

Efficiency in the Use of Plant Nutrients for Rice

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Introduction

The efficient use of fertilizer nutrients is one of the most important factors influencing rice yields and maximum dollar return for a grower's expenditures of time and money. In the past, fertilizer costs have been comparatively low in relation to the value of harvested rice. Rice farmers have frequently found it more convenient to apply excess nutrients to be sure of adequate supplies rather than to strive for maximum crop use efficiency of the applied fertilizer. However, recent increases in fertilizer costs, particularly for fertilizer nitrogen, have caused both growers and agricultural research scientists to increase emphasis on improving nutrient utilization efficiency by rice.

Lowland rice is noted for its inefficient utilization of applied fertilizer nutrients compared to upland crops, and this is especially true for added nitrogen (Mitsui, 1954). This is because the soil and climate conditions which favor lowland rice production also favor processes which reduce the availability of fertilizer nitrogen to rice (Patrick and Mahapatra, 1968). While upland crops are grown in well-drained or moderately well-drained soils, lowland rice is grown in soils subjected to alternate flooding and drainage cycles. This type of water management results in the development of a predominately aerobic soil profile during drainage and deep anaerobic soil conditions during flooding. A typical flooded rice soil is characterized

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by an oxygenated surface water layer and a thin oxidized (aerobic) surface soil horizon overlying a thick reduced (anaerobic) soil layer. Chemical processes affecting fertilizer nutrient availability are greatly affected by the oxidation-reduction status of soils.

The objective of this report is to discuss recent research conducted in the Department of Agronomy at Louisiana State University designed to develop methods of improving fertilizer nutrient utilization by crops. Particular attention has been directed to physical and chemical processes affecting nutrient availability in flooded soils. Selected data from recent field and laboratory studies will be used to illustrate the factors influencing nitrogen, phosphorus, and trace metal utilization efficiency by rice in flooded soils. For details of the methods used and results obtained, the reader is referred to reports and soon-to-be published literature citations accompanying the data.

Nitrogen

To improve the efficiency of fertilizer nitrogen utilization by rice, it is important to determine the fate of the applied nitrogen. This is difficult to do using conventional nitrogen measurement techniques as rice soils contain appreciable amounts of potentially available soil nitrogen relative to most upland soils in the South. To distinguish the plant uptake and soil loss patterns of fertilizer nitrogen from the soil nitrogen, it is necessary to label the fertilizer nitrogen source. Fertilizer nitrogen sources artificially enriched with Nitrogen-15 are useful in following the applied nitrogen through the soil-plant-water system. Nitrogen-15 is a naturally occurring isotope which has a slightly larger atomic weight than the more abundant Nitrogen-14. Modern analytical procedures make it possible

to separate and quantitatively determine these nitrogen isotopes, though both behave almost identically in physical, chemical, and biological processes.

Figure 1 illustrates some of the important transport processes and chemical transformations of soil and fertilizer nitrogen in a flooded soil. Soil organic nitrogen may mineralize to the ammonium form which is the same form usually applied to rice as fertilizer. Ammonium-nitrogen is readily available to rice plants. However, leaching, assimilation by soil microorganisms, and adsorption to soil colloids may reduce the plant availability of ammonium-nitrogen. In addition, ammonium-nitrogen in flooded soils may diffuse from the reduced soil layer to the thin oxidized surface soil or overlying floodwater. In oxidized soil or water environments, ammonium-nitrogen may combine with oxygen by the action of certain soil bacteria to form nitrate-nitrogen, a process called nitrification. Nitrate-nitrogen is also readily available as a nutrient source to rice under most conditions where it is found in soils. However, nitrate is very mobile in the soil-water system and may diffuse into the subsurface reduced soil horizon where it is transformed to nitrous oxide or molecular nitrogen by a process called denitrification. These nitrogen forms are not available to plants and readily escape the soil and return to the atmosphere as gases. Because of this process, it is usually not economically feasible to apply nitrate-nitrogen to a lowland rice crop.

Figure 2 illustrates the upward diffusion of ammonium from an underlying reduced soil horizon to a thin surface oxidized horizon. In this laboratory study, ammonium-nitrogen was uniformly distributed throughout a soil column. The top of the column was open to the atmosphere so that

any ammonium-nitrogen present in or transported to the oxidized surface layer would be subject to nitrification. After 120 days, the thickness of the oxidized layer increased slightly, but it is apparent that the ammonium was also lost from the initially reduced soil material by upward diffusion.

Figure 3 indicates the accumulation of nitrate-nitrogen formed through nitrification of applied ammonium in the surface oxidized layer. Only a portion of the ammonium lost could be accounted for at any given time by nitrate accumulation in the surface oxidized layer, and no nitrate was detected in the reduced soil layer. This is because the nitrate formed in the surface soil diffused into the underlying reduced soil and was removed from the soil by denitrification.

Figure 4 graphically illustrates the distribution of applied labelled ammonium-nitrogen among various forms with time in a flooded soil column. The soil was incubated in a sealed chamber under a 30 percent oxygen, 70 percent argon atmosphere. A small proportion of the added nitrogen accumulated in the organic nitrogen form at the end of 100 days. Much of the ammonium that disappeared was transformed to the molecular nitrogen form after 100 days. Though nitrate is an intermediate in this transformation, little nitrate accumulated. Nitrate formed in the oxidized surface layer likely diffused from this horizon into subsurface reduced layers.

