Abstract:
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The addition of phosphorus to the soil was effective in increasing the vegetative growth of sorghum when calcium was addeds but less significant alone.

Phosphorus and potassium without calcium appear to have relatively little fertilizer value at the rates used in this study.

Although the vegetative yield increased with phosphorus and calcium additions, the recovery of added phosphorus by plants and chemical extractions decreased, indicating phosphorus fixation.

The aluminum phosphate increased markedly with phosphorus additions. Calcium and iron phosphates also increased, but to a lesser degree.

PHOSPHORUS FERTILITY STUDY ON A MICHOACAN, MEXICO SOIL

by

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ABSTRACT

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The experiment was conducted in the greenhouse at Montana State College at Bozeman. A series of phosphate dressings were applied in pot culture experiments in order to determine the extent to which sorghum plants respond. Sorghum yield data, the percent recovery of applied phosphorus, and phosphorus fraction content were used as criteria of response to test the effect of the interactions.

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Phosphorus and potassium without calcium appear to have relatively little fertilizer value at the rates used in this study.

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The aluminum phosphate increased markedly with phosphorus additions. Calcium and iron phosphates also increased, but to a lesser degree.

CHAPTER I

INTRODUCTION

Preliminary soil fertility studies were conducted in the Sierra Tarasca of the State of Michoacan, Mexico, in 1960 (29). The selected area lies generally within a triangle made by connecting Patzcuaro, Acambaro, and Ario de Rosales. These studies, carried on mainly by personnel of The Rockefeller Foundation working with local Mexican government personnel and farmers, indicated that applications of nitrogen, phosphorus, potassium and calcium have, in some cases, relatively little effect on crop yields, even though unfertilized yields were low. In further studies phosphorus was given major consideration since preliminary observations indicated that the soils were particularly deficient in this element. One of the interesting results of this study was the relatively poor crop response to commercial fertilizer forms of phosphorus along with other elements in relation to chicken manure and phosphorus. The need for further information concerning the adverse effects of general deficiencies or toxicities and phosphorus fixation was pointed out.

The soil used for the present research project was taken from the Sierra Tarasca area between San Gregorio and Opopeo, in the State of Michoacan, Mexico, in March 1961. This area is about 19 degrees north latitude with an elevation of approximately 2600 meters.1/ The mean annual temperature is about 10 degrees Centigrade, with the general frost-

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1/ One meter equals approximately 3.28 feet.

free period being from mid- or late October.[2]

The soils of this area are subjected to periods of extremely low rainfall during the winter and spring months, October to the middle or latter part of June, and a rainy season, during which approximately 100 centimeters of rain falls, which corresponds to the remaining part of the year.[3]

One of the most striking facts is that corn is practically the only cultivated crop. The general practice is to take one crop of corn every two years. The primary reason given for this is the need to replenish fertility by a year of rest. It is doubtful that this is a valid reason. It is more likely that the type of corn used requires residual moisture, which is stored during the fallow year. By leaving the fields one rainy season, sufficient moisture is stored so that corn can be planted in March and reach physiological maturity before early frosts occur.[4]

This research project was primarily concerned with the effects of varying levels of phosphorus fertilization as affected by calcium and potassium additions under greenhouse conditions and with investigating the possible phosphorus fixation mechanisms.

2/ $0(^{\circ}C \times 1.8) + 32 = {}^{\circ}F$.

3/ 1 centimeter equals approximately 0.3937 inches.

4/ Correspondence with Dr. R. E. Laird, Rockefeller Foundation, Mexico City, Mexico.

CHAPTER II

REVIEW OF LITERATURE

Phosphate fixation by acid soils has been the subject for research by many investigators, and various theories relative to the mechanism of such fixation have been evolved.

In general, authors such as Chang and Jackson (4), (6), Dean (13), Hibbard (16), and Pierre and Norman (23), indicate that inorganic phosphates in the soil can be classified into four main groups: Calcium phosphate, aluminum phosphate, iron phosphate, and the reductant-soluble phosphate extractable after the removal of the first three forms. It is widely accepted that iron, aluminum and calcium phosphates also include absorbed and surface-precipitated phosphates associated with soil particles.

Harris (15) suggests that the available phosphorus level of soils can be accurately estimated by water extraction and that the water-soluble phosphorus is a good indicator of the phosphorus fixation capacity of some soils with a history of phosphorus fertilization. This method assumes that the level of water-soluble phosphorus is directly related to the equilibrium phosphorus concentration in the soil solution. Nevertheless, he suggests that, just as a lime requirement test is valuable in addition to a pH determination, a phosphorus fixation capacity determination is of value in addition to a phosphorus soil test. He further indicates fixation of phosphorus added to a soil proceeds rapidly in its initial stages and although the rate decreases, it continues for many weeks. Results have been reported by Hibbard (16) and Olson (22) which indicate that phosphorus fixation under laboratory conditions is nearly complete (80 to 100%) within a few hours. Because of this rapid fixation, short term experiments have been used to measure the capacity of soils to fix phosphorus in the unavailable form.

Many researchers (2), (4), (5), (13), (16) point out the importance of knowledge concerning the specific chemical forms of inorganic phosphates in understanding the chemistry of soil phosphorus and also illuminating problems concerning soil genesis (17) and soil fertility (23), (30), (32) associated with phosphorus. The distribution of various forms of inorganic phosphorus in the soil is no doubt controlled by the activities of the various ions in the soil, in turn reflecting soil pH, age, drainage and mineralogical nature (6). Fractionation of soil phosphorus also permits tracing the fate of applied phosphate fertilizer under different soil conditions, possibly giving some insight into a balanced fertilizer application program and expected response.

Based on the pH-solubility relationships, when the soil phosphates are compared with those of known phosphate minerals, it is generally accepted that the inorganic phosphates are dominantly bonded by calcium in calcareous soils (14) and by aluminum or iron in acid soils (10). This is supported by Dean (11) in his study on the fate of the phosphate fertilizer applied to two Rothamsted soils, which indicates that acid-soluble phosphate increased in calcareous soils and that the alkali-soluble phosphate increased in acid soils.

Iron, aluminum, and calcium have been shown by Lawton (20) to be important factors in phosphorus fixation, but the total amounts present did not correlate significantly with increases in the soil test values. Bass and Sieling (2) developed a method for determining the relative phosphorus fixing capacity of acid soils in which the amount of iron and aluminum extracted was found to be a measure of the relative phosphorus fixing capacity of the soil. In this work the results indicated that there is no absolute value for phosphate-fixing capacity of a soil. Phosphate fixation by acid soils and soil colloids is highly correlated with the amounts of active aluminum and iron associated with them, as shown by Coleman (9) and Ghani and Islam (14). Chang and Jackson (4) found that although there is a relationship between the phosphorus fixation capacity of soils and the extractable aluminum and iron, that the extractable aluminum and iron were not a quantitative measure of this capacity. They further suggest that, since the various forms of phosphates have different solubilities, their distribution might give an indication of the availability of phosphorus to plants in the soil. Work by Dean and Rubins (12) indicates the latter apparently is largely determined by the amount or extent of the phosphate surface of the various chemical species. The extraction of active iron and aluminum from acid soils by citric acid solution was found by Bass and Sieