

THE INFLUENCE OF HIGH RATES OF P FERTILIZATION
ON WHEAT PRODUCTION, AVAILABLE
SOIL NUTRIENTS AND SOIL
SOLUTION COMPOSITION

By

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CHAPTER I

INTRODUCTION

Phosphorus fertilization on croplands is used to increase available P in the soil to meet the needs of plant nutrition. Proper P fertilization on wheat can maximize yields. It has often been said that increasing fertilizer P applications on wheat can continue to increase grain yields although little data has been collected to document this idea.

The soil testing methods for P, such as Bray and Kurtz P 1, are widely used among soil testing laboratories to quickly and accurately assess the P status of a soil. These soil tests are used in conjunction with field tests to determine correct fertilizer rates for optimum production, but few of these experiments deal with extremely high rates of P fertilization.

The plant obtains its nutrients from the soil solution which is the aqueous phase of the soil. The soil solution is extremely low in P when compared to plant available P given by the soil testing procedures. The concentration of P in the soil solution is affected by P fertilization as are other constituents of the soil solution so they can be used as a measure of P availability to the plant, but the chemistry of

soil solutions is complex. The ion activity is that which is available to the plant, and does not equal the measured concentrations. Ions in the soil solution form ion-pairs and ion activities that are lower than the measured concentrations.

The objectives of this study were to determine the effects of extremely high rates of P fertilization on wheat yield and nutrient uptake, available soil nutrients, and soil solution composition.

CHAPTER II

THE INFLUENCE OF HIGH RATES OF P FERTILIZATION ON WHEAT PRODUCTION, AVAILABLE SOIL NUTRIENTS AND SOIL SOLUTION COMPOSITION

Abstract

Treatments of 0, 30, 60, 120, 300 and 600 kg ha⁻¹ of P were applied annually at Haskell, OK, from 1977 and 1979 and three residual years from 1980 to 1983 to evaluate the response of P fertilization upon winter wheat (Triticum aestivum L.), the available soil nutrients, and the soil solution composition. Nitrogen and K were kept constant at 112 and 93 kg ha⁻¹ respectively.

Grain yield and concentration of N, P, and K in grain were determined for the three years of P applications and three residual years. Grain yields were increased with 30 kg ha⁻¹ of P, however higher rates decreased yields. Phosphorus concentration in grain was increased with increasing P rates.

Standard soil fertility indices (N, P, K, pH, and BI) were determined for most years. Bray and Kurtz P 1 increased linearly with application rates.

Soil samples were taken in 1983 in five increments down to a depth of 120 cm (0-15, 15-30, 30-60, 60-90, and 90-120 cm). Bray and Kurtz P 1 increased linearly at 0 to 15 and 15

to 30 cm with no increases from 30 to 120 cm. Calcium increased at 0 to 15 cm but there were no differences at lower depths. Nitrate-N increased at lower depths in the control while $\text{NH}_4\text{-N}$ increased at lower depths in the highest P rate.

Soil solutions were displaced from samples of the 0-15 cm depth of soil collected in 1983. Ion activities and ion-pair formation were evaluated by using the concentration of anions and cations through both GEOCHEM and an Adams procedure program. Activity of P was increased at the highest P rate. Nitrate-N and Ca activity were related and also were related inversely to yield with an increase at 300 and 600 kg ha^{-1} P. No toxic effects could be found due to Al or Mn. A comparison of the two computer programs to estimate ion activities showed good correlation except with Al, Mn, and Fe.

CHAPTER III

REVIEW OF LITERATURE

The increase in the acreage of winter wheat (Triticum aestivum L.) over the past two decades in Oklahoma has come from lands that were primarily used as pasture, either native or introduced species. The native pastures are primarily Mollisols which have a significant amount of organic matter and a high reserve of N. Many of these areas do not respond to N fertilization. Soils in eastern Oklahoma have long been used primarily as pastureland and recently a large portion have been converted to wheat acreage. Much of this area is extremely deficient in P (Westerman, 1984a) and responds well to P fertilization. Westerman et al. (1984b) found that arrowleaf clover in this area responded well to P fertilization and that the highest yield was found at the P rate indicated by Bray and Kurtz P 1 (1:20 dilution) soil test index according to Oklahoma State University Soil Testing Lab procedures. However little work has been done on the effect of high P fertilization rates and residual effects on winter wheat.

Westerman et al. (1984b) stated that higher P rates could decrease the time needed to build up the soil P to where it had an adequate supply and reduce the total P

fertilizer needed for long-term P fertilization. Peck et al. (1971) observed a similar trend and found that it took about four units of applied P fertilizer to observe a single unit increase in available soil P. Yost et al. (1981) found that high rates of up to 560 kg ha⁻¹ P kept increasing corn yields and soil P analyses on a high P absorbing Oxisol in central Brazil. Adams et al. (1982) found that P rates of 196 and 392 kg ha⁻¹ and pH around 7.0 induced a Zn deficiency in soybeans. This deficiency occurred when the soil solution had a pH of 6.3 or above and was corrected by foliar-applied ZnEDTA.

The soil solution composition can also be used to define the effect of P fertilization since the soil solution bathes the plant roots. It is from this solution that plants obtain inorganic nutrients and provides its chemical environment (Adams, 1974). Water extracts are a valuable tool but only estimate the true soil solution and does not give satisfactory data for P. The water extracts overestimate the concentration of P in the soil solution.

Several methods have been devised in order to obtain the true soil solution. Adams et al. (1980) compared column-displacement and two centrifuge methods to obtain the soil solution and found that there were no differences in composition of displaced solutions. They did find that column-displacement gave a greater volume of displacement per volume of soil.

The activity of the ions in the soil solution has been

recognized as a more accurate index of availability to the plant than the actual concentration (Sparks, 1984). Once the concentrations of the ions of interest are known, the activities and ion-pairs can be calculated by a step-wise procedure such as Adams (1971) or GEOCHEM (Sposito and Mattigod, 1979).

Early research showed a poor correlation between concentration of soil solution P and plant response to P fertilization (Adams, 1974). Soltanpour et al. (1974) did find a significant correlation between P rates, soil solution P and dry matter yield of a sorghum-sudangrass hybrid in a greenhouse study. They found that soil solution P was an excellent estimate of P availability. They also found that the yield curve was highest at the 150 ppm P rate but remained constant to the 300 ppm rate. Adams et al. (1982) found that Zn deficiency could be induced at 196 and 392 kg P ha⁻¹ with high pH but that there was no difference of Zn concentration in the soil solution. The Zn deficiency is induced by the complexing of Zn and P when excessive rates of P are applied. They also found that soil solution P was affected primarily by P rates. Petrie and Jackson (1984) found no effect of P fertilization on the Mn concentration in the soil solution, but the pH of the soil solution did show good correlation with Mn concentration. Khasawneh (1971) recognized that the relationship between nutrient ion activity and rate of uptake was curvilinear and did suggest that when nutrient ion activity is continually increased,

uptake and/or plant growth would decrease due to toxic levels, nutrient imbalances or osmotic effects. Curtin and Smillie (1983) studied the effect of liming and incubation on the soil solution and found increases in both Ca and NO_3^- activity with increasing lime rates. High rates of P fertilization could result in similar effect since several P fertilizers also contain a high amount of Ca.

The objectives of this study were to determine the effects of high rates of P fertilization on wheat yield, nutrient uptake in grain, available soil nutrients and soil-solution composition.

CHAPTER IV

MATERIALS AND METHODS

Field Experiment

The experiment was established and conducted on a Taloka silt loam (fine, mixed, thermic Mollic Albaqualfs) at the Eastern Research Station at Haskell, OK. Initial soil pH, $\text{NO}_3\text{-N}$, P, and K indices were 5.0, 44 kg ha⁻¹, 15 kg ha⁻¹, and 141 kg ha⁻¹ respectively using 1:1 H₂O, specific ion electrode, Bray and Kurtz no. 1 (1:20 dilution), and 1 M neutral NH_4OAc . The experiment consisted of four replications of six treatments in a randomized complete block design. Rates of P were 0, 30, 60, 120, 300, and 600 kg ha⁻¹ applied in August 1977, 1978, and 1979. The study consisted of three annual applications of P from 1977 to 1979 and three residual years from 1980 to 1983. Nitrogen and K were applied uniformly over the entire study yearly at rates of 110 kg ha⁻¹ and 90 kg ha⁻¹ respectively. Ammonium nitrate (NH_4NO_3 , 34-0-0), treble superphosphate ($\text{Ca}(\text{H}_2\text{PO}_4)_2$, 0-46-0), and murate of potash (KCl, 0-0-62) were used as sources of N, P, and K respectively. All fertilizers were broadcast and incorporated prior to planting. Winter wheat (Triticum aestivum L., CV TAM W 101) was planted in September of each

year. Grain yield was sampled each year from a 3 by 15 m strip harvested within each plot by a self propelled combine. Samples of grain were taken at harvest and N, P, and K concentrations were determined and uptake calculated from the grain yield and nutrient concentration in grain. Nitrogen was determined by micro-Kjeldahl (Bremner and Mulvaney, 1982). Total P and K in grain were determined after nitric-perchloric acid digestion by colorimetry (Murphy and Riley, 1962) and atomic absorption (Issac and Kerber, 1972) respectively. Soil samples were taken after harvest in 1978, 1979, 1980, and 1982 from the surface 0 to 15 cm of each plot, combined from within plots, dried, crushed, and analyzed for pH, BI (buffer index), NO_3^- -N, Bray and Kurtz no. 1 (1:20 dilution) P, and extractable K.