The previous figures indicated how a labelled nitrogen source can be used to follow physical processes and biochemical transformations affecting the crop availability of applied fertilizer nitrogen. The labelled nitrogen technique can also be used to determine how various nitrogen sources, timing of application, and other treatments may affect uptake efficiency by rice (Figure 5). Note that in this particular study, urea resulted in greater

nitrogen uptake from both early and mid season applications over the ammonium sulfate nitrogen source. However, the smaller fertilizer uptake efficiency from the ammonium sulfate was compensated for by the greater native soil nitrogen uptake from this treatment. This resulted in little difference in total nitrogen uptake from the two nitrogen sources. From both sources, a mid season application resulted in greater fertilizer and soil nitrogen uptake than an early season application in this study.

Table 1 indicates the influence of different methods and times of nitrogen application on the yield, and fertilizer and soil nitrogen utilization by rice grown in a Crowley silt loam during 1974. In addition to grain yield and total nitrogen uptake, data available from conventional nitrogen fertilization experiments, labelled nitrogen techniques permit us to distinguish between the treatment effects on fertilizer nitrogen utilization efficiency and soil nitrogen availability. It is apparent from these labelled nitrogen experiments that fertilizer nitrogen enhances the availability of soil nitrogen. In conventional nitrogen fertilization studies, the control plot results are generally subtracted from the total nitrogen uptake to calculate fertilizer nitrogen recovery. Labelled nitrogen experiments indicate that fertilizer nitrogen recovery may be considerably overestimated by such procedures. In this particular study, rice grown in control plots receiving no nitrogen accumulated 48.2 kg nitrogen/ha from soil nitrogen sources. It is apparent from Table 1 that soil nitrogen availability was substantially enhanced by the addition of fertilizer nitrogen in all treatments.

Figure 6 indicates the accumulative uptake of total nitrogen, labelled fertilizer nitrogen, and native soil nitrogen during the growing season for

three application treatments. It is apparent that the uptake pattern differs considerably for the two nitrogen sources. After a short initial lag, presumably during which the root system is becoming established, the rate of soil nitrogen uptake is uniform over most of the growing season. However, fertilizer nitrogen uptake is greatest during approximately the first 3 to 4 weeks after application. After about 3 to 4 weeks, little additional fertilizer nitrogen accumulated in the rice plant. The same pattern was noted for other treatments studied.

A labelled nitrogen source is very useful in developing an accurate balance sheet for applied fertilizer nitrogen. The key to improving nitrogen utilization efficiency requires an understanding of how various fertilization practices affect nitrogen availability. Table 2 indicates a fertilizer nitrogen balance for rice grown in a Crowley silt loam during the 1974 season. One-hundred kg nitrogen/ha was applied 14 days after planting by deep placement. Of the nitrogen applied, 31 percent of the fertilizer nitrogen was recovered in the grain, and an additional 18 percent was recovered in the straw at harvest. Twenty-six percent was recovered in the roots plus soil. Approximately 25 percent of the applied nitrogen was lost from the soil-plant-water system in this particular study. The nitrification-denitrification sequence previously discussed likely accounted for most of this loss.

Tracer fertilization techniques such as these using labelled nitrogen fertilizers will be useful in improving our understanding of the factors influencing the availability of applied nitrogen and in developing management techniques to maximize fertilizer nitrogen use efficiency.

Phosphorus

Other than by plant uptake, fertilizer phosphorus removal from rice soil:

is minimal. Leaching losses of phosphorus are generally considered insignificant in most agricultural soils, and no processes exist which result in gaseous losses of phosphorus as occurs for nitrogen. However, the availability of phosphorus to rice is strongly influenced by soil properties. The oxidation-reduction status of rice soils is known to affect phosphorus chemistry, and several research projects have been conducted within the Department of Agronomy at Louisiana State University in this area.

Figure 7 indicates the influence of oxidized and reduced conditions on the levels of four common forms of phosphorus in a Perry soil. While changes in the redox status of this soil had little influence on aluminum and calcium phosphates, a considerable change was noted in the levels of ferrous iron phosphates and reductant-soluble phosphate. Flooding the aerobic Perry soil resulted in the development of reducing conditions. Subsequent reduction processes reduced the levels of the relatively unavailable reductant soluble phosphorus found in the aerobic soil and transformed this phosphorus to the more soluble and available ferrous phosphate form. This process is considered somewhat reversible and depends on the degree of soil oxidation or reduction.

In aerobic soils, discrete colloidal particles of ferric oxyhydroxide and coatings of this material may form on clay particles. Within these particles or coatings, several forms of phosphorus (and trace metals) may be coprecipitated with the insoluble ferric oxyhydroxide material. Some of this phosphorus would be available to crops if not occluded in the insoluble ferric oxyhydroxide. Reduction of this colloidal ferric oxyhydroxide to more soluble ferrous iron compounds as a result of waterlogging a soil releases some of the occluded phosphorus to plant available forms.

Table 3 gives the quantity of soluble phosphorus from several rice soils

as affected by soil oxidation or reduction conditions. In every soil but one, soluble phosphorus levels were greatly increased under reduced conditions, presumably due to the phosphorus released from the reduction of ferric oxyhydroxide particles and coatings containing occluded phosphorus.

Conventional soil test methods such as the Bray No. 2 extractable phosphorus test have been used to determine the phosphorus requirements of lowland rice soils. These extraction techniques have been employed on air dried samples under an oxygen atmosphere without any consideration of changes in soil phosphorus levels due to waterlogged or reduced conditions present in paddy fields. Recent research has indicated that soil test correlations for phosphorus with rice yields may be improved by modifying soil testing procedures to account for the influence of soil reduction processes on phosphorus availability. Soil samples were collected from the phosphorus experimental sites of the Rate and Ratio Fertilization Experiments conducted in various parts of Louisiana. Soil properties and various parameters of soil phosphorus were determined under oxidized and reduced conditions in the laboratory. Multiple regression analysis presented in Table 4 indicates that 71 percent of the variation in yields was due to soil properties, including four parameters of soil phosphorus. Linear correlation coefficients between rice yield and soil variables indicated that only phosphorus sorbed at 0.1 and 0.2 ppm phosphorus in solution under reduced conditions were significantly correlated with rice yields. These results suggest that phosphorus adsorption characteristics of soils measured under reduced conditions approximating field conditions for rice culture may be useful in predicting soil phosphorus needs of lowland rice soils.

Trace Metals

Recently, research has been conducted on the effects of soil pH and oxidation-reduction conditions on trace metal uptake by rice plants. Figure 8 indicates the effect of oxidized and reduced conditions on labelled iron and manganese uptake by rice plants at two pH levels. The rice plants were grown in the laboratory in stirred soil suspensions in which pH could be controlled by manual additions of acid or base, and the oxidation status of the suspensions was regulated by adding or excluding air. At pH 5.5, the greater iron uptake under anaerobic conditions was due to the presence of relatively soluble ferrous iron (Fe^{2+}) which is stable in moderately acid, reduced soils. The relatively low iron uptake under aerobic conditions at pH 5.5 and at both oxidation levels at pH 7.5 resulted from the very low solubility of ferric (Fe^{3+}) oxyhydroxides which are favored under these conditions. Recall the effects of iron chemistry on phosphorus availability.

Like iron, the valence state and subsequent solubility of manganese is also altered by changes in pH and oxidation-reduction levels commonly encountered in agricultural soils, especially in rice soils. The relatively soluble manganous (Mn^{2+}) form is favored by reduced conditions, and the sparingly soluble manganic form predominates under oxidized conditions. These differences in form and manganese solubility contribute to the uptake differences noted in Figure 8.

The effect of soil pH and oxidation-reduction levels on regulating trace metal availability involves more than simple changes in the metal's valence state. Numerous chemical and biochemical processes may be influenced by pH and oxidation levels which affect trace metal uptake. Figure 9 illustrates the effect of oxidized and reduced soil conditions on zinc uptake by rice at

four pH levels in a laboratory experiment similar to the one previously described. The valence of zinc is not altered over the range of pH and oxidation levels normally encountered in agricultural soils. However, significant pH and oxidation level effects are noted on zinc accumulation by rice plants. The formation of sparingly soluble zinc carbonate and hydroxide is favored by increases in soil pH and likely contributed to reduced zinc uptake as this soil became less acid. The formation of stable zinc complexes with insoluble humic materials and insoluble zinc sulfide precipitates in reduced soils may have contributed to less zinc uptake by rice from reduced soil suspensions at all pH levels.

Conclusions

It is well known that both soil pH and oxidation-reduction levels significantly influence the availability of most plant nutrients. Though the effect of soil pH have received considerable attention from agricultural scientists, much less research has been directed toward the effects of soil oxidation-reduction levels on nutrient availability. Rice production is especially dependent on soil chemical processes occurring in soils which possess both oxidized and reduced horizons or alternate between these conditions. Field and laboratory research conducted by the Laboratory of Flooded Soils and Sediments in the Department of Agronomy has been directed specifically at the soil chemical processes affecting nutrient and trace metal chemistry in reduced soils and sediments. Recent work has included plants in the soil-water system previously studied to develop techniques for determining factors affecting the biological availability of nutrients and metals in soils. Research to improve our understanding of processes affecting nutrient availability in flooded rice soils will eventually result in improved fertilizer use efficiency.

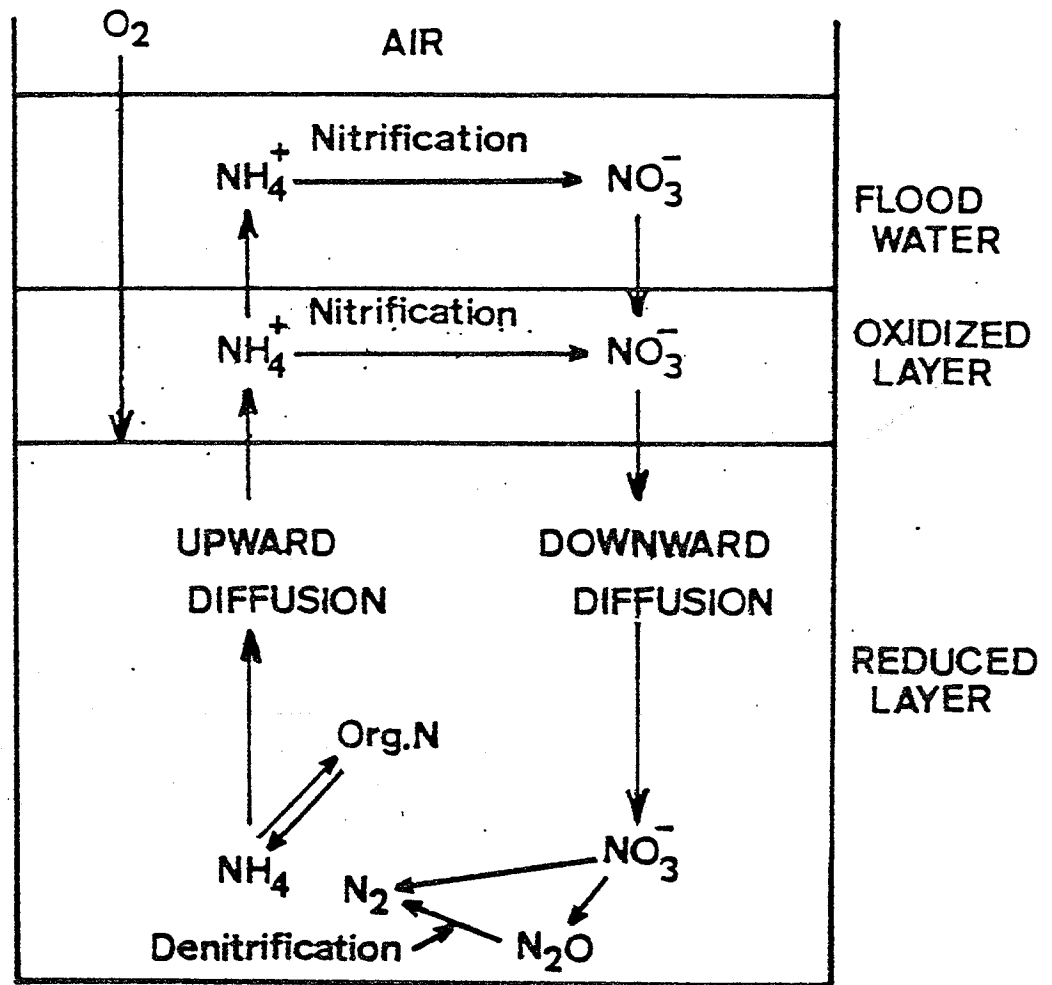


Figure 1. Chemical Transformations and Transport Processes Affecting Nitrogen Availability in Flooded Soils.

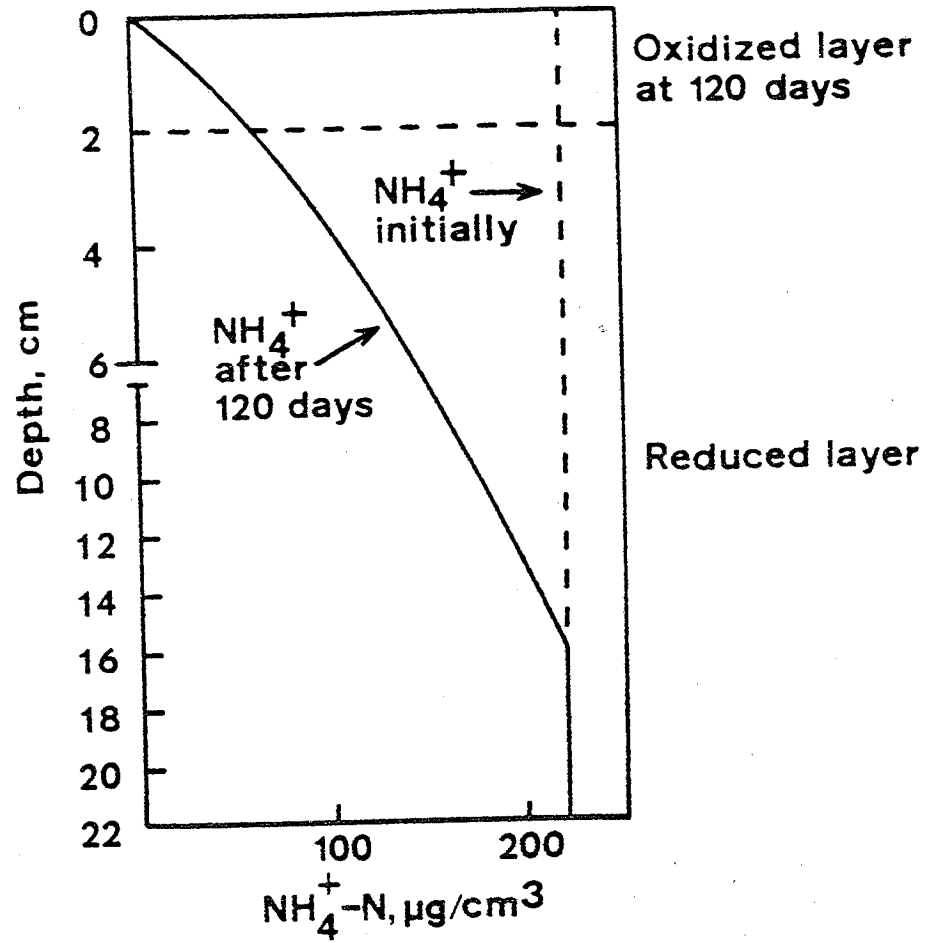


Figure 2. Removal of Ammonium-Nitrogen from a Flooded Rice Soil by Nitrification and Upward Ammonium Diffusion (adapted from Reddy, Patrick, and Phillips, 1976).

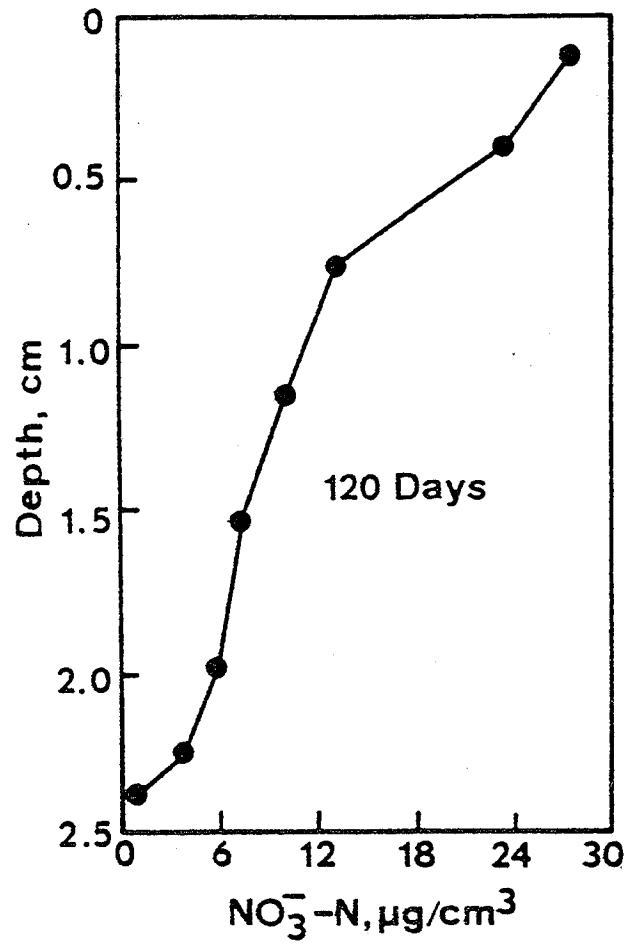


Figure 3. The Distribution of Nitrate-Nitrogen in the Surface Oxidized Horizon of a Flooded Rice Soil after a 120-Day Incubation (adapted from Reddy, Patrick, and Phillips, 1976).

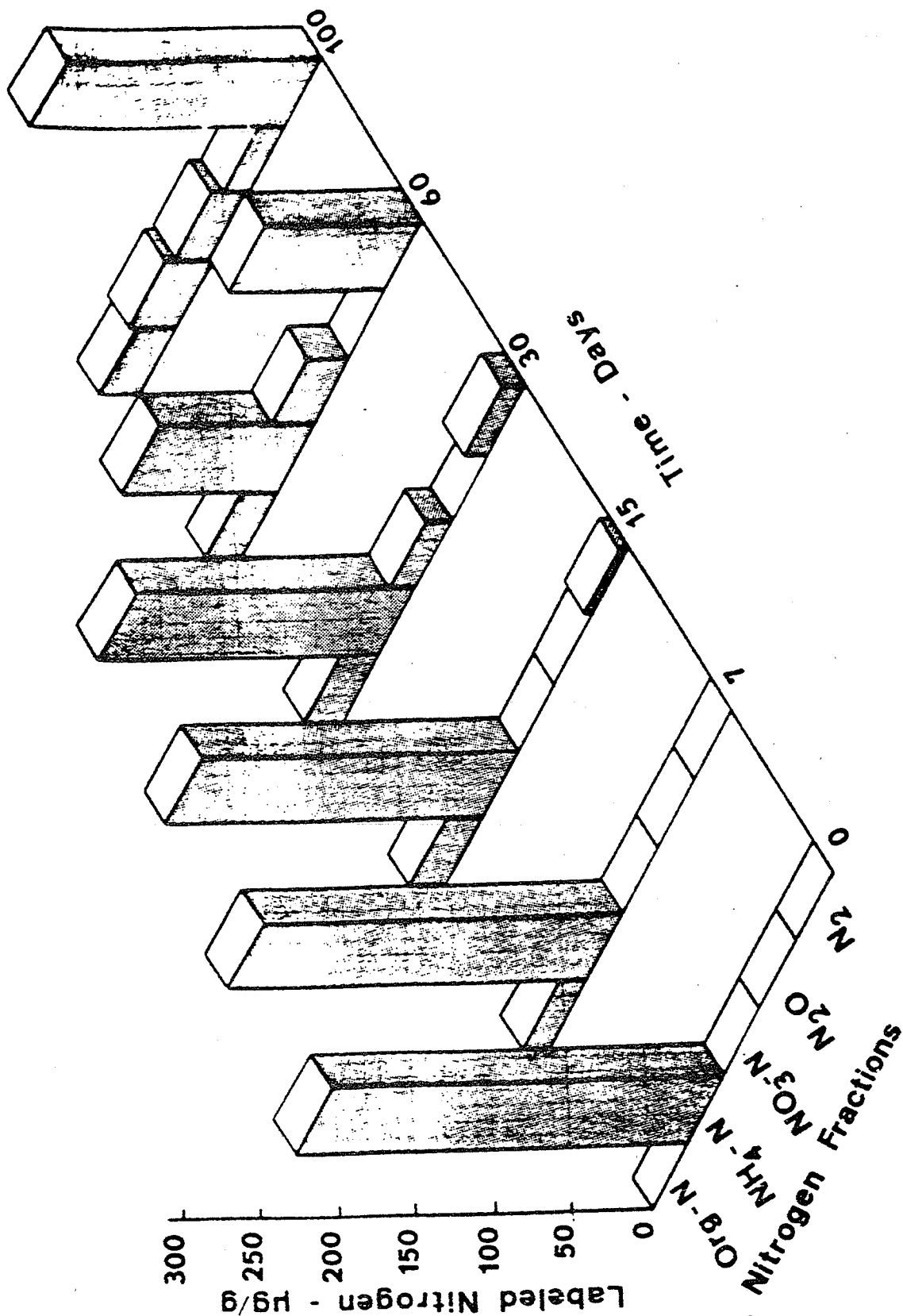


Figure 4. The Distribution of Applied Labeled Ammonium-Nitrogen Among Various Nitrogen Fractions During a 100-Day Incubation Under a 30%

