concentrations in the plant tissue for both soil redox conditions was observed. Concentration of P in the plant tissue consistently decreased with each stepwise increase of pH and was approximately twice as much at pH 5 as at pH 8 for both soil redox conditions. As pH increased, P in soil solution may have been precipitated as ferric phosphate under aerobic conditions and as
ferrous phosphate under anaerobic conditions. Williams and Patrick (1973) found that ferric phosphate solubility increased markedly at low pH and ferrous phosphate precipitation favored strengite formation at high pH.

The data illustrated in Figure 17b show the effect of aerobic and anaerobic conditions and pH on specific activity of $^{32}$P in the plant tissue. In this experiment, carrier-free $\text{H}_3^{32}\text{PO}_4$ was uniformly dissolved in sodium phosphate solution to attain equilibrium conditions prior to adding to various soil redox condition-pH treatments at transplanting time. Relatively similar trends were observed with the specific activity of labelled P in the plant tissue (Figure 17b) as with the concentration of P in the plant tissue (Figure 17a). These results indicated an attainment of equilibrium conditions between $^{32}$P and P in the soil solution.

Tissue analysis data for Fe, Mn, Zn, and P contents in the above ground portion of the rice plants are tabulated in Table 3. A close examination of P content in this data revealed a slightly higher P content in the plant tissue grown under anaerobic conditions at pH 5 and 8 as compared to aerobic conditions at the same pH levels. Soil P released as a consequence of ferric phosphate reduction to more soluble ferrous phosphate under reducing conditions, as reported by Williams and Patrick (1973) must be responsible for the slightly higher P content in the plants grown under anaerobic than aerobic conditions. If this is the case, anaerobic soil should have higher amounts of P in soil solution than should aerobic soil. Therefore, the remarkable lower amount of Zn concentration in the plants grown under anaerobic conditions than under aerobic conditions as observed might be partly due to higher
Table 3. Effect of aerobic and anaerobic conditions and pH on nutrient contents in the top portion of the rice plants.

<table>
<thead>
<tr>
<th>pH</th>
<th>Dry Matter Wt.(^1/) of Shoots (g)</th>
<th>Nutrient Contents ((\mu g/g))</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Zn</td>
<td>Fe</td>
<td>Mn</td>
<td>P</td>
</tr>
<tr>
<td>5</td>
<td>3.14</td>
<td>83</td>
<td>111</td>
<td>420</td>
<td>7360</td>
</tr>
<tr>
<td>6</td>
<td>2.64</td>
<td>75</td>
<td>145</td>
<td>136</td>
<td>7010</td>
</tr>
<tr>
<td>7</td>
<td>2.54</td>
<td>70</td>
<td>154</td>
<td>137</td>
<td>5780</td>
</tr>
<tr>
<td>8</td>
<td>1.95</td>
<td>32</td>
<td>129</td>
<td>109</td>
<td>4460</td>
</tr>
</tbody>
</table>

**AEROBIC**

| 5  | 2.06                             | 50     | 2025   | 361    | 8110  |
| 6  | 2.80                             | 35     | 1131   | 358    | 6360  |
| 7  | 2.68                             | 31     | 266    | 568    | 5790  |
| 8  | 1.92                             | 19     | 193    | 402    | 5060  |

**ANAEROBIC**

| 5  | 0.78                             | 35     | 125    | 80     | 4500  |

CK = Twenty 20-day-old rice seedlings used at transplanting.

\(^1/\) Dry matter weight of shoots of twenty plants in a container (pot) at harvest.
amounts of soil P in the solution under the former than under the latter conditions. P-induced Zn deficiency in other crops have been reported (Lucas and Knezek, 1972). Similar phenomena has been reported in the rice plants grown in the field conditions (Mueller, 1970). IRRI (1970) likewise reported the results obtained from greenhouse that as the available P content of the soil increased, the Zn content of the straw decreased and that the interaction between available P and pH influenced the Zn content of the straw. However, the Zn content in the rice plant grown under anaerobic conditions were low but were above the critical content of Zn in the rice plant of 10 ppm for Zn deficiency as reported by Ishizuka (1971).

Fe content in the plants grown under aerobic conditions was especially low as compared to that in the plants grown under anaerobic conditions. The low Fe content in the rice plants lead to chlorotic symptoms typical of Fe deficiency as observed in the young leaves a few days after transplanting rice. There seemed to have no pH effect on the Fe content in the plants grown under aerobic conditions. Under anaerobic conditions, on the other hand, plants grown at low pH, pH 5 and 6, had Fe content much higher than the toxic levels. It appears that the rice plants did respond to increased solubility of Fe as a result of soil reduction intensity and pH levels. Bronzing, a typical iron toxicity symptom as observed in the plants grown under these treatments was apparently caused by high iron contents in the plant tissue.

Mn content in the plants grown under aerobic conditions was very low except at pH 5 where the content was equally high as compared to the Mn content in the plant grown under anaerobic conditions. Apparently
either soil acidity or Fe content in the plants or both variables must have regulated the absorption of Mn by the rice plants. The Fe and Mn contents in the rice plants grown under these soil oxidation-reduction conditions and pH treatments showed similar patterns as had been shown in the previous study on Fe and Mn utilizations by the rice plants. The content of Fe, Mn, and Zn in the plant tissue gave no indication that Fe or Mn interfered with the absorption of Zn. This result agrees with the findings of IRRI (1970).

7. Effect of Aerobic and Anaerobic Conditions and pH on Uptake of Nonlabelled and Labelled Zn and P by the Rice Plants

The effect of aerobic and anaerobic conditions on the uptake of nonlabelled and on the total activity of labelled Zn and P by the plants grown at pH 5, 6, 7, and 8 is shown in Figure 18a, 18b, 19a, and 19b.

Uptake of Zn by the plants was markedly affected by soil oxidation-reduction conditions and pH as shown in Figure 18a. The higher Zn uptake by the plants grown under aerobic conditions was due to a higher concentration of Zn in the plant tissue. The greater difference in Zn uptake of the plants grown between the two soil redox conditions at pH 5 was due to greater differences in both the concentrations of Zn in the plant tissue and the dry matter weight. However, the difference in Zn uptake of the plants grown between the two soil redox conditions at higher pH levels was due to differences in concentrations of Zn in the plant tissue alone as the dry matter weight of the plants for the two soil redox conditions did not differ appreciably. Under both soil conditions, the uptake of Zn by the plants consistently decreased as pH increased. The decreased uptake of Zn by the plants as pH increased
Figure 18. Effect of aerobic and anaerobic conditions on the uptake of native Zn (a) and on total activity of added $^{65}$Zn (b) by the rice plants at pH 5, 6, 7, and 8.

Figure 19. Effect of aerobic and anaerobic conditions on the uptake of native and added nonlabelled P (a) and on total activity of added $^{32}$P (b) by the rice plants at pH 5, 6, 7, and 8.
was due to decreased concentration of Zn in the plant tissue and decreased dry matter weight.