Soil samples were taken after harvest in 1983 from three cores from the center of each plot and subdivided into five depths: 0 to 15 cm, 15 to 30 cm, 30 to 60 cm, 60 to 90 cm, and 90 to 120 cm. The samples were dried, crushed, and part of that sample combined with other samples from the same plot and depth to form composite samples. Composite soil samples were analyzed for pH using 1:1 H_2O , NH_4^+ -N, and NO_3^- -N (using 2M KCl with Techicon Auto Analyzer), and exchangeable K, Na, Ca, Mg, and Al using 1 M NH_4OAc adjusted to pH 4.8 and modified to work with a soil extractor. Bray and Kurtz no. 1 (1:20 dilution) P was determined on the soil samples in which the three cores were kept separate.

Displaced Soil Solutions

A bulk sample, approximately 15 kg, was collected from each field plot from the surface 15 cm, air dried, crushed, and screened and saved for displacement of the soil solution. Six hundred g of soil was moistened to approximately 50% field capacity and packed tightly into 5 X 60 cm glass cylinders for soil solution displacement. Additional deionized water was added to bring the soil to field capacity and the soil was allowed to equilibrate for 24 hr. A saturated solution of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ containing 0.4% KCNS as a tracer (Adams, 1971) was used for displacement. Soil solutions were collected in 10-ml increments until the extracting solution was detected in the displacement by spot checking with FeCl_3 . The displacement procedure for the soil from each field plot was performed in triplicate. The soil solution was analyzed for pH, P by modified colorimetry (Murphy and Riley, 1962), SO_4^{--} by turbidity, Cl^- by AgNO_3 titration, HCO_3^- by dilute sulfuric acid titration, NO_3^- and NH_4^+ by colorimetry using a Techicon Auto Analyzer, K^+ , Na^+ , Ca^{++} , Mg^{++} , Mn^{++} , Fe^{+++} and Al^{+++} by atomic absorption. Ionic activities and ion-pair concentrations were estimated by inputting the measured ion concentrations in computer models designed after the method of Adams (1971) and GEOCHEM (Sposito and Mattigod, 1979). Correlation coefficients were

calculated through SAS (1982) using the Pearson method in order to compare the results from the Adams procedure and GEOCHEM.

CHAPTER V

RESULTS AND DISCUSSION

Grain Yield

Average wheat grain yield and yield for each year except 1982 is illustrated in Figure 1. Data for 1982 was not used due to a severe weed infestation. Grain yield increased dramatically with the first P rate of 30 kg ha⁻¹ fertilization. Highest yields were obtained at the 30 kg ha⁻¹ P rate which is the rate indicated by the Oklahoma State University soil test calibration. Yields for P rates above 30 kg ha⁻¹ steadily declined and the 300 and 600 kg ha⁻¹ P rates yielded less than the control. Grain yields for each individual year always increased at 30 kg ha⁻¹ P and always decreased at 300 and 600 kg ha⁻¹ P. Yields in 1978 and 1979 decreased above 30 kg ha⁻¹ P and in 1980 and 1981 there were no differences between 30 and 60 kg ha⁻¹ P. Yield in 1983 again increased at 30 kg ha⁻¹ P and there were no differences between 30, 60, and 120 kg ha⁻¹ P and then decreased at the highest two P rates. It is not known at the present time what caused the decline in yield, but there are relationships in the soil and soil solution which suggest possible causes for the decline. Nutrient concentration of grain is shown in Figure 2. Phosphorus concentration in grain is curvilinearly

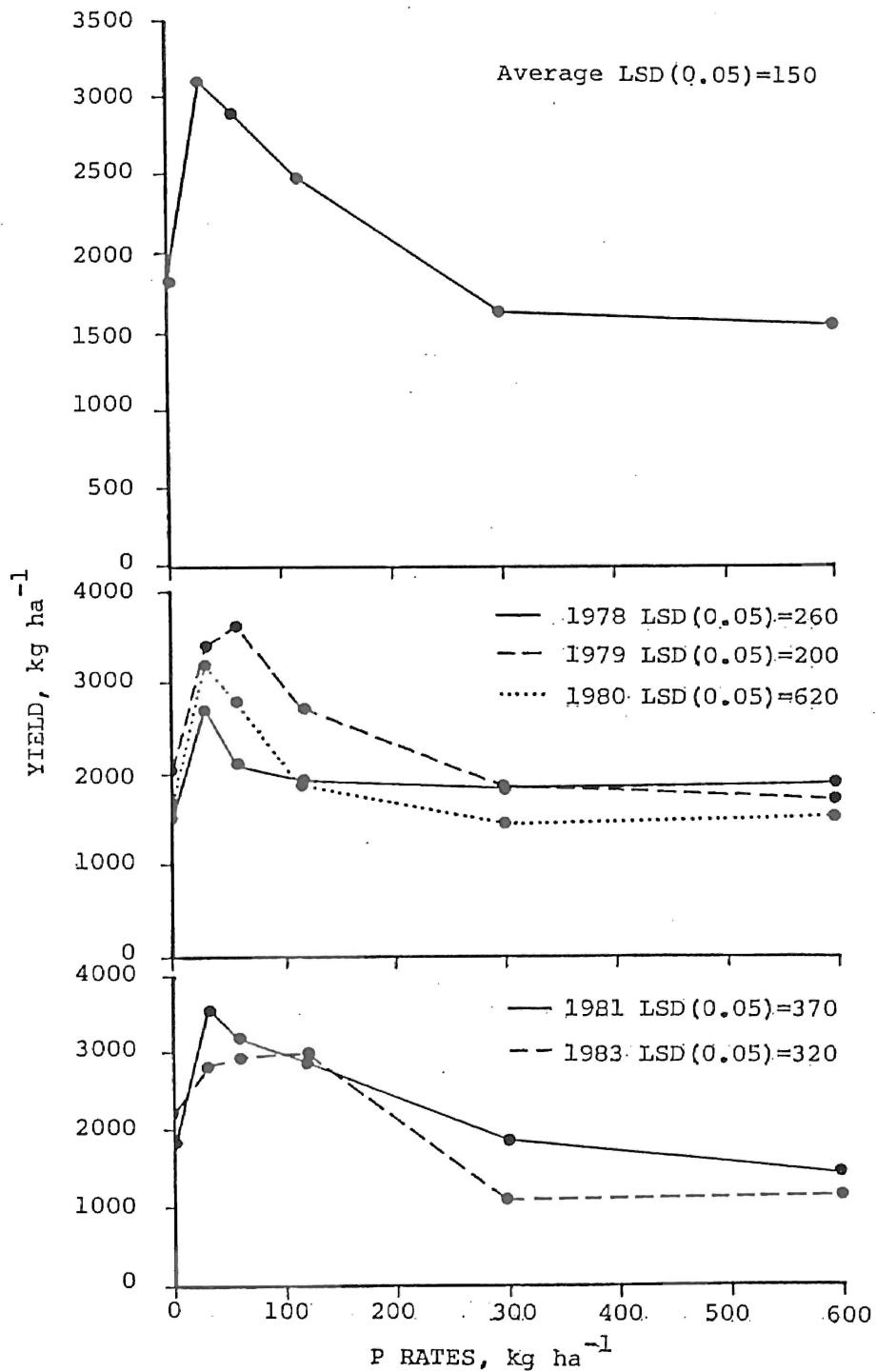


Figure 1. Effect of Three Annual Applications of P and Three Residual Years on Grain Yield Averaged over Years, the Three Years of Annual Applications, and the Three Residual Years.

related to P fertilization. Regression analyses gave the relationship between P concentration in the grain and the P rate as $Y = 2.62 + 0.011 X - 2.4 X^2 + 1.9 X^3$ with a R^2 of 0.65. Potassium concentration in grain responded linearly to P treatments. The N concentration of grain decreased in response to the 30 kg ha⁻¹ then steadily increased with increasing rates of P.

Uptake of N, P and K in grain is illustrated in Figure 3. Nitrogen and K uptake was closely related to the yield with correlation coefficients of .96 and .92 respectively. Phosphorus uptake increased at 30 kg ha⁻¹ and decreased at the highest two P rates.