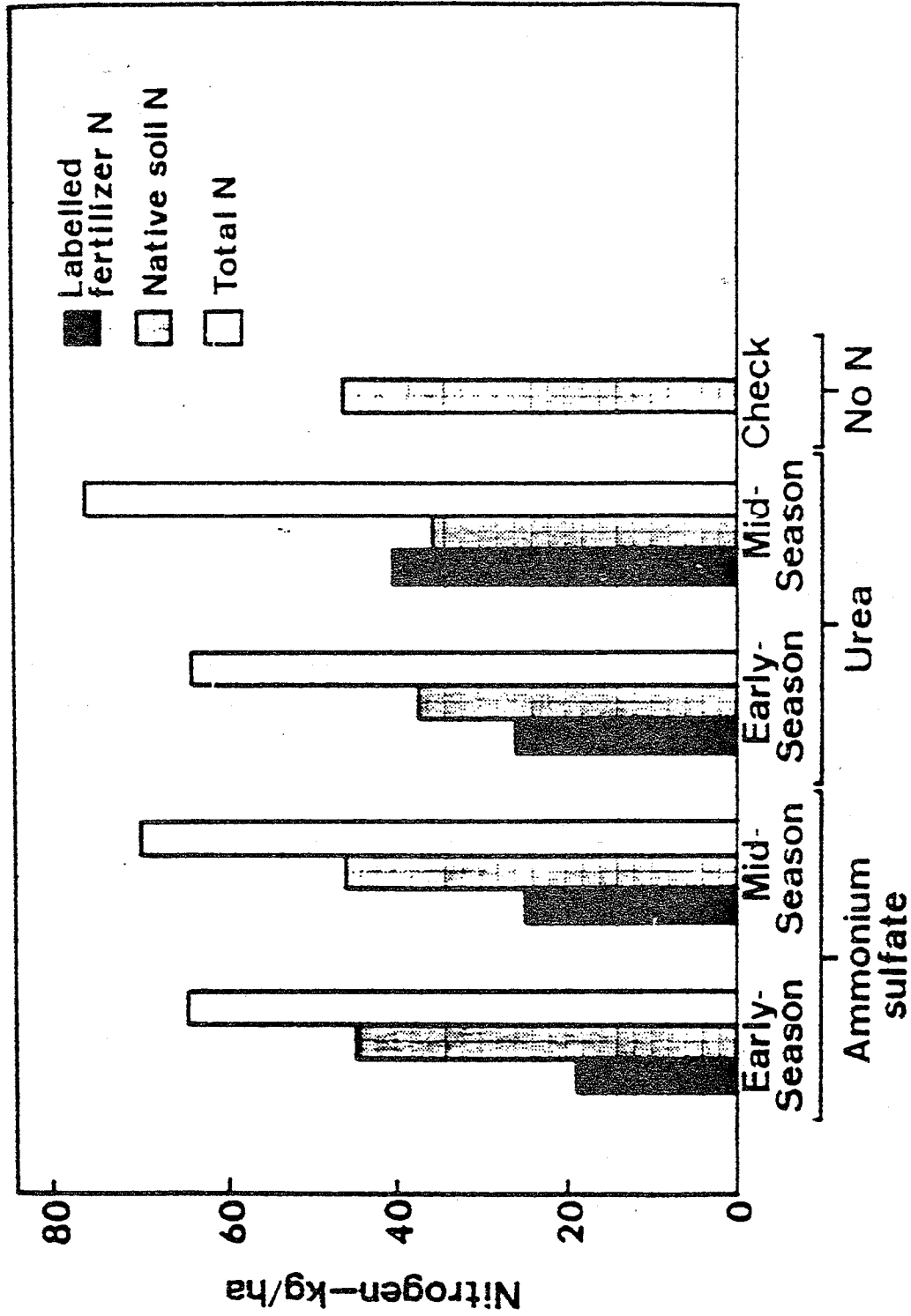


Figure 5. Uptake of Labelled Fertilizer and Native Soil Nitrogen as Influenced by Nitrogen Source and Time of Application (unpublished data, Reddy, K. R., and W. H. Patrick, Jr.).