Data in Figure 18b illustrate the effect of soil oxidation-reduction conditions and pH on the uptake of labelled Zn by the plants. Uptake of labelled Zn by the plants was reported as total activity of $^{65}\text{Zn}$ in microcurie per dry matter weight of shoot in a pot. An identical relationship was obtained between specific activity and total activity of $^{65}\text{Zn}$ in the plants. The greater difference in total activity of $^{65}\text{Zn}$ in the plants grown under aerobic and anaerobic conditions at pH 5 was due to greater differences in specific activity of $^{65}\text{Zn}$ in the plant tissue and dry matter weight. Slight differences in total activity of $^{65}\text{Zn}$ was observed as pH approached pH 8 since there was no appreciable difference in specific activity of $^{65}\text{Zn}$ in the plant tissue and no appreciable difference in dry matter weight.

Data illustrated in Figure 19a show the effect of soil oxidation-reduction conditions and pH on the uptake of P by the plants. The uptake of P by the plants grown under aerobic and anaerobic conditions did not differ appreciably except in the case of the plants grown under these redox conditions at pH 5. The differences in P uptake by the plants grown under these treatments were due to differences in dry matter weight as well as concentration of P in the plant tissue. A stepwise increase in soil pH from 5 to 8 resulted in an essential decrease in P uptake by the plants grown under both soil redox conditions. The decreased P uptake by the plants as pH increased was due to decreased P concentration in the plant tissue and decreased dry matter weight.
The effect of soil oxidation-reduction conditions and pH on the uptake of $^{32}\text{P}$ by the plants is shown in Figure 19b. The uptake of $^{32}\text{P}$ is reported as total activity of $^{32}\text{P}$ per dry matter weight of shoots in a pot. Relatively identical trends were obtained with the total uptake of $^{32}\text{P}$ by the plants (Figure 19b) as with the concentration of $^{32}\text{P}$ in the plant tissue (Figure 17a).

8. Effect of Aerobic and Anaerobic Conditions and pH on Recoveries of Added Labelled Zn and P by the Rice Plants

The effect of aerobic and anaerobic conditions on recovery of $^{65}\text{Zn}$ and $^{32}\text{P}$, by the rice plants maintained at pH 5, 6, 7, and 8 is shown in Figures 20a and 20b.

Data in Figure 20a show the effect of soil oxidation-reduction conditions and pH on percent recovery of $^{65}\text{Zn}$ in the plants. Soil oxidation-reduction conditions and pH had a marked effect on the recovery. From the initially added 50 μCi/pot of $^{65}\text{Zn}$, after appropriate correction for half-life disintegration was made, as much as 6.0, 6.0, 4.6, and 0.6% found its way to the shoots of the plants grown under aerobic conditions at pH 5, 6, 7, and 8, respectively. In contrast, only 1.1, 1.3, 1.0, and 0.3% were recovered in the plants grown under anaerobic conditions at pH 5, 6, 7, and 8, respectively. Higher recovery percentage of $^{65}\text{Zn}$ in the plants grown under aerobic conditions was due to higher total activity of $^{65}\text{Zn}$ in the plants as compared with under anaerobic conditions.

The data displayed in Figure 20b show the effect of soil oxidation-reduction conditions and pH on percent recovered of $^{32}\text{P}$ in the plants. Almost identical relationships between utilization of P by plants and soil pH-redox conditions were obtained when percent recovered of $^{32}\text{P}$
Figure 20. Effect of aerobic and anaerobic conditions on recoveries of added $^{65}$Zn (a) and $^{32}$P (b) by the rice plants at pH 5, 6, 7, and 8.
was considered instead of total activity of $^{32}\text{P}$. The initial amount of 40 μCi/pot of $^{32}\text{P}$ was added. After necessary correction for half-life disintegration was made, 18.8, 11.5, 9.4, and 2.6% of added $^{32}\text{P}$ was recovered in the plants grown under aerobic conditions in comparison with 6.8, 10.6, 6.7, and 2.9% recovered under anaerobic conditions at pH 5, 6, 7, and 8, respectively. The difference of approximately 13.0% of added $^{32}\text{P}$ recovered in the plants grown under aerobic and anaerobic conditions at pH 5 was due to the difference in total activity of this labelled element in the plants.

C. **Effect of Aerobic and Anaerobic Conditions and pH on Soil Redox Potential, Electrical Conductivity, Growth, and Recoveries of Added Labelled Ammonium-N and Nitrate-N by Rice in a Flooded Soil**

This experiment consisted of a comparative study of nitrogen utilization by rice from applied ammonium sulfate-$^{15}\text{N}$ and sodium nitrate-$^{15}\text{N}$ grown under two oxidation-reduction conditions, each condition being maintained at pH 4.5, 6.0, and 7.5 in flooded soil suspensions. A nitrification inhibitor was added to prevent biologically oxidation of ammonium under aerobic soil conditions in order to effectively study the utilization of ammonium nitrogen as compared with nitrate nitrogen by rice under aerobic conditions.

1. **Effect of Aerobic and Anaerobic Conditions and pH on Soil Redox Potential**

The effect of aerobic and anaerobic conditions maintained at pH 4.5, 6.0, and 7.5 on redox potential of the soil during the 14 days after transplanting rice is shown in Figure 21. The results shown for aerobic conditions represent combined averages of the potential values
Figure 21. Effect of aerobic and anaerobic conditions on redox potential of the soil maintained at pH 4.5, 6.0, and 7.5 after transplanting rice.
measured from treatments of applied $^{15}\text{N}$-labelled ammonium sulfate and $^{15}\text{N}$-labelled sodium nitrate. The results shown under anaerobic-conditions represent the potential values measured from treatments of applied $^{15}\text{N}$-labelled ammonium sulfate alone because $^{15}\text{N}$-labelled sodium nitrate was not applied under this soil condition.

Eight days after the beginning of soil incubation and before different pH levels were controlled, the average redox potential value was +698 mv at pH 5.2 for aerobic soil and +184 mv at pH 5.7 for anaerobic soil.

As indicated by redox potential value measured at the end of soil incubation, the soil under anaerobic conditions was not sufficiently reduced. At an equal length of incubation period, anaerobic soil conditions obtained from previous experiments showed much lower redox potential values. A possible explanation for the soil failing to be sufficiently reduced is that in the present experiment the soil was incubated aerobically for 9 days prior to being anaerobically incubated for 8 days. The organic matter which was an energy source for soil microorganisms was partially oxidized. As a result, probably very little organic matter remained for obligate anaerobic bacteria to use as an energy source for soil reduction.

The redox potential values of aerobic conditions which were controlled at pH 4.5, 6.0, and 7.5 were more or less constant above 300 mv during the 14 days after transplanting rice. An increase of one unit in pH over experimental ranges under aerobic conditions resulted in a decrease in redox potential of approximately 70 mv. Under anaerobic conditions, on the other hand, redox potential at pH 4.5 was greatly affected by acidity as indicated by a large positive redox potential
value of +225 mv. Redox potential at pH 6.0 was not constant. The redox potential values gradually increased during the last 7 days after transplanting rice.

An explanation for the increase in redox potential during the experimental period for the anaerobic soil conditions controlled to pH 6.0 was deduced by the better growth of rice under this treatment. Better growth of rice indicated better oxidizing power of the roots which allowed increased oxygen diffusion into the soil. This is indicated by an increase in redox potential of the soil suspension in this treatment during the last 7 days after transplanting rice. Such an increase in redox potential during the experimental period was not observed in other experiments in which younger (20- or 25-day-old) rice seedlings were used. Thirty-day-old rice seedlings were used in this experiment.

There was appreciable soil reduction in the treatment under anaerobic conditions controlled at pH 7.5. Redox potential values gradually decreased from approximately a constant value of -120 mv during the first four days after transplanting to an approximate value of -280 mv towards the end of the experiment. During the first four days after transplanting rice the oxidative power of the rice roots was probably still active enough to stabilize the redox potential to a relatively high value. An intense soil reduction set in, reduced substances produced as a consequence of reducing conditions may have been toxic to the root and destroyed the oxidative power of the roots. This is indicated by a decrease in redox potential of the soil suspension in this treatment during the last 10 days after transplanting.
At the conclusion of the experiment, examination of rice roots revealed that the roots of rice plants grown under anaerobic conditions were white with a slightly orangish-brown coating at pH 4.5 and at pH 6.0. The roots were blackened and apparently unhealthy at pH 7.5. The soil under anaerobic conditions at pH 7.5 smelled strongly of H₂S. The roots of the plants grown under aerobic conditions at all pH levels were creamish-white and apparently healthy.

Young leaves of the plants grown under aerobic conditions were chlorotic at all pH levels. Rice grown under anaerobic conditions were normal.

2. Effect of Aerobic and Anaerobic Conditions and pH on the Amounts of Acid and Alkali Required to Maintain pH

The total amounts of acid or alkali required to maintain pH levels of aerobic and anaerobic soil conditions at pH 4.5, 6.0, and 7.5 are shown in Figures 22a and 22b.

As shown in Figure 22a, both acid and alkali were required to maintain pH values at 4.5 under aerobic soil conditions. Acid was only required to bring the initial pH of aerobic soil from pH 5.2 to pH 4.5 during the first few days after transplanting. The amount of alkali added to aerobic soil to maintain pH 4.5 was required only a few days after this soil pH level was maintained by acid. The amount of acid added was decreased while the amount of alkali was increased as pH levels of soil to be maintained increased. Additions of ammonium sulfate or sodium nitrate to the aerobic soil suspension at time of transplanting rice resulted in a slight difference in the amounts of acid or alkali required to maintain the soil pH.
Figure 22. Effect of aerobic (a) and anaerobic (b) conditions on soil electrical conductivity and the amount of acid and alkali required to maintain pH 4.5, 6.0, and 7.5.
The aerobic soil suspension receiving ammonium sulfate required 1.28, 0.16, and 0 meq of acid per 100 grams of soil as compared with 1.84, 0.32, and 0.40 meq when sodium nitrate was added to maintain pH 4.5, 6.0, and 7.5, respectively. On the other hand, the aerobic soil suspension receiving ammonium sulfate required 1.44, 3.92, and 10.88 meq of alkali per 100 grams of soil as compared with 1.12, 4.00, and 9.44 meq when sodium nitrate was added to maintain pH 4.5, 6.0, and 7.5, respectively. Lower amounts of acid or higher amounts of alkali added to ammonium sulfate treated soil was attributed to acidity produced by plants uptake of $\text{NH}_4^+$-N and by the acid production due to soil oxidation. Rapid uptake of ammonium by plants decreased the pH of the medium and rapid uptake of nitrate increased it. This phenomenon has also been observed in water culture by many workers (Tanaka, Patnaik, and Abichandani, 1959; Karim and Vlamis, 1962).

The amounts of acid and alkali required to maintain different pH levels under anaerobic conditions are shown in Figure 22b. Only ammonium sulfate was added as a source of nitrogen for the rice plants grown under anaerobic conditions. However, similar patterns were observed in the amounts of acid and alkali required to maintain different pH levels under anaerobic conditions as was the case under aerobic conditions. There are at least two reasons which can explain these identical patterns: (1) the initial pH values of the aerobic and anaerobic soil suspensions did not differ appreciably, (2) active rice roots which were transferring oxygen into the soil suspensions retarded the decrease in redox potential of anaerobic suspension thus retarding the increase in soil pH. In general, soil reduction tended to increase the pH and soil oxidation tended to decrease it. Thus, the overall
changes in soil reactions under aerobic and anaerobic conditions were probably the same. Therefore, the amounts of acid and alkali required to maintain different pH levels under the two soil oxidation-reduction conditions were almost identical.

3. **Effect of Aerobic and Anaerobic Conditions and pH on Soil Electrical Conductivity**

The effect of aerobic and anaerobic conditions on electrical conductivity of soil maintained at pH 4.5, 6.0, and 7.5 is shown in Figures 22a and 22b.

Figure 22a shows the electrical conductivity measured under aerobic conditions. The changes in electrical conductivity values were closely related to the changes in the amounts of acid or alkali added. As the amounts of acid or alkali added to maintain soil pH levels increased, the electrical conductivity values of the aerobic soil suspension also increased. The electrical conductivity values were slightly different between ammonium sulfate treated soils and sodium nitrate treated soils, being lower with ammonium sulfate treated soils at low pH levels and higher at high pH levels. This occurred due to lower amounts of acid added to ammonium sulfate treated soil at low pH levels (pH 4.5 and 6.0) and higher amounts of alkali added to ammonium sulfate treated soil at pH 7.5 as compared with sodium nitrate treated soil.

The effect of anaerobic conditions and pH on electrical conductivity is shown in Figure 22b. Almost identical relationships between electrical conductivity and pH levels were obtained between aerobic and anaerobic soil conditions as shown in Figures 22a and 22b, respectively. These results indicated that soil reaction rather than soil
oxidation-reduction conditions caused an increase or a decrease in electrical conductivity.

4. **Effect of Aerobic and Anaerobic Conditions and pH and Nitrogen Source on Dry Matter Weight of the Rice Plants**

The effect of aerobic and anaerobic soil conditions, pH levels, and nitrogen sources on dry matter weight of the plant is shown in Figures 23a, 23b, and 23c. The data illustrated in these figures also show the ratio of the above ground portion of the plant (shoot) and underground portion of the plant (root).

In general, aerobic and anaerobic soil conditions, pH levels, and nitrogen sources influenced the dry matter weight of the plant.

Dry matter weight of the plant was higher with ammonium sulfate-treated aerobic and anaerobic soils (Figures 23a and 23c) than with sodium nitrate-treated aerobic soil (Figure 23b) when comparison was made at the corresponding pH levels. No difference in dry matter weight of the plant was observed between ammonium sulfate-treated aerobic and anaerobic soil conditions except at pH 4.5, where a sharp decrease in dry matter weight of the plant was obtained under anaerobic conditions.

In all cases, the plants grew best at pH 6.0 as indicated by greatest dry matter weight of the plant than when grown at lower or higher pH levels. The greatest dry matter weight of the plant grown under these conditions at pH 6.0 might be due to lesser amounts of soluble salts in the soil solution as indicated by lower electrical conductivity value of the soil solution. Higher amounts of soluble salts in the soil solution at two extreme pH levels may be one of the causes in retarding growth of the plant. It has been reported that
Figure 23. Effect of aerobic (a, b) and anaerobic (c) conditions and nitrogen source on dry matter weights of shoots and roots and shoot/root ratio of the rice plants at pH 4.5, 6.0, and 7.5.
electrical conductivity value of solution exceeding 4 mmhos/cm could be injurious to rice plants (IRRI, 1967). However, the electrical conductivity values obtained from the soil solutions under the two extremely controlled pH levels in this study were slightly lower than the value reported by IRRI. It appears that both electrical conductivity and soil pH, partially at least, regulate the growth of the plant.

The effect of nitrogen sources on the growth of the plant under aerobic conditions is noteworthy. When sodium nitrate was used as a source of nitrogen, dry matter weight of the plants was smaller than when ammonium sulfate was used as a source of nitrogen for rice. The smaller dry matter weight of the plant grown under sodium nitrate than those grown under ammonium sulfate-treated aerobic soil conditions was partially due to higher electrical conductivity values of the former condition than the latter condition. Elsewhere, the inferiority of nitrate nitrogen to ammonium nitrogen in nutrition of rice grown in water culture solution at an early growth stage has been reported (Tanaka, Patnaik, and Abichandani, 1959; Karim and Vlamis, 1962).

Ammonium sulfate-\textsuperscript{15}N under anaerobic soil conditions as a source of nitrogen for rice behaved similarly in increasing dry matter weight of the plant as when added to aerobic soil.

Large amounts of added ammonium sulfate under ammonium sulfate-treated aerobic soil conditions were still in the ammonium form of nitrogen. This is indicated by the results of soil analysis for this treatment at the conclusion of the experiment as is shown in Table 4. These results suggested that N-serve added was effective in preventing ammonium oxidation. An important feature of this study was that if nitrogen was maintained in the ammonium form, aerobic and anaerobic
Table 4. Distribution of NH$_4^+$-N and NO$_3^-$-N in the soil applied with nitrification inhibitor as affected by soil conditions, nitrogen sources, and pH levels.

<table>
<thead>
<tr>
<th>Soil N</th>
<th>Aerobic (15NH$_4$)$_2$SO$_4$</th>
<th></th>
<th>Aerobic Na$^{15}$NO$_3$</th>
<th></th>
<th>Anaerobic (15NH$_4$)$_2$SO$_4$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pH 4.5</td>
<td>pH 6.0</td>
<td>pH 7.5</td>
<td>pH 4.5</td>
<td>pH 6.0</td>
<td>pH 7.5</td>
</tr>
<tr>
<td>NH$_4^+$-N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>17.05</td>
<td>15.01</td>
<td>22.04</td>
<td>4.11</td>
<td>2.70</td>
<td>4.09</td>
</tr>
<tr>
<td>NO$_3^-$-N</td>
<td>2.29</td>
<td>2.28</td>
<td>2.23</td>
<td>36.49</td>
<td>29.24</td>
<td>40.44</td>
</tr>
<tr>
<td>Total Soil Inorganic N</td>
<td>19.34</td>
<td>17.29</td>
<td>22.27</td>
<td>40.60</td>
<td>31.94</td>
<td>44.53</td>
</tr>
</tbody>
</table>
soil conditions were equally effective in increasing dry matter weight of the plant. If this is the case, use of nitrification inhibitor and ammonium fertilizer may be of significant value in increasing yields of upland rice.

However, if ammonium nitrogen was not maintained, anaerobic conditions were more effective in increasing the dry weight of the plants than aerobic conditions. This latter conclusion is supported by the work of Senewiratne and Mikkelsen (1961) who found that flooded conditions consistently produced better vegetative growth and higher grain yields of rice than did nonflooded culture. The advantage of anaerobic conditions was attributed to large release of Fe, Mn, and P in soils required for the growth of rice plants.

Sharp decrease in the dry matter weight of the plants under anaerobic conditions at pH 4.5 might be due to an adverse effect caused by high acidity and absorption of relatively greater amounts of soluble salts including ferrous iron and ammonium ions, and their accumulations might have exerted toxic effects which will be discussed in the following section.

The shoot/root ratio of the plant grown under all experimental soil conditions steadily decreased as pH levels increased. Sharp decrease in shoot/root ratio of the plant grown under ammonium sulfate-treated anaerobic conditions was due to increase in weight of the root as pH levels increased. Decreased dry matter weight of the roots at low pH levels was probably due to root injury caused by high acidity of the medium.
5. **Effect of Aerobic and Anaerobic Conditions and pH on Recoveries of Added Labelled Ammonium-N and Nitrate-N by the Rice Plants**

The effect of aerobic and anaerobic soil conditions, pH levels, and nitrogen sources on percent recovery of labelled N in the plant is shown in Figures 24a, 24b, and 24c. The data illustrated in these figures also show percent recovery of labelled N in soil organic and soil inorganic fractions as affected by these experimental conditions.

Recovery of fertilizer nitrogen from ammonium sulfate-treated aerobic soil was greatly affected by soil pH as shown in Figure 24a. There was a sharp decrease in the percent recovered of labelled N in the plant grown under ammonium sulfate-treated aerobic soil conditions as the pH levels increased from 4.5 to 6.0 to 7.5. These results show a plant recovery of applied labelled N of 74, 64, and 51%, respectively. Approximately the same magnitude of labelled N was recovered in the plant grown under ammonium sulfate-treated anaerobic soil conditions as shown in Figure 24c.

Recovery of fertilizer nitrogen applied as sodium nitrate under aerobic conditions, on the other hand, was slightly affected by soil pH. Figure 24b shows a slight decrease in the percent recovery of labelled N in the plant as soil pH level increases. These results show a recovery of applied labelled N of 65, 65, and 63% in the plant for pH 4.5, 6.0, and 7.5, respectively.

In all cases, however, recovery of applied labelled N in the plant decreased as recovery of labelled N in the soil organic fraction increased. Increased pH levels may be more favorable to nitrogen immobilization in the soil by microbial activities and hence decrease
Figure 24. Effect of aerobic (a, b) and anaerobic (c) conditions on recoveries of added labelled ammonium-N and nitrate-N by the soil and plants at pH 4.5, 6.0, and 7.5.
labelled N recovered in the plant. Increase in pH levels from 4.5 to 7.5 resulted in an increase of approximately 20 to 30% recovery of labelled N into soil organic pool at all experimental conditions.

It is interesting to note that a relatively high percent of labelled N recovered in the plants was observed in this experiment as compared with the results observed elsewhere, both in the greenhouse and in the field (IAEA, 1970; Patrick, DeLaune, and Peterson, 1974). The low recovery of applied fertilizer nitrogen by rice plants grown in waterlogged conditions was often attributed to N losses through nitrification and subsequent denitrification processes. The loss of applied nitrogen in the soil system in the present study is unlikely because the soils are uniformly maintained under complete aerobic and complete anaerobic conditions. Tusneem and Patrick (1971) reported considerable amounts of applied fertilizer N was lost under waterlogged conditions, in contrast to no loss under optimum moisture and completely anaerobic conditions.

The significant conclusions from this study may be summarized as follows: 1) rice plants grew best at pH values around 6.0; 2) aerobic and anaerobic soil conditions were equally effective in increasing dry matter weight of the plant when nitrogen was present in the ammonium form; 3) when ammonium nitrogen was not maintained, aerobic conditions were inferior to anaerobic conditions; 4) utilization of applied fertilizer nitrogen was high at low pH and low at high pH; and 5) equally high amounts of applied labelled N was recovered in the plants under aerobic and anaerobic conditions where no losses of applied nitrogen occurred.
D. Effect of Aerobic and Anaerobic Conditions and pH on Soil Redox Potential, Electrical Conductivity, Growth and Recoveries of Added Labelled Ammonium-N and Urea-N by Rice in a Flooded Soil

A laboratory experiment consisted of a comparative study of the recovery of two nitrogen sources, ammonium sulfate and urea by the rice plants grown under two soil oxidation-reduction conditions. Each soil condition was maintained at pH 5.5 and 7.5. No nitrification inhibitor was added in this experiment. Twenty-five-day-old rice seedlings were used for transplanting. The plants were allowed to grow for an additional 14 days under experimentally controlled conditions. Tracer techniques involving the stable isotope of nitrogen, $^{15}$N, were employed to determine the recovery of both applied nitrogen sources in the plants and in the soil inorganic and organic nitrogen fractions. In addition to determining nitrogen recovery, the amounts of acid and alkali added to maintain soil pH, soil redox potential, electrical conductivity of soil solutions, and vegetative growth of the rice plant were determined. Soil solutions were taken periodically to determine the amounts of NH$_4^+$-N and NO$_3^-$-N remaining as a result of urea hydrolysis, ammonium oxidation, and plant uptake. The results obtained were discussed in the following sections.

1. Effect of Aerobic and Anaerobic Conditions and pH on Soil Redox Potential

The redox potential values measured under aerobic and anaerobic soil conditions at pH 5.5 and 7.5 during the 14 days after transplanting are shown in Figure 25.

The Eh values for aerobic and anaerobic treatments maintained at pH 5.5 and 7.5 were more or less constant during the 14 days after
Figure 25. Effect of aerobic and anaerobic conditions on redox potential of the soil maintained at pH 5.5 and 7.5.
transplanting. The daily average Eh values under aerobic conditions were +608 and +480 mv; under anaerobic conditions, -106 and -243 mv for the two pH levels, respectively. A stepwise increase in one pH unit resulted in a decrease of 64 mv and 68 mv under aerobic and anaerobic soil conditions respectively. The magnitude of Eh values of aerobic and anaerobic soils found in this study were similar to the one found in the previous study, where the same pH levels were maintained.

2. **Effect of Aerobic and Anaerobic Conditions, pH Level and Nitrogen Source on the Amounts of Acid and Alkali Added**

The effect of aerobic and anaerobic conditions, pH level, and nitrogen source on the amounts of acid and alkali added is shown in Figures 26a and 26b.

In general, soil oxidation-reduction conditions, pH levels, and nitrogen sources had a marked effect on the amounts of acid and alkali added to maintain soil pH values of 5.5 and 7.5.

Ammonium sulfate-treated soil required higher amounts of NaOH but lower amounts of HCl to maintain its soil pH level than did urea-treated soil regardless of soil oxidation-reduction conditions and pH levels. The data showed approximately 2 meq of NaOH per 100 g soil higher were required to maintain soil pH level at 7.5 for ammonium sulfate-treated soil than for urea-treated soil. In contrast, urea-treated soil required approximately 2 meq of HCl per 100 g soil higher to maintain soil pH level at 5.5 than did ammonium sulfate-treated soil.

An explanation for higher requirement of NaOH and lower requirement of HCl for ammonium sulfate-treated soil than for urea-treated soil was deduced from the difference in the chemical reaction of these
Figure 26. Effect of aerobic and anaerobic conditions and nitrogen source on the amounts of acid (a) and alkali (b) required to maintain pH and on the electrical conductivity (c) of the soil maintained at pH 5.5 and 7.5.
two fertilizers when added to soil. With ammonium sulfate added, the soil pH decreased, and with urea added, it increased. Following the initial increase caused by the hydrolysis of urea the pH fell as ammonium was oxidized to nitric acid (Alexander, 1961). The acid effect of urea hydrolysis was considerable although not as much as ammonium sulfate. For 20 pounds of N supplied by the fertilizer, the amount of CaCO$_3$ required to neutralize the acidity produced was 107 pounds for ammonium sulfate and 36 pounds for urea (Buckman and Brady, 1960).

No HCl was required to maintain the soil pH levels at 7.5 regardless of soil oxidation-reduction conditions and nitrogen sources. In contrast, large amounts of HCl were required to maintain the soil pH level at 7.5 but no NaOH was required to maintain the soil pH level at 5.5 except for the soil under aerobic conditions where small amounts of NaOH was essential to maintain the soil pH level at 5.5. Small amounts of alkali required by aerobic soil conditions to maintain its pH level at 5.5 may be due to two reasons: 1) biologically soil oxidation tended to decrease soil pH below the initial set value of 5.5, and 2) application of acid producing fertilizer such as ammonium sulfate also decreased the soil pH below the set value.

Another important feature of maintaining pH levels under various soil oxidation-reduction conditions, regardless of nitrogen sources applied, is that large amounts of acid were required to maintain pH 5.5 of anaerobic soil as compared with little or no acid being required to maintain the same pH level under aerobic conditions. This observation is in close accordance with the findings in the previous Fe and Mn
study where a large amount of Fe$^{++}$ was released with large amounts of acid added under anaerobic conditions at pH 5.5.

3. **Effect of Aerobic and Anaerobic Conditions, pH Level, and Nitrogen Source on Soil Electrical Conductivity**

The effect of the various redox potential, nitrogen source and pH treatments on electrical conductivity of soil suspensions is shown in Figure 26C.

Soil oxidation-reduction conditions, pH levels, and nitrogen sources applied had a marked effect on electrical conductivity of soil suspensions. The greater the amounts of acid or alkali added, the higher the electrical conductivity values of the soil suspension. At pH 5.5 approximately twice as high an electrical conductivity value was recorded under anaerobic conditions as compared to that recorded under aerobic soil conditions, regardless of nitrogen sources. As already discussed in the previous section, the acid effect of urea was considerable but not as much as ammonium sulfate. Urea-treated soil required 8.5 meq/100 g of HCl while ammonium sulfate-treated soil required only 6.0 meq/100 g of HCl to maintain pH 5.5 under anaerobic conditions. There was an approximate difference of 2 meq/100 g HCl between the two treatments. In spite of this difference, there appeared to be no difference in the electrical conductivity values between ammonium sulfate-treated and urea-treated soils. The explanation for an approximately equal electrical conductivity value of the two treatments is deduced from the fact that both soil treatments were maintained at the same pH level, i.e. pH 5.5. The electrical conductivity of a soil has been shown to be pH dependent (Ponnampерuma, 1965). At higher pH (pH 7.5), on the other hand, the higher amount of NaOH added to
ammonium sulfate-treated soil (2 meq/100 g) resulted in twice as high an electrical conductivity value as compared to urea-treated soil under both soil conditions.

4. Effect of Aerobic and Anaerobic Conditions and pH on the Fate of Applied Nitrogen Source in the Soil

Analyses of soil for \( \text{NH}_4^+ \)-N and \( \text{NO}_3^- \)-N contents at 5-day intervals, from the time of nitrogen application (at transplanting) until the conclusion of the experiment 15 days after transplanting as affected by the various treatments are presented in Figures 27a, 27b, and 27c. It should be pointed out that these values include both native and applied nitrogen remaining in the soil. The amount of added N recovered and the amount of soil N taken up by the plant are discussed in the latter section.

Regardless of pH levels, \( \text{NH}_4^+ \)-N concentration produced by ammonium sulfate-treated soil decreased much more rapidly under aerobic conditions than under anaerobic conditions, as is shown in Figures 27a and 27c. The rapid decrease of \( \text{NH}_4^+ \)-N and generally lower amount of \( \text{NH}_4^+ \)-N under aerobic soil was due to biologically ammonium oxidation to nitrate. The \( \text{NO}_3^- \)-N accumulated from this reaction under aerobic conditions is shown in Figure 27b.

\( \text{NH}_4^+ \)-N concentration in the urea-treated soil, on the other hand, increased during the first five days after application as a result of urea hydrolysis and then decreased with time in the manner similar to \( \text{NH}_4^+ \)-N concentration produced by ammonium sulfate. The increase and subsequent decrease of \( \text{NH}_4^+ \)-N following urea application under aerobic and under anaerobic conditions appeared to have a similar trend.
Figure 27. Effect of aerobic (a, b) and anaerobic (c) conditions and plant growth on the amounts of NH$_4^+$-N and NO$_3^-$-N remaining at different periods of time in the soil applied with ammonium sulfate and urea at pH 5.5 and 7.5.
DeLaune and Patrick (1970) reported urea hydrolysis to ammonia proceeded at approximately the same rate in 1/3 bar moisture (aerobic) and in waterlogged (anaerobic) soil conditions.

An explanation for the general decrease in the NH$_4^+$-N content of aerobic and anaerobic soils (Figures 27a and 27c) is deduced from plant uptake of nitrogen. However, a sharp decrease in NH$_4^+$-N contents of aerobic soil (Figure 27a) was due not only to plant uptake, but also to nitrification. Part of the nitrate so produced was also taken up by the plant, the remaining nitrate accumulated. Elemental N loss under the completely aerobic and anaerobic soil systems being employed in this study was unlikely (Tusneem and Patrick, 1971).

It should be noted that the amount of total inorganic (NH$_4^+$-N + NO$_3^-$-N) nitrogen remaining in the soil at the end of a 15-day period under aerobic conditions and the amount of inorganic (NH$_4^+$-N) nitrogen remaining in the soil at the end of the same period under anaerobic conditions did not differ appreciably. It is expected that approximately the same amount of inorganic nitrogen would have been taken up by the plant under these two oxidation-reduction conditions, regardless of nitrogen sources applied and pH levels. It is further expected that larger amounts of plant nitrogen would have been derived from added nitrogen sources than from soil nitrogen, because of the low loss of added nitrogen in the soil system under study.

5. **Effect of Aerobic and Anaerobic Conditions, pH level, and Nitrogen Source on Dry Matter Weight of the Rice Plants**

The effect of aerobic and anaerobic conditions, pH level, and nitrogen source on shoot weight, root weight, and shoot/root ratio of the rice plants is shown in Figures 28a, 28b, and 28c. There were
Figure 28. Effect of aerobic and anaerobic conditions and nitrogen source on weights of shoots (a) and roots (b) and shoot/root ratio (c) of the rice plants at pH 5.5 and 7.5.
marked differences in the weight of shoots of the plants which were
grown under ammonium sulfate-treated aerobic and anaerobic soils at
pH 5.5 as compared with slight or no differences observed among other
treatments in which either ammonium sulfate or urea was applied at
pH 5.5 and pH 7.5. Aerobic soil conditions produced greater shoot
weight than did anaerobic soil at pH 5.5 where ammonium sulfate was
applied. This result agrees with that obtained from previous experi­
ments in this study in which the same source and amount of N was
applied. An explanation for smaller shoot weight of plants grown under
anaerobic soil as compared with aerobic soil at low pH in this experi­
ment was deduced from higher electrical conductivity values of soil
under anaerobic conditions. However the change in soil electrical
conductivity values obtained from other experimental conditions were
not consistent with the corresponding change in the shoot weight. The
greater shoot weight of the plants grown under aerobic soil as com­
pared with anaerobic soil at an early growth stage agrees with the
finding of Senewiratne and Mikkelsen (1961). Except for the high
shoot weight of plants grown under ammonium sulfate-treated aerobic
soil at pH 5.5, which was discussed above, there appeared to be no
differences among the shoot weights in the plants grown under other
experimental conditions.

In spite of the differences in the shoot weight, no differences
in the root weight was observed for the ammonium sulfate-treated aerobic
and anaerobic soils at pH 5.5, as is shown in Figure 28b. The root
weights of plants grown under anaerobic soil, regardless of nitrogen
sources and pH levels, were all equally high. The higher root weight
of the plants grown under anaerobic soil than under aerobic soil was
due to better root proliferation under reducing soil conditions as compared with oxidizing soil conditions. Better root proliferation may be due to the role of the root in overcoming reducing toxic conditions.

Figure 28c shows the effect of aerobic and anaerobic soil conditions, pH levels and nitrogen sources on shoot/root ratio of the rice plants. Nitrogen sources and pH levels did not seem to have any effect on the shoot/root ratio. On the other hand, soil oxidation-reduction conditions had a marked effect on the shoot/root ratio. Aerobic soil produced greater shoot/root ratio than did the counterpart anaerobic soil. As pointed out above, this was apparently due to generally lower root weight of the plants which were grown under aerobic soil as compared to anaerobic soil. There appeared to have been no appreciable differences in the shoot/root ratio among the aerobic soil and among the anaerobic soil conditions.

6. Effect of Aerobic and Anaerobic Conditions and pH Level on Recoveries of Applied Labelled Ammonium-N and Urea-N by the Rice Plants

The effect of aerobic and anaerobic conditions and pH level on percent recovery of applied labelled ammonium-N and urea-N by the plant tissue and in soil organic and soil inorganic nitrogen fractions is shown in Figures 29a and 29b.

In general, recovery of added labelled ammonium and urea nitrogen in the plant was relatively low, ranging from approximately 21.5 to 41.1%. Recovery of added labelled nitrogen in previous experiments in which the same source of $^{15}$N enriched ammonium sulfate was applied ranged as high as 60 to 80%.
Figure 29. Effect of aerobic (a) and anaerobic (b) conditions on recoveries of added labelled ammonium and urea nitrogen by soil organic and inorganic nitrogen fractions and by the rice plant at pH 5.5 and 7.5.
The low recovery of added labelled nitrogen by the plant in the present study was probably due to generally low weight of the rice plant. A large amount of the added labelled nitrogen remained in the soil inorganic nitrogen fraction especially under anaerobic conditions, as is shown in Figure 29b.

Total recovery of added labelled nitrogen in the plants in the soil organic and soil inorganic nitrogen fractions was very high under anaerobic conditions as compared with aerobic conditions. Total recovery figures under anaerobic conditions were 105.9 and 98.2% for added labelled ammonium-N and 105.7 and 102.3% for added labelled urea-N at pH 5.5 and 7.5, respectively. In contrast, under aerobic conditions, the total recovery figures were 73.3 and 56.2% for added labelled ammonium-N and 62.8 and 60.3% for added urea-N, respectively at pH 5.5 and 7.5. High inorganic nitrogen fraction contributed to high total recovery of added labelled nitrogen under anaerobic conditions. As much as 43.8% of added labelled nitrogen was unaccounted for under aerobic conditions as compared with only 5.9% under anaerobic conditions. There is no satisfactory explanation for the losses of labelled nitrogen applied under aerobic conditions.

Notwithstanding the large losses of labelled nitrogen under aerobic conditions there was little difference in uptake of labelled ammonium sulfate and urea. An increase in soil pH level from 5.5 to 7.5 did not affect recovery of added nitrogen in the plants grown under aerobic conditions except for a high recovery in an ammonium sulfate-treated aerobic soil at pH 5.5 but did increase the recovery of added nitrogen in the plants grown under anaerobic conditions. The two-pH unit increase from pH 5.5 to 7.5 resulted in an approximate 10%
increase in recovery of added nitrogen in the plants grown under anaerobic conditions. The high recovery of added labelled nitrogen (41.1%) found in the plants grown under ammonium sulfate-treated aerobic soil at pH 5.5 was due to high dry weight of plant material.

Plant tissue analysis for Fe content revealed that relatively higher concentration of Fe was found in the plant tissue under anaerobic conditions at pH 5.5 than at pH 7.5. It may be possible that these two elements at least partially regulate the absorption of one another in the rice plants under anaerobic conditions. Under aerobic conditions Fe absorption is not high enough to interfere with nitrogen uptake. The total uptake of Fe and added labelled nitrogen by the rice plants is shown in Figures 30a and 30b.

About 20 to 30% of applied nitrogen was recovered in the organic nitrogen fraction under these experimental conditions. Other studies have shown approximately 25 to 60% of applied nitrogen remaining immobilized in the soil (Bartholomew, 1965).

As expected most of the plant nitrogen (77 to 92%) was derived from added nitrogen under these conditions. As is shown in Table 5 only 7 to 23% of plant nitrogen was derived from soil nitrogen. These results differ somewhat from the results reported under field conditions where, at harvest time the rice plant had utilized much more native soil nitrogen than applied nitrogen (Takahashi, 1965). Koyama (1971) likewise reported that native soil nitrogen constituted 63 to 80% of the total nitrogen in the plant at harvest time. The main reason for the difference is the short duration of the rice plants grown in this experiment. At a comparable growth period of the rice plant under field conditions, Patrick, DeLaune, and Peterson (1974) found that the
Figure 30. Effect of aerobic (a) and anaerobic (b) conditions on the uptake of native Fe and added $^{15}$N by the rice plants at pH 5.5 and 7.5.
Table 5. Uptake of total nitrogen (soil N + labelled N), labelled N and percent of plant N derived from soil N and from added labelled N as affected by soil conditions, pH levels and nitrogen sources.

<table>
<thead>
<tr>
<th>Plant N</th>
<th>Aerobic pH 5.5</th>
<th>Aerobic pH 7.5</th>
<th>Anaerobic pH 5.5</th>
<th>Anaerobic pH 7.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AS</td>
<td>UR</td>
<td>AS</td>
<td>UR</td>
</tr>
<tr>
<td>Total N (mg/pot)</td>
<td>105.7</td>
<td>63.4</td>
<td>61.5</td>
<td>61.5</td>
</tr>
<tr>
<td>Labelled N (mg/pot)</td>
<td>82.3</td>
<td>55.4</td>
<td>50.6</td>
<td>50.9</td>
</tr>
<tr>
<td>% Derived from Soil N</td>
<td>22.2</td>
<td>12.6</td>
<td>17.6</td>
<td>17.0</td>
</tr>
<tr>
<td>% Derived from Labelled N</td>
<td>77.9</td>
<td>87.4</td>
<td>82.4</td>
<td>82.8</td>
</tr>
</tbody>
</table>

AS = Ammonium Sulfate-$^{15}$N

UR = Urea-$^{15}$N
fraction of plant nitrogen coming from fertilizer was relatively high (about three-fourths). They also reported that fertilizer nitrogen in the plant decreased to as little as one-fifth at the end of the season.
SUMMARY AND CONCLUSIONS

Experiments were conducted to evaluate the effects of soil oxidation-reduction conditions and pH on the early vegetative growth and nutrient uptake by rice in laboratory culture. Mhoon silt loam soil was used in all experiments. Different soil oxidation-reduction conditions were obtained by slowly bubbling either air for oxidized (aerobic) or N\textsubscript{2} gas for reduced (anaerobic) conditions through soil kept in suspension with a magnetic stirrer. Different pH levels of aerobic and anaerobic soil suspensions were maintained by adding either 2N HCl or 2 N NaOH to the soil suspensions daily during the growth of the rice plants. Redox potential measurements were also made daily. Young rice seedlings (var. Saturn), previously grown in culture solution were transplanted and allowed to grow under controlled soil conditions. Growth and nutrient uptake by rice were evaluated at the conclusion of the experiments approximately 2-3 weeks after transplanting.

The effect of aerobic and anaerobic conditions and pH on early vegetative growth of the rice plants in a flooded soil was determined. A wide range of soil pH levels, 5, 6, 7, and 8 were maintained. In general, rice plants which were grown under anaerobic (reduced) conditions produced greater dry weight of shoots and roots than those which were grown under aerobic (oxidized) conditions. However, if nitrogen was maintained in the ammonium form, aerobic and anaerobic conditions were equally effective in increasing dry weight of the rice plants. One of the major beneficial effects of anaerobic conditions
may be to maintain inorganic nitrogen in the ammonium form. Dry weight of shoots of plants grown under both soil conditions steadily decreased as soil pH increased. An important feature of this study is that at pH 5 there was a sharp drop of dry weight of shoots and roots of the rice plants grown under anaerobic conditions as compared to aerobic conditions. This decrease in growth was apparently due to iron toxicity. Plants which were grown under anaerobic conditions at pH 6 and 7 were normal, the redox potential values at these pH values being -195 and -240 mv, respectively, while at pH 8 the plants showed toxic symptoms apparently caused by soluble sulfide. Plants which were grown under aerobic conditions at all pH levels were chlorotic, typical of iron deficiency symptoms. The results of this study showed that the weight of the plant material was considerably reduced when the rice plants were grown under aerobic conditions at pH 8 and under anaerobic conditions at pH 5 and 8.

The effect of aerobic and anaerobic conditions and pH on uptake of native and added labelled Fe and Mn by the rice plants in a flooded soil was determined. Two soil pH levels, i.e. 5.5 and 7.5 were maintained. The uptake of native Fe by the rice plants under anaerobic conditions was high at low pH and was low at high pH. The native Fe uptake by the rice plants under aerobic conditions, in contrast, was low and did not differ appreciably between the two pH levels. The native Fe content in the rice plants grown under anaerobic conditions at pH 5.5 exceeded the apparent toxic level for the rice plants. The native Fe content in the rice plants grown under aerobic conditions at both pH levels, on the other hand, was well below the normal level for rice plants. The uptake of native Mn by the rice plants under both
soil conditions was lower at low pH than at high pH. The native Mn uptake by the rice plants was higher under anaerobic conditions than under aerobic conditions. The recovery of added labelled Fe and Mn by the rice plants further suggested that Mn uptake was partially governed by Fe uptake, with Mn uptake being low when Fe uptake was high and vice versa. Higher requirements for Mn than for Fe by the rice plants were suggested by higher recovery of added labelled Mn than recovery of added labelled Fe. Low recoveries of less than 1% for both added labelled Fe and Mn by the rice plants also suggest that rice plants do not normally take up large amounts of added Fe and Mn since these two elements are abundant in flooded soils.