Available Soil Nutrients

The available soil nutrients, pH and buffer index for all years are illustrated in Figure 4. There were no differences due to P treatments in the available soil N as NO₃-N, exchangeable K, pH and buffer index. Bray and Kurtz no. 1 (1:20) P increased with increasing P rates ($Y = 21.7 + 0.59 X$ with a $R^2 = 0.86$). All differences were significant at the .05 level except between the control and 30 kg ha⁻¹ P.

The available soil nutrients and pH measured in soil collected in 1983 for the 5 different depths are illustrated in Figures 5, 6, 7, 8, and 9. Bray and Kurtz no. 1 (1:20) P increased linearly with P rates in both the 0 to 15 cm and 15 to 30 cm depths. At lower depths the P rates had no effect

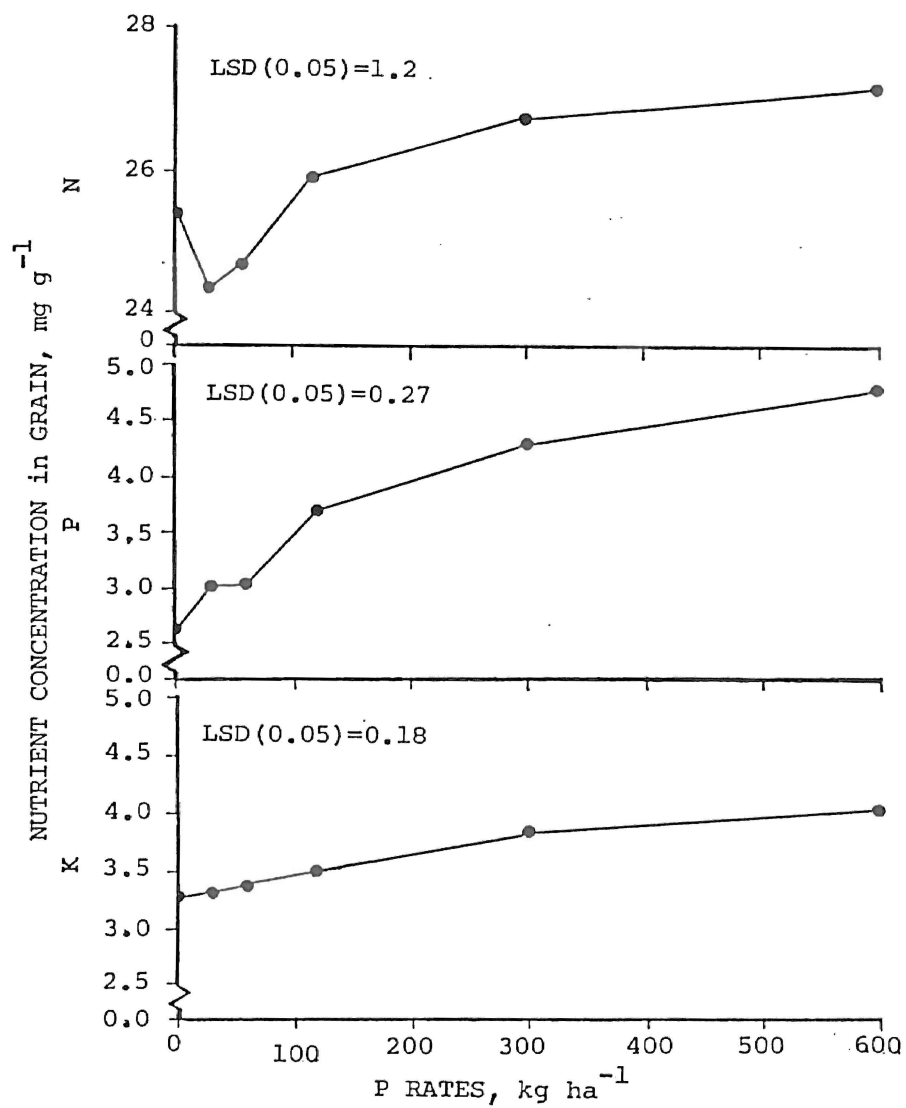


Figure 2. Effect of Three Annual Applications of P and Three Residual Years on N, P, and K concentration in Grain.

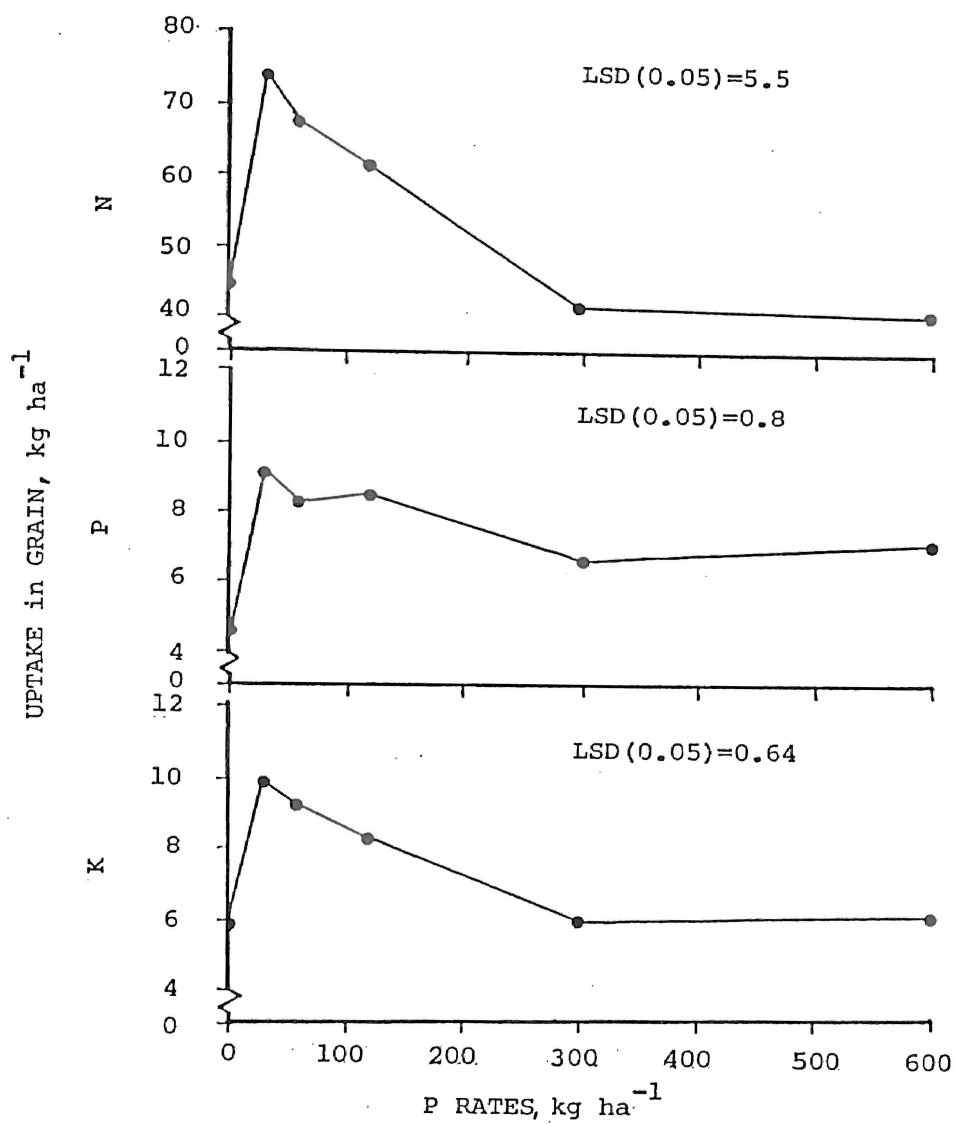


Figure 3. Effect of Three Annual Applications of P and Three Residual Years on N, P, and K Uptake in grain.

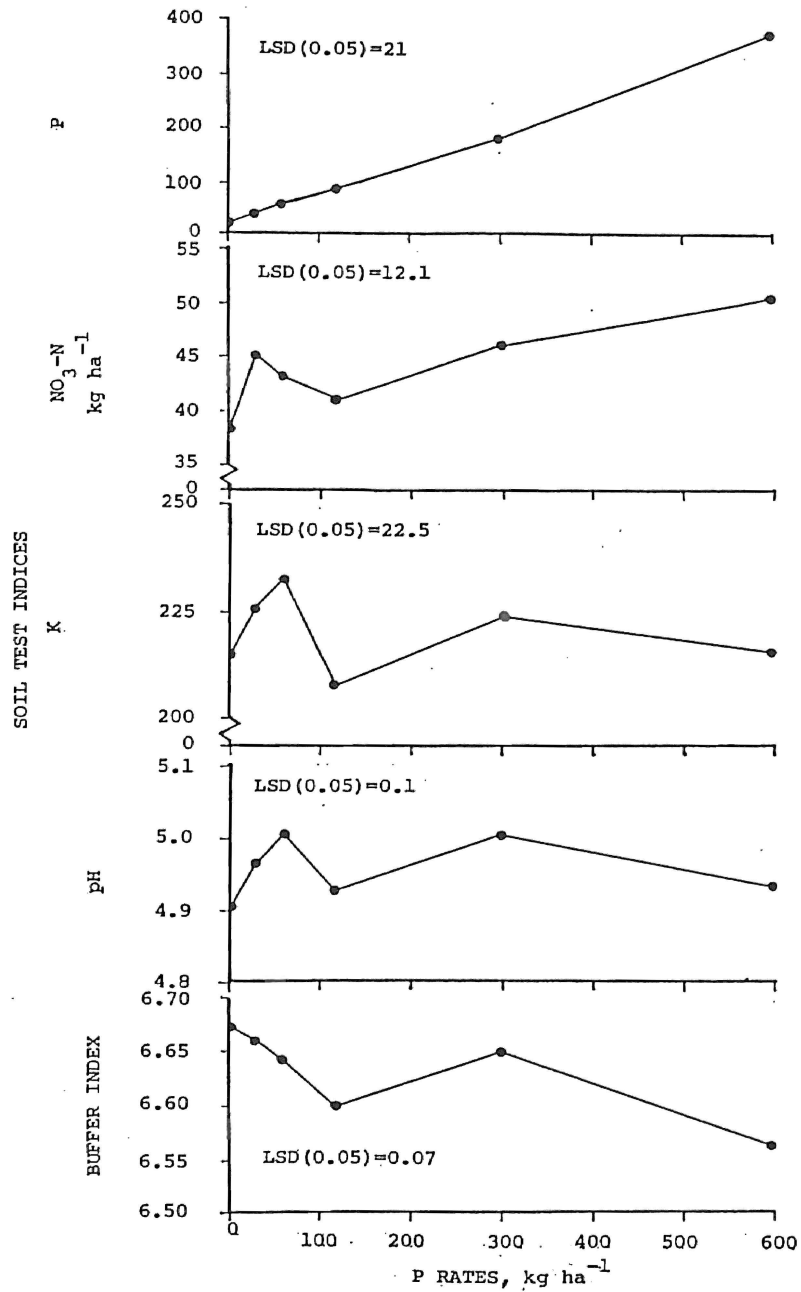


Figure 4. Effect of Three Annual Applications of P and Three Residual Years on Bray and Kurtz no. 1 (1:20) P, $\text{NO}_3\text{-N}$, Exchangeable K, pH, and Buffer Index.

upon the available P. There was movement of P to the 15 to 30 cm depth due to incorporation by tillage but there was no movement of P to lower depths. Exchangeable Ca increased linearly with P rates in the 0 to 15 cm depth. This was expected due to the Ca content of the P fertilizer. Calcium rates supplied with the P fertilizer were approximately 0, 19, 39, 77, 193 and 387 kg ha⁻¹ respectively with increasing rates of 0, 30, 60, 120, 300, and 600 kg ha⁻¹ P. There were no differences in exchangeable Ca at depths lower than 15 cm but there was an increase between the depths with increasing depth. There were no differences in NO₃-N at the 0 to 15 cm depth, but at lower depths the control had an increase of NO₃-N. Nitrate-N also increased over all treatments in lower depths for each depth as a whole when compared to the 0 to 15 cm depth, except for the 90 to 120 cm depth. Ammonium-N was inversely related to NO₃-N with no differences observed from 0 to 60 cm and an increase at depths 60 to 90 cm and 90 to 120 cm at the 600 kg ha⁻¹ P rate. This indicates some type of relationship between N and either P or Ca. Potassium was not effected among depths due to P rates but it did show a decrease between each depth from 0 to 15 cm to 30 to 60 cm, then an increase from 30 to 60 cm and 90 to 120 cm. There were no differences among depths due to P rates in the available Mg, Na, and Al in all depths. Magnesium and Na did increase with depth. Aluminum increased from depths 0 to 15 cm to 30 to 60 cm with a decrease at 90 to 120 cm. There were no differences in pH within each depth. There were no

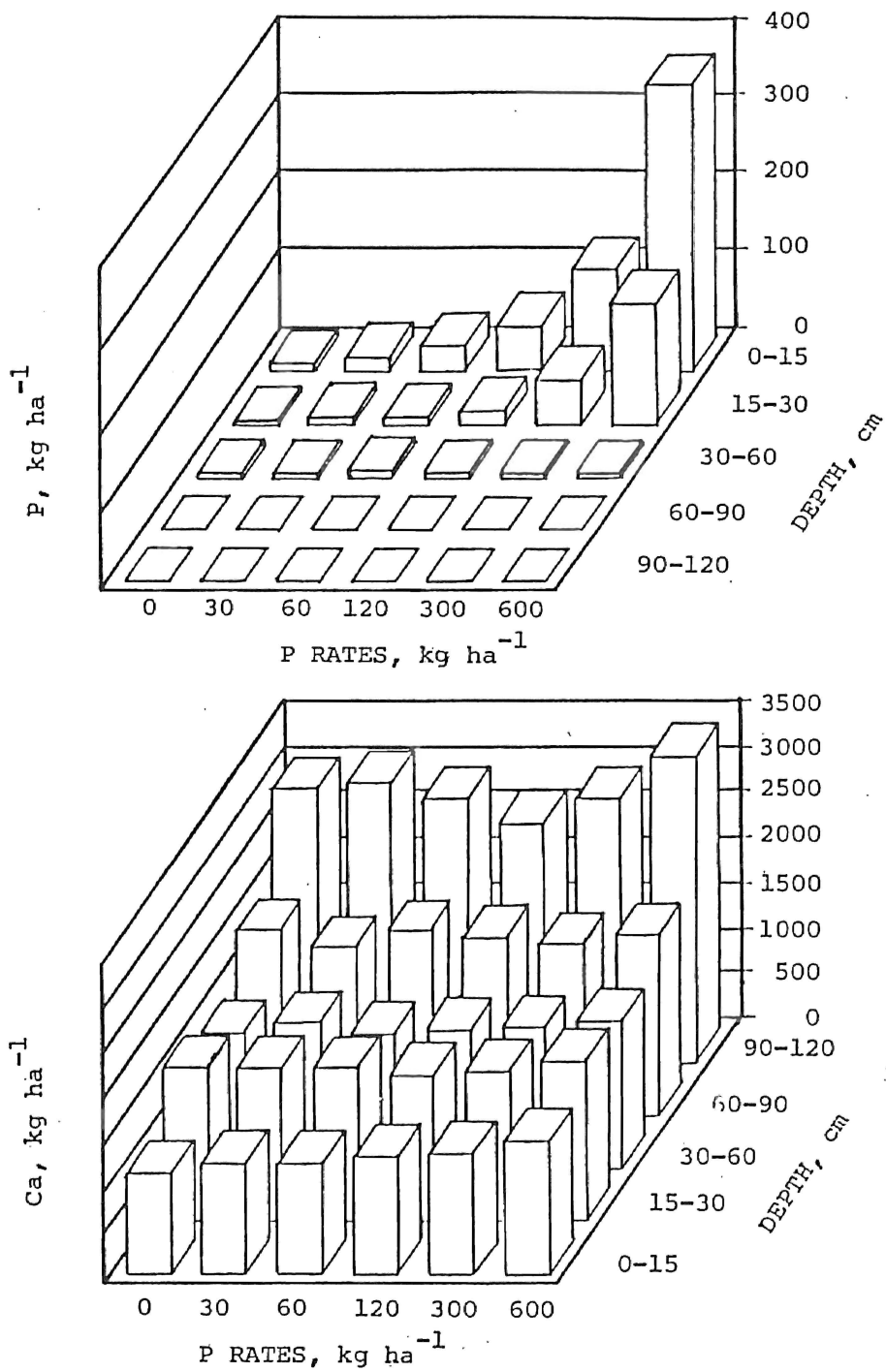


Figure 5. Effect of Three Annual Applications of P and Three Residual Years on Bray and Kurtz no. 1 (1:20) P and Exchangeable Ca, 5 depths.