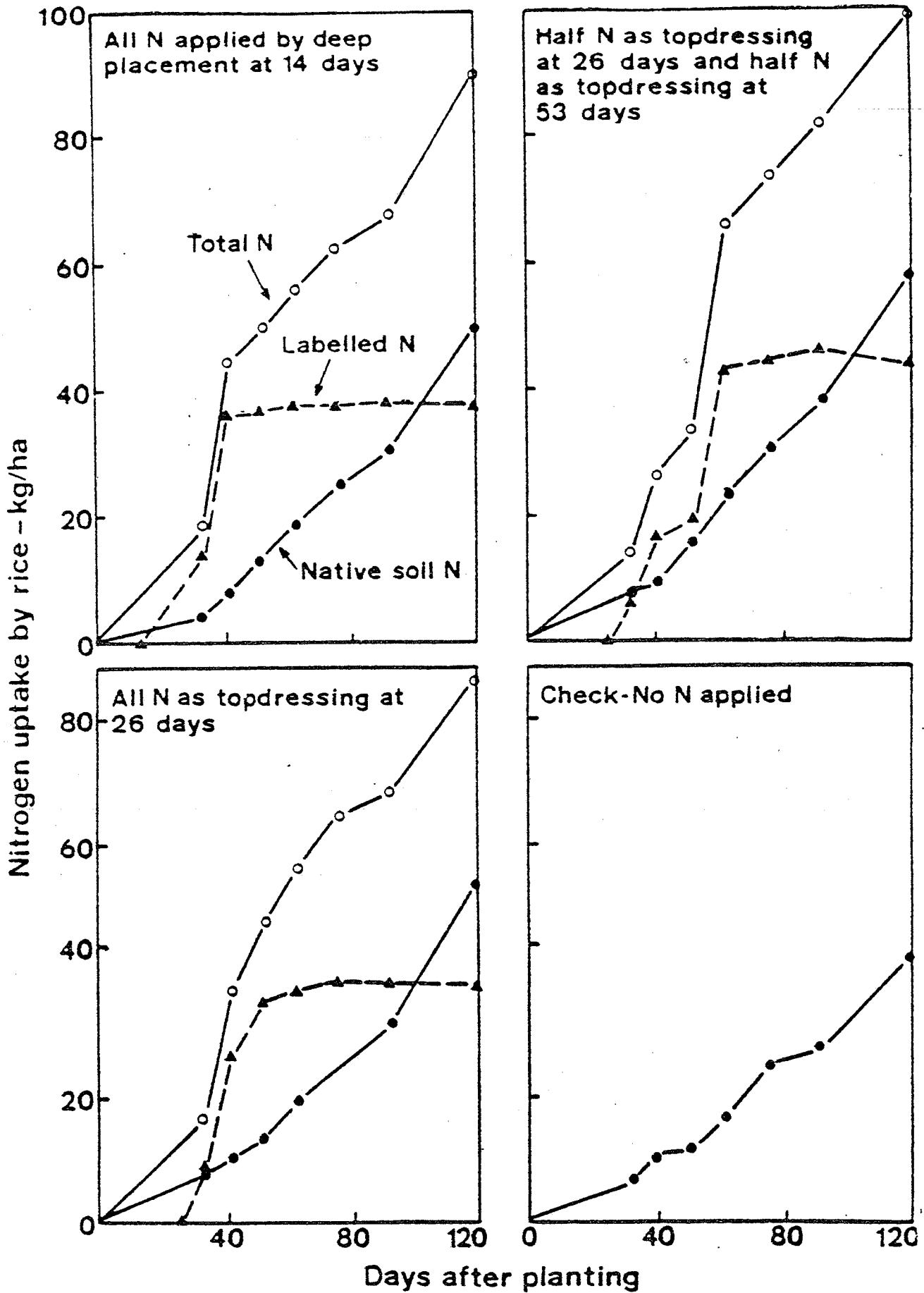


Figure 6. The Effect of Nitrogen Placement and Time of Application on Fertilizer and Soil Nitrogen Uptake by Rice During the Growing Season (Patrick and Reddy, 1975).

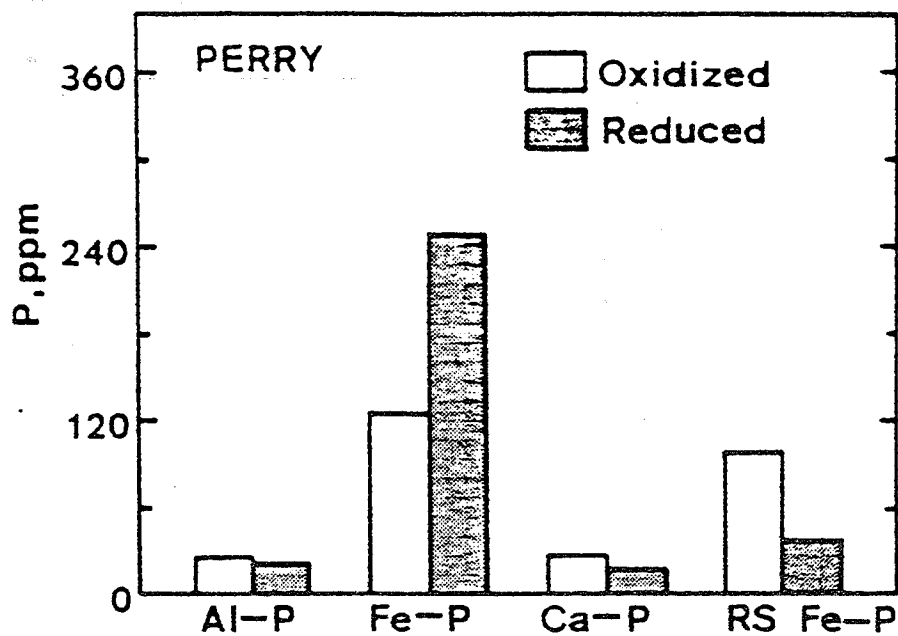


Figure 7. The Levels of Aluminum, Iron, Calcium, and Reductant Soluble Phosphorus as Affected by Oxidized and Reduced Soil Conditions (Patrick and Mahapatra, 1968).

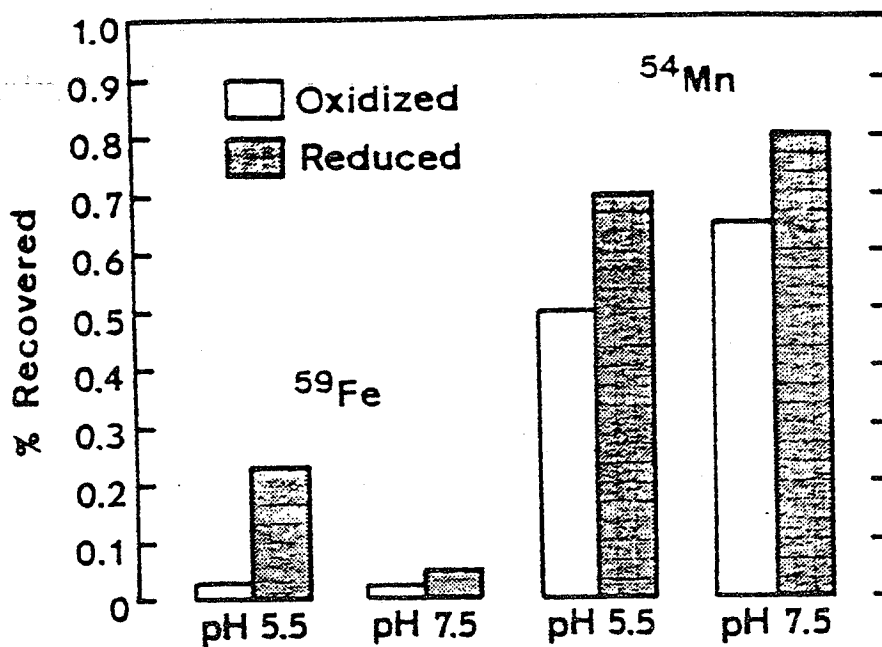


Figure 8. The Effect of Soil pH and Oxidation-Reduction Levels on Iron-59 and Manganese-54 Uptake by Rice (Jugsujinda, 1975).

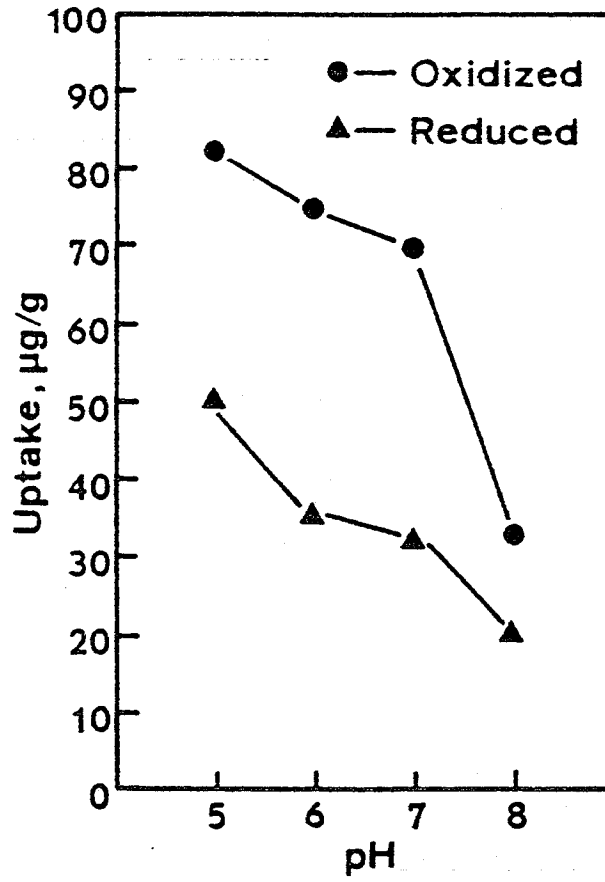


Figure 9. The Effect of Soil pH and Oxidation-Reduction Levels on Zinc Uptake by Rice (Jugsujinda, 1975).

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Table 1. The Effect of Placement and Time of Application on Yield and Fertilizer Nitrogen Utilization by Rice on a Crowley Silt Loam, 1974 (Reddy and Patrick, 1976)

Treatment	Grain Yield*	Total N Removed	Recovery of Applied N-15 (grain + straw)	Recovery of Soil N (grain + straw)
	tons/ha	kg/ha	kg/ha	kg/ha
1. All N applied by deep placement, early season	7.7	123.7	52.6	71.1
2. Half N topdressed at early season + half N at mid season	7.5	106.6	38.8	67.7
3. All N at early season	8.0	115.0	42.1	72.8
4. All N at mid season	6.9	100.6	37.0	62.6
5. Half N at early season + half N at late season	6.4	106.1	43.9	63.1
6. Check (No N applied)	3.6	48.2		48.2

*Yield expressed on 12% moisture basis.

Table 2. Fertilizer Nitrogen Balance at Harvest
for Rice Grown on a Crowley Silt Loam, 1974
(Patrick and Reddy, 1976b)*

Fraction	Recovery of Applied Nitrogen, %
Grain	31
Straw	18
Soil	26
Nitrogen Unaccounted for at Harvest	25

*Applied ammonium nitrogen, 100 kg/ha.

Table 3. Soluble Phosphorus in Selected Rice Soils Under Oxidized and Reduced Conditions (Unpublished data, Khalid, R. A., Patrick, Jr. W. H., and DeLaune, R. D.)

Soil Type	Soil pH	P, $\mu\text{g/ml}^*$	
		Oxidized	Reduced
Bernard V.F.S. Loam	4.65	0.012	0.022
Midland F.S. Loam	5.73	0.063	0.445
Midland Si. Loam	5.81	0.025	0.520
Crowley Si. Loam	6.10	0.004	0.040
Harris Si. Loam	5.01	0.005	0.025
Sharkey Clay	6.40	0.055	1.910
Iberia Clay	5.84	0.020	0.020

*Soil - 0.01 M CaCl_2 Ratio = 1:5

Table 4. Rough Rice Yield as a Function of Selected Soil Variables*
(Unpublished data, Khalid, R. A., Patrick, Jr., W. H., and Peterson, F. J.)

Soil Variable	R-Square	% Increase in R-Square	Simple Correlation Coefficient 'r'
P sorbed at 0.2 ppm P in solution (reduced)	0.218	21.8	-0.467**
0.01 M CaCl ₂ Extractable P (reduced)	0.509	29.1	-0.042 ^{ns}
P sorbed at 0.1 ppm P in solution (reduced)	0.592	9.3	-0.395**
Bray No. 2 Extractable P	0.616	2.5	-0.046 ^{ns}
% clay	0.642	2.6	-0.068 ^{ns}
Soil pH (reduced)	0.682	4.0	-0.280 ^{ns}
Soil pH (oxidized)	0.713	3.1	-0.261 ^{ns}

* Multiple regression, n = 46.

** Significant at 1% level.

^{ns} Non-significant.