The effect of aerobic and anaerobic conditions and pH on uptake of native and added labelled Zn and P by the rice plants in a flooded soil was determined. Four pH levels, 5, 6, 7, and 8 were maintained. The uptake of native and added labelled Zn by the rice plants was higher under aerobic than under anaerobic conditions. Under both soil conditions, the uptake of native and added labelled Zn by the rice plants decreased as pH increased. A sharp decrease in the Zn content at pH 7 to 8 was observed. Recoveries of added labelled Zn by the plants grown under aerobic conditions were approximately 6, 6, 5, and 1% and under anaerobic conditions were 1, 1, 1, and 0.25% for pH 5, 6, 7, and 8, respectively. The uptake of added labelled and non-labelled P by the rice plants grown under both soil conditions did not differ appreciably except at pH 5 where a sharp drop of the dry weight of the rice plants grown under anaerobic conditions resulted in a lower uptake of both labelled and nonlabelled P and a lower recovery of added labelled P than those found under aerobic conditions.
The uptake of both added labelled and nonlabelled P by the rice plants under both soil conditions consistently decreased as pH increased. Recoveries of added labelled P by the rice plants grown under aerobic conditions were approximately 20, 12, 9, and 2% and under anaerobic conditions were 7, 11, 7, and 3% for pH 5, 6, 7, and 8, respectively.

The effect of aerobic and anaerobic conditions and pH on recovery of added labelled ammonium-N and nitrate-N by the rice plants in a flooded soil was determined. A nitrification inhibitor was added to prevent biological oxidation of ammonium under aerobic conditions in order to effectively study the utilization of ammonium nitrogen as compared with nitrate nitrogen by rice under aerobic conditions. Three pH levels, 4.5, 6.0, and 7.5 were maintained. Aerobic and anaerobic conditions did not affect nitrogen recovery consistently. Soil pH, on the other hand, influenced recoveries of both added labelled nitrogen forms in the rice plants. There was a sharp decrease in the percent recovery of added labelled ammonium-N in the rice plants grown under both aerobic and anaerobic conditions as soil pH level increased. Percent recovery of added labelled nitrate-N in the rice plants grown under aerobic conditions slightly decreased as soil pH level increased. In all cases, the decreased recovery of added labelled N in the rice plants as pH increased corresponded to the increased recovery of added labelled N in the soil organic nitrogen fraction. High recovery of added labelled N in the rice plants was obtained for both aerobic and anaerobic conditions. The recovery percentage figures of added labelled ammonium-N in the rice plants grown under anaerobic conditions were 74, 64, and 51%, respectively for pH 4.5, 6.0, and 7.5. Approximately the same magnitudes of added labelled ammonium-N were recovered
in the rice plants grown under aerobic conditions. The recovery percentage figures of added labelled nitrate-N in the rice plants grown under aerobic conditions, on the other hand, were 65, 65, and 63% for pH 4.5, 6.0, and 7.5, respectively.

The effect of aerobic and anaerobic conditions and pH on recovery of added labelled ammonium-N and urea-N by the rice plants in a flooded soil was determined. Two pH levels, 5.5 and 7.5 were maintained. An increase in soil pH level from 5.5 to 7.5 did not consistently affect recovery of added nitrogen in the rice plants grown under aerobic conditions but did increase the recovery of added nitrogen in the rice plants grown under anaerobic conditions. The two-pH unit increase from pH 5.5 to 7.5 resulted in an approximate 10% increase in recovery of added nitrogen in the rice plants grown under anaerobic conditions. However, no appreciable difference in the recovery of added labelled ammonium and urea nitrogen was observed at each of the two pH values. Recovery of added labelled ammonium and urea nitrogen in the rice plants was generally low, ranging from approximately 21.5 to 41.1%. The low recovery of added labelled nitrogen by the rice plants in the present study was probably due to the generally low weight of the rice plants.

The effect of aerobic and anaerobic conditions and pH on redox potential, total sulfide-sulfur, amounts of acid and alkali added, and electrical conductivity in a flooded soil during the early growth period of the rice plants was determined. Sharp differences between aerobic and anaerobic soil conditions were indicated by a large positive redox potential value (+640 mv) for aerobic conditions and a relatively large negative redox potential value (-60 mv) for anaerobic conditions.
when both soil conditions were maintained at pH 5. An increase of one pH unit for the aerobic soil resulted in a decrease in redox potential close to the theoretical value of 60 mv. For anaerobic soil conditions at pH 5, on the other hand, soil biological activity was very likely affected by the acidity and soil reduction was not as intense as for soil maintained at pH 6, 7, or 8. This probably accounted for the 140 mv difference between pH 5 and pH 6. No sulfide was detected under aerobic conditions at any pH level nor under anaerobic conditions at pH 5. The total amount of NaOH required to maintain soil pH steadily increased as the pH increased under aerobic conditions. Little or no HCl was required to maintain pH 5 under aerobic conditions. Under anaerobic conditions, on the other hand, either HCl or NaOH was required to maintain a pH level lower or higher than 6.5 which was the pH value of the anaerobic soil before pH adjustment. An increase in pH level steadily increased the electrical conductivity of the aerobic soil suspensions. Under anaerobic conditions, electrical conductivity steadily increased as pH decreased or increased from the original 6.5 value. The electrical conductivity values were closely related to the amounts of acid and alkali added. In all cases, the electrical conductivity values did not exceed a level suitable for normal growth of the rice plants.
LITERATURE CITED


VITA

Aroon Jugsujinda was born October 7, 1938, in Sakolnakorn, Thailand. He was graduated from Udornpithyanukul High School, Udornthani, in 1957.

He attended Kasetsart University, Bangkok, Thailand in May 1957 and was employed as a trainee in a soil testing laboratory of Thailand Department of Agriculture, Bangkok, while attending the last year in school. He was graduated in June 1962, and received a Bachelor of Science degree in Agriculture. He continued working under the Department of Agriculture as an agronomist until the present time. His work, involving rice fertilization research, has received cooperation and support from several organizations, i.e., Food and Agriculture Organization of the United Nations Development Plan, Tennessee Valley Authority, Rockefeller Foundation, and International Rice Research Institute.

He was awarded the South-East Asia Treaty Organization Post-Graduate Scholarship and began his graduate study at West Pakistan Agricultural University in September 1963. He received his Master of Science degree in September 1965 and returned to his post in Thailand.

In January 1966 he married the former Sareeya Panvichien and they now have three children, Arojphorn, Sirat, and Issara.

He attended a nine-month Post-Graduate Training Course in Soil Science and Plant Analysis at the International Agricultural Center, Wageningen, the Netherlands in September 1967 and received a Certificate in Soil and Plant Analysis in June 1968.
He was awarded the Rockefeller Foundation Scholarship to further his graduate study at Louisiana State University, Baton Rouge in August 1972. He is presently a candidate for the degree of Doctor of Philosophy.
Candidate: Aroon Jugsujinda

Major Field: Agronomy

Title of Thesis: Growth and Nutrient Uptake by Rice under Controlled Oxidation-Reduction and pH Conditions over:

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

Date of Examination:

November 6, 1975