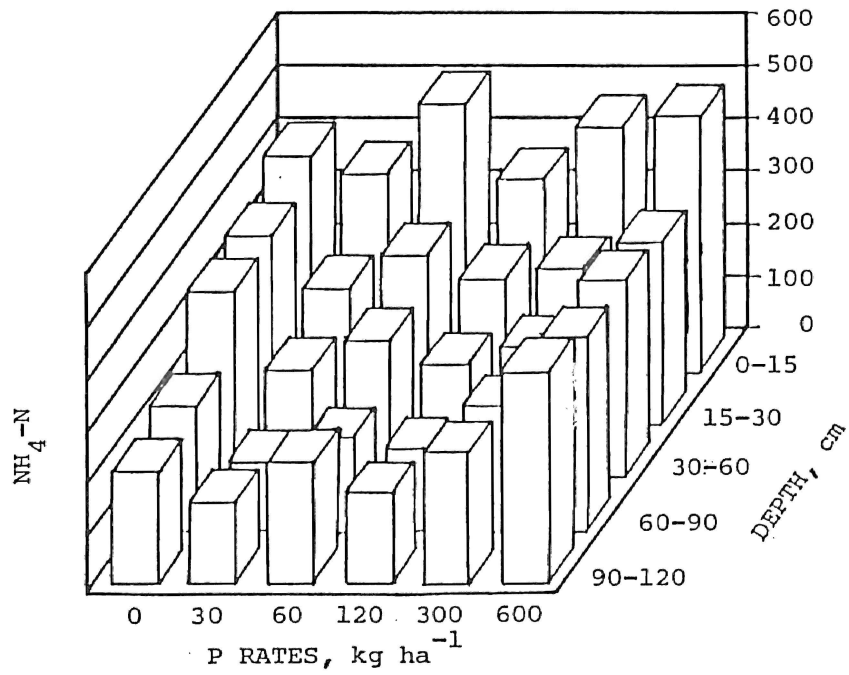
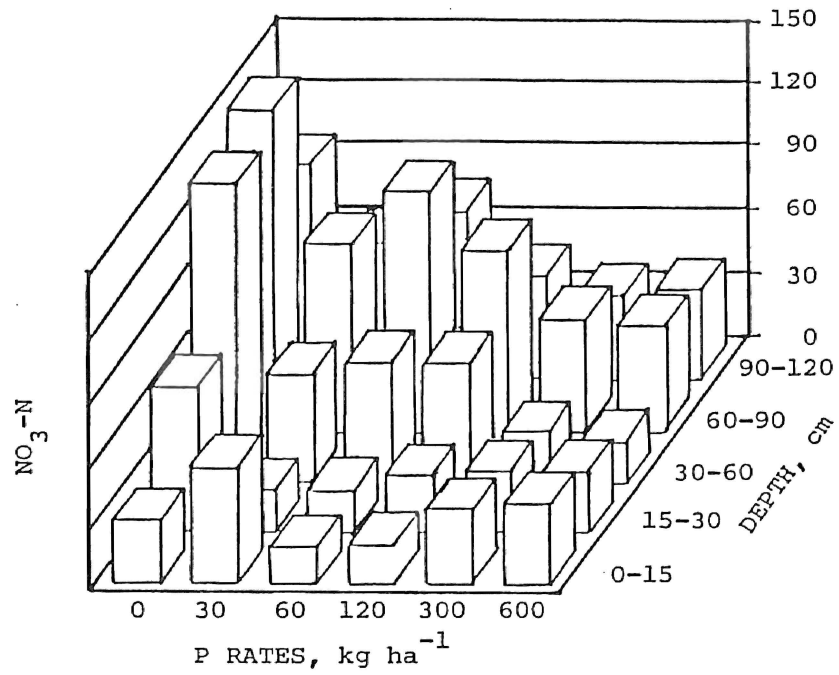


Figure 6. Effect of Three Annual Applications of P and Three Residual Years on NO₃-N and NH₄-N, 5 depths.

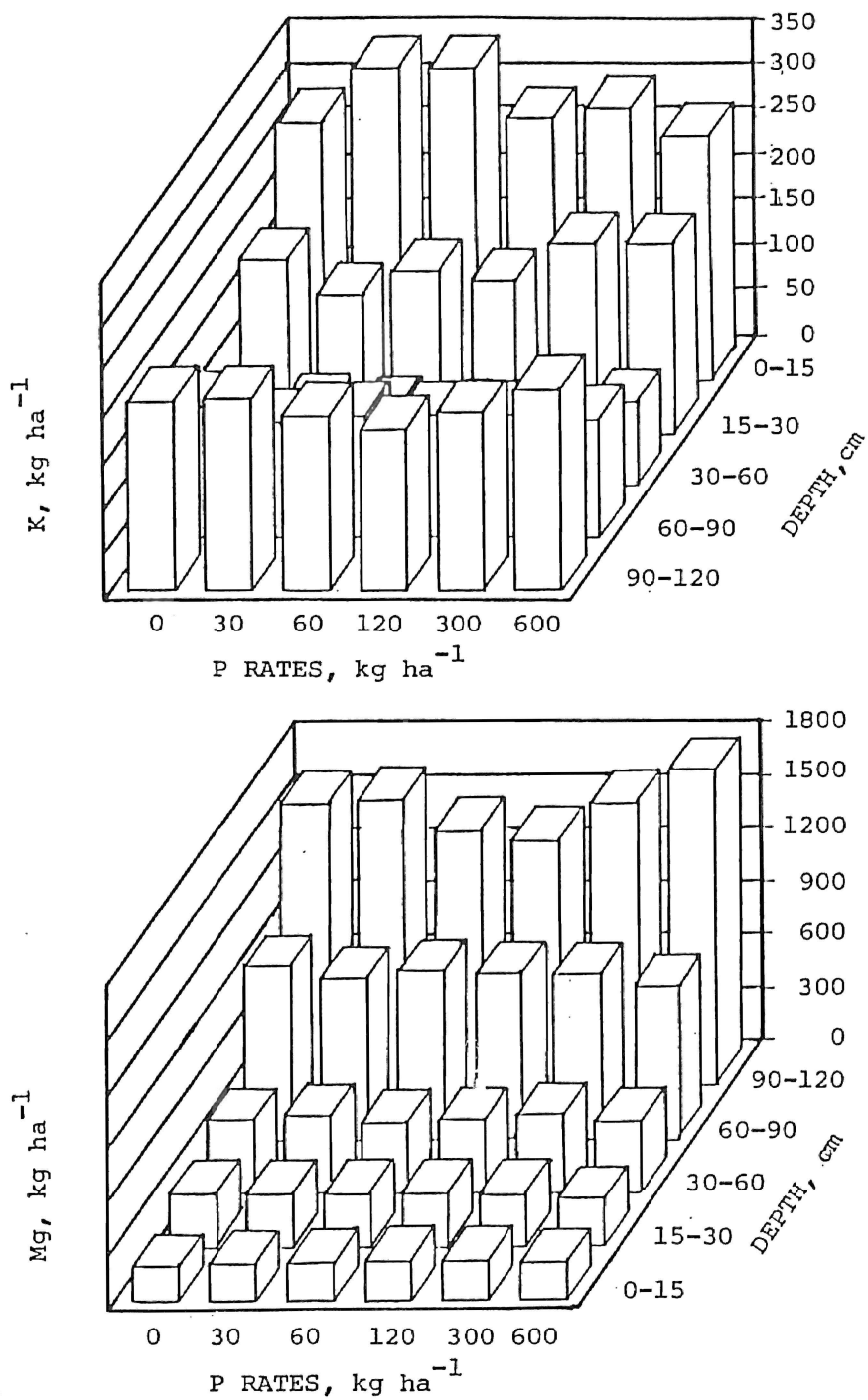


Figure 7. Effect of Three Annual Applications of P and Three Residual Years on Exchangeable K and Mg, 5 depths.

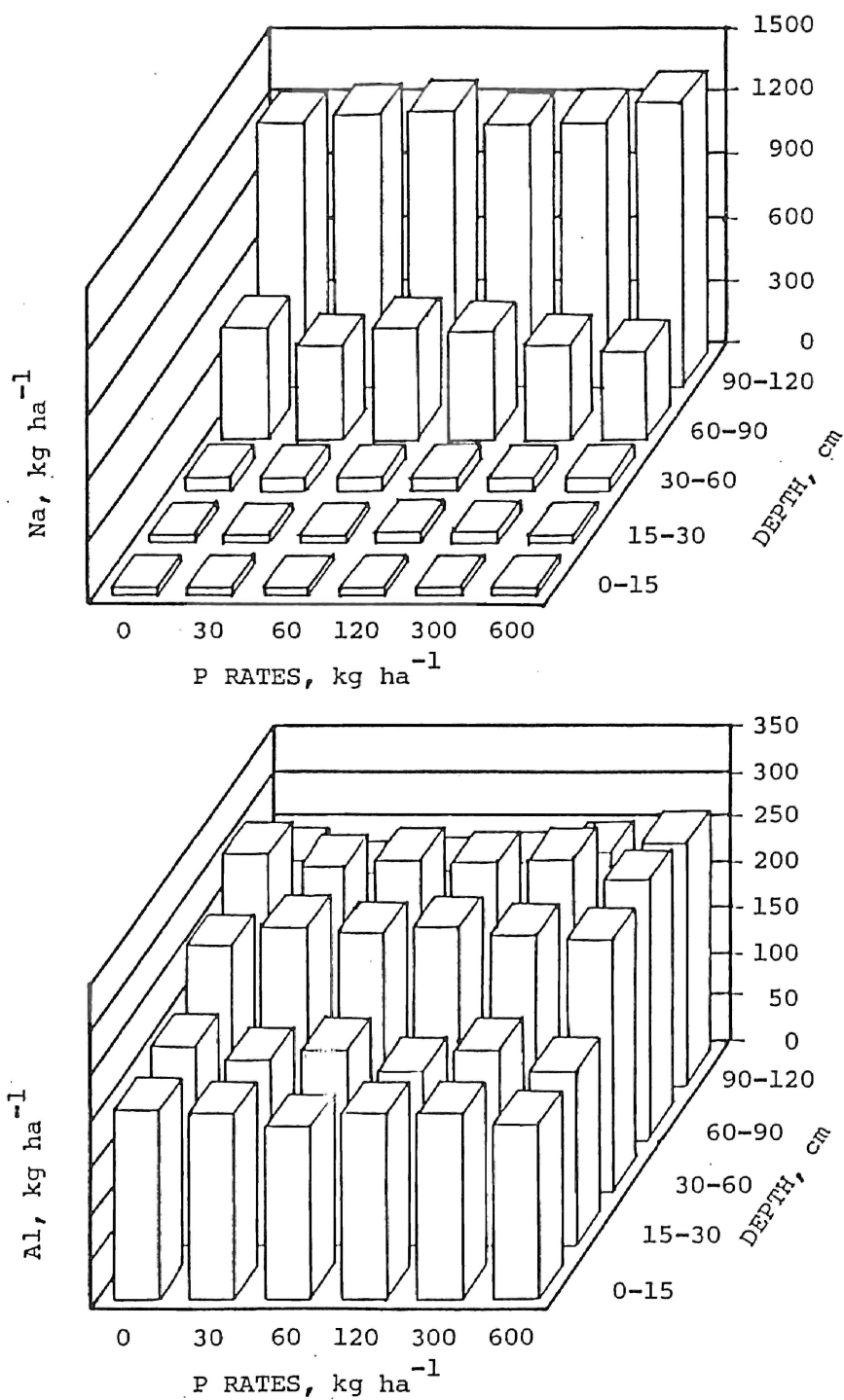


Figure 8. Effect of Three Annual Applications of P and Three Residual Years on Exchangeable Na and Al, 5 depths.

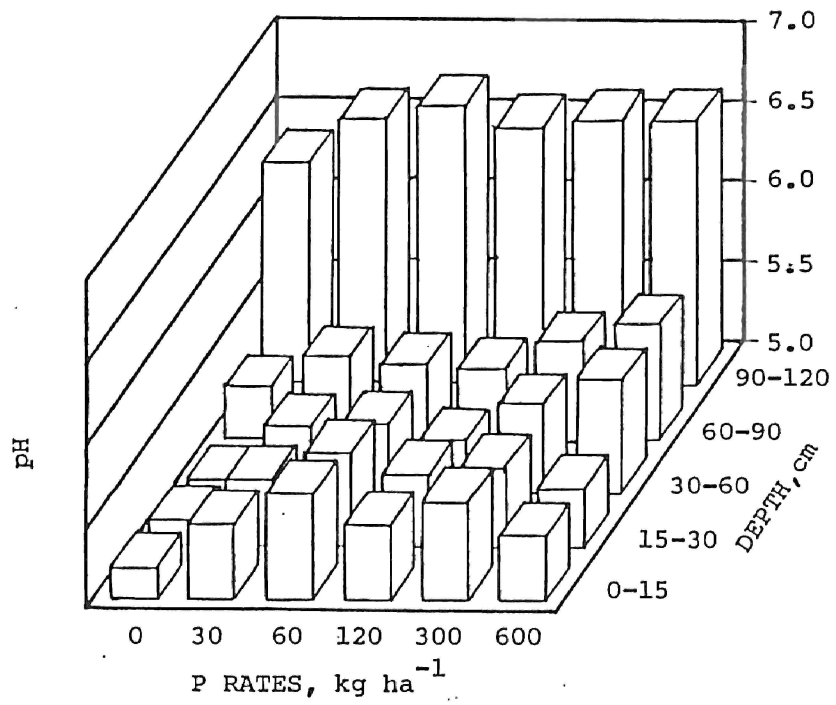


Figure 9. Effect of Three Annual Applications of P and Three Residual Years on pH, 5 depths.

differences between depths in pH from 0 to 15 cm and 60 to 90 cm, but there was an increase of pH at 90 to 120 cm.

Soil Solution

The activity of P species and its ion-pairs is illustrated in Figure 10. There were no differences in the activity of H_2PO_4^- over the different rates of P except at the highest rate of 600 kg ha^{-1} P and suggests that it has taken three years for the rates less than 600 kg ha^{-1} P to equilibrate with the soil while the highest rate has not yet equilibrated. There were no differences in the activity of HPO_4^{--} . Ion pairing of H_2PO_4^- with Ca and Mg increased with increasing P rates. There were no differences in the ion-pairing of HPO_4^{--} with Ca and Mg. The activity of P in the soil solution was not related to P concentration in grain, available soil P and grain yield. The activities of NO_3^- , NH_4^+ , Ca and some of its ion-pairs are illustrated in Figure 11. The activity of NO_3^- and Ca was inversely related to the yield with correlation coefficients of -0.78 and -0.69 respectively. The activity of Ca and NO_3^- did increase significantly at the higher rates of P, beyond what is accounted for by the relationship to yield and were related with a correlation coefficient of 0.95 . This is in agreement with the relationship that Curtin and Smillie (1983) found between Ca and NO_3^- activity.

The activities of the cations of the soil solution are illustrated in Figure 12. There were no differences in

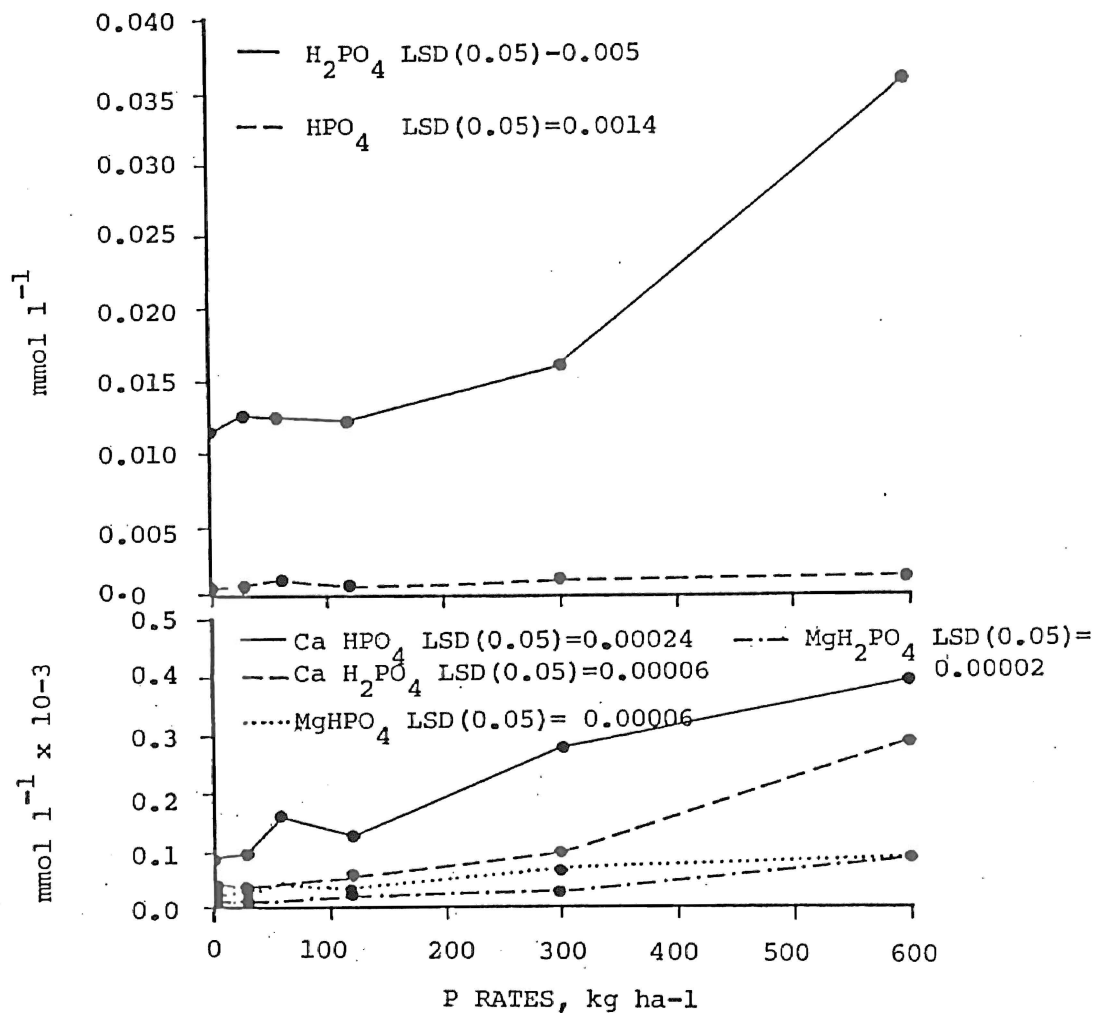


Figure 10. Effect of Three Annual Applications of P and Three Residual Years on Activities of the Soil Solution Species of P and its Ion-Pairs.

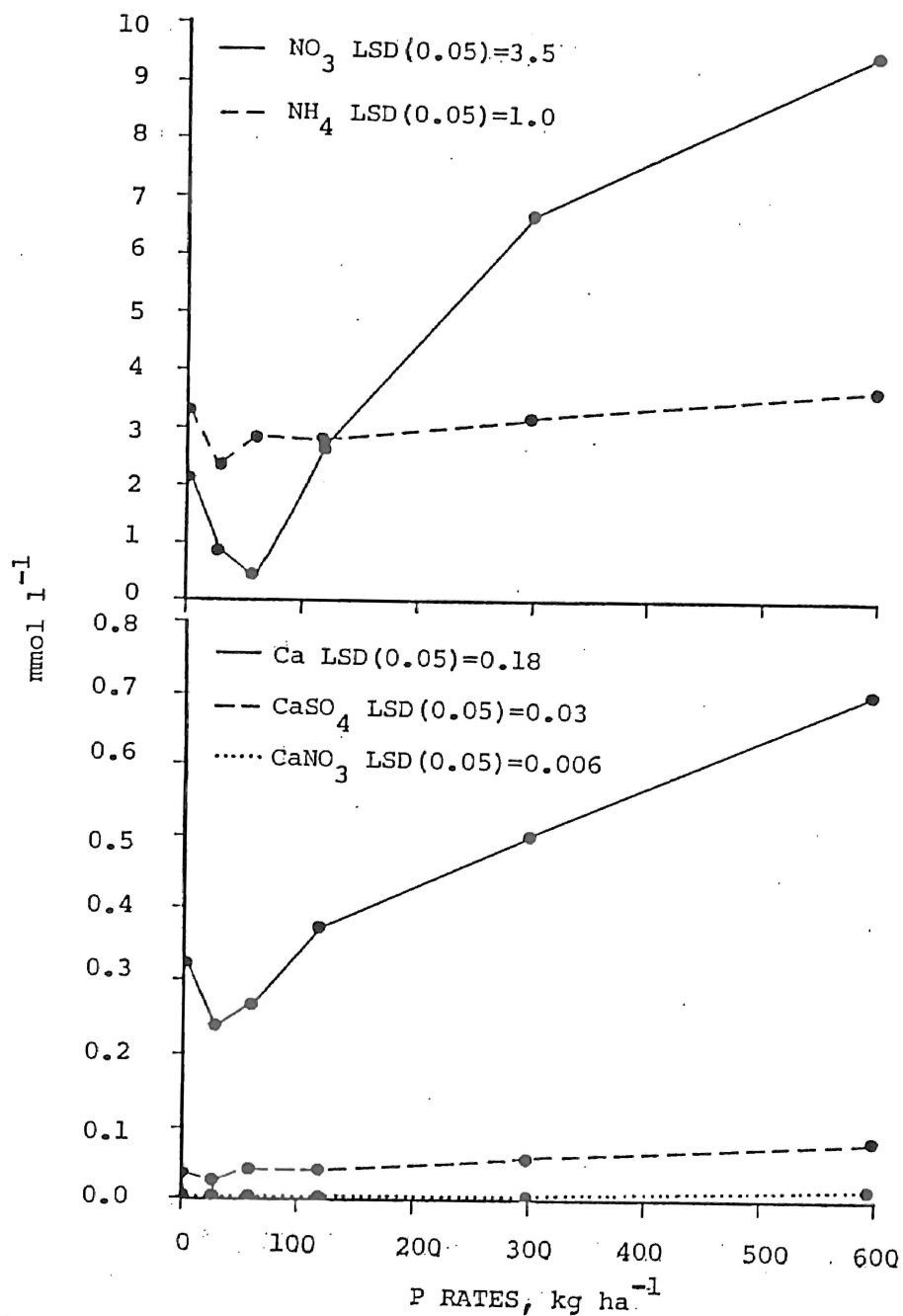


Figure 11. Effect of Three Annual Applications of P and Three Residual Years on Activities of the Soil Solution NO_3^- -N, NH_4^+ -N, and Ca and its Ion-Pairs.

activities of Mn and K. Manganese toxicity was suggested as a possible cause of the decrease in yield at higher P rates, but according to the Mn in soil solution it would not cause the decrease on the basis that there were no differences in Mn activity. Toxicity of Al was also suggested as a possible cause for the decrease in yield, but there were no differences in Al activity in the soil solution. Sodium and Mg activity response was similar to Ca with an increase in activity at higher P rates. There were no differences in Fe activity in the soil solution.

The responses of several anion activities, pH and the ionic strength of the soil solution are illustrated in Figure 13. There were no differences found in the activities of SO_4 , HCO_3 , Cl and the pH. The ionic strength of the soil solution increased at the highest two P treatments primarily due to the significant increase of NO_3 at these levels.

The decreasing yields of wheat at P rates higher than 30 kg ha^{-1} could possibly be due to several reasons. Khasawneh (1971) suggested that when extremely high amounts of nutrients are added to a soil system, some nutrients may become available in toxic amounts or become imbalanced or there could be an osmotic effect on the plant due to higher amounts of salts in the soil solution. The increase of activity in the soil solution of NO_3 , Ca, Mg, Na and P suggests that one of these effects may occur.

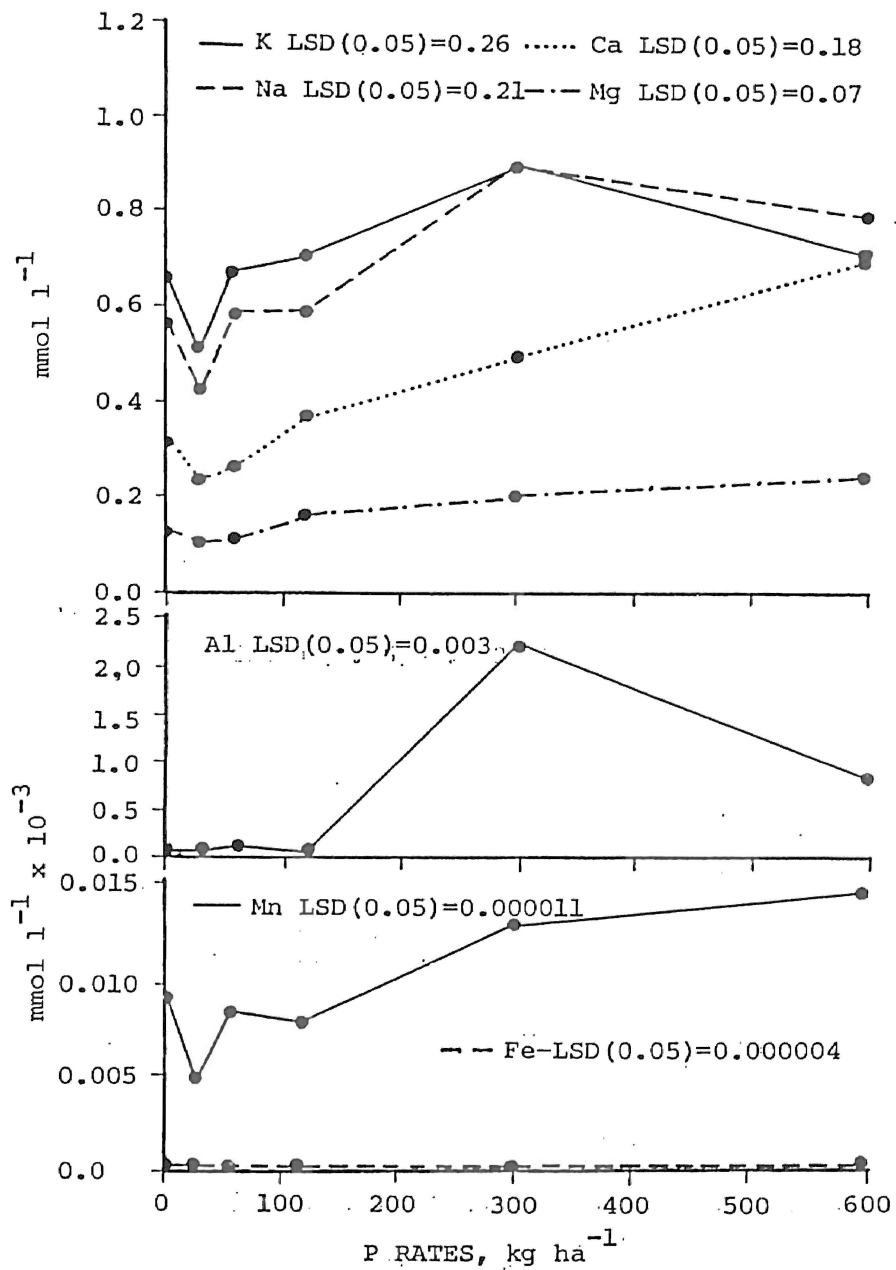


Figure 12. Effect of Three Annual Applications of P and Three Residual Years on Activities of the Soil Solution Ca, Mg, K, Na, Al, Mn, and Fe.

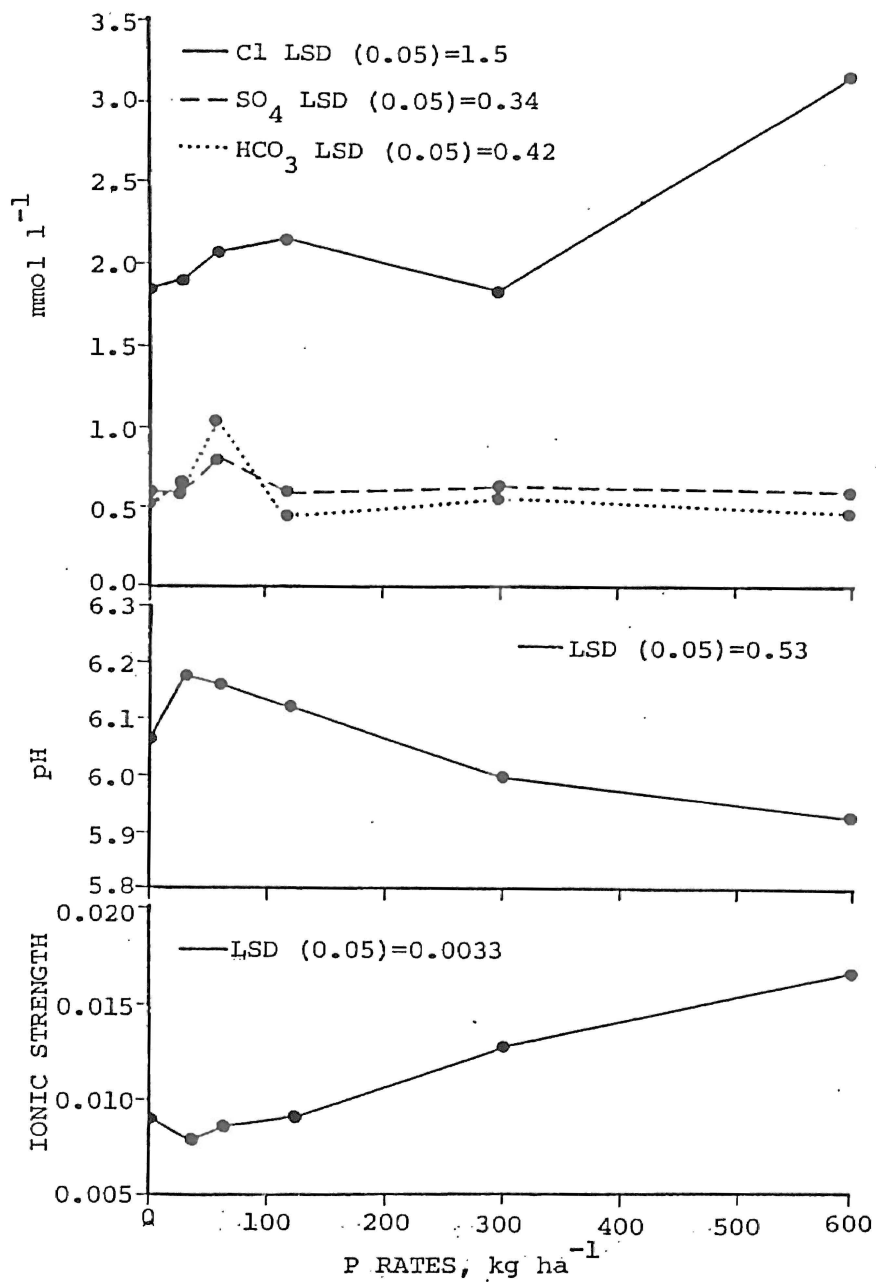


Figure 13. Effect of Three Annual Applications of P and Three Residual Years on the Soil Solution pH, Ionic Strength and Activities of SO_4 , HCO_3 , and Cl .

Comparison of GEOCHEM and Adams Procedure

The results from the comparison of data between GEOCHEM and Adams programs are presented in Table I. Most of the data between the two soil solution programs were similar. There are some major differences. The Adams procedure simply uses the measured concentration of ions as the initial concentration except for P where it calculates the two major species according to pH. GEOCHEM will make similar calculations on P, CO_3 and NH_3 . The correlation between the two programs for P was extremely good for both species concentration, activity and ion-pairs. Major differences exist in the way the two programs calculated CO_3 and the results were quite different. Carbonate could not be measured in the soil solution and Adams procedure calculated it as such, however GEOCHEM calculated values for different species of CO_3 from the measured HCO_3 values. The correlation between the two programs for HCO_3 was good, but Adams procedure reported as much as three to four times as much HCO_3 and its ion-pairs as did GEOCHEM. Major differences existed in the way the two programs calculate Al and Fe. The GEOCHEM program is much more extensive in the number of ion-pairs it calculates. Iron and Al according to GEOCHEM exist primarily as hydroxides and the hydroxides will not form other ion-pairs. There was very poor correlation for Fe and Al and its ion-pairs. Sulfate also did not

TABLE I
CORRELATION COEFFICIENTS FOR COMPARISON
BETWEEN ADAMS PROCEDURE AND GEOCHEM

Ion	Concentration	Activity*	Ion-Pairs	Concentration
Ca	1.0	.991	CaSO4	.994
Mg	1.0	.988	CaHCO3	.882
K	1.0	.951	CaHPO4	.996
Na	1.0	.945	CaH2PO4	.999
Mn	.670	.708	CaNO3	.999
Al**	.976	.916	MgSO4	.990
Fe**	.449	.346	MgHCO3	.898
NH4	.999	.919	MgHPO4	.996
H2PO4	.998	.987	MgH2PO4	.999
HPO4	.994	.952	KSO4	.992
SO4	.996	.869	NaSO4	.992
NO3	1.0	.994	NaHCO3	.964
Cl	1.0	.951	MnSO4	.634
HCO3	.926	.883	AlSO4	-.319
pH		1.0	FeCl	-.212
Ionic Strength		.991		

* Activities for GEOCHEM were calculated from concentration by using the Debeye-Huckle equation.

** Al and Fe concentration in GEOCHEM for the correlation were taken from AlOH and FeOH respectively.

correlate well nor did its ion-pairs due primarily to differences of ion-pairing with Al and Mn. Manganese did not correlate well nor did its ion-pairs. Most other ions and their ion-pairs correlated well. The Adams procedure will work well when working with macro nutrients but cannot work as well with the micro nutrients. GEOCHEM does not output activities but only concentrations and it may provide too many ion-pairs to conveniently work with soil fertility problems.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Highest yield of wheat grain was obtained at a P rate of 30 kg ha⁻¹. Higher rates of P decreased yield. Concentration of P in grain increased with increased P applications as did the concentration of K. Concentration of N in grain was inversely related to yield.

Bray and Kurtz no. 1 (1:20) P responded a linearly to P applications. This response was observed at both the surface soil and at 15 to 30 cm. Calcium response was similar to P in the surface 15 cm of soil. Below these depths there was no effect on P and Ca. Nitrate-N increased in the control at depths lower than 15 cm. Ammonium-N increased in the highest P rates at depths lower than 60 cm.

The soil solution had an increase of H₂PO₄⁻ activity at the highest rate of P as did its ion-pairs. There was no effect upon HPO₄²⁻ and its ion-pairs. Soil solution P did not respond linearly to fertilizer P. There was a relationship between Ca and NO₃ activity with an increase of both at the two highest rates of P. Sodium and Mg activity response was similar to Ca. Potassium, Mn, Al, Fe, SO₄, HCO₃, Cl, and pH showed no differences.

The optimum concentration of P in the soil solution for maximum wheat production could not be found due to the inconsistent response of soil solution P to the different P fertilizer rates. Causes for the decrease of wheat yield at P treatments above 30 kg ha⁻¹ could possibly be due to toxic concentrations of several different ions, or could be a nutrient imbalance. The cause is not known and will require further investigation.

The computer programs modeled after Adams procedure and GEOCHEM correlated very well except for Al, Fe and Mn and their ion-pairs. GEOCHEM allocated most of Al and Fe as ion-pairs with hydroxide which reduced the amount available for activity and formation of other ion-pairs. These differences also affected the different forms of SO₄. GEOCHEM did not output final activities but only concentrations and it provided many more ion-pairs than the Adams procedure which can make it more difficult to work with. The Adams procedure is simple in form and use and can be easily modified but it does not allocate micro-nutrients properly. The Adams procedure could be used for most soil fertility problems.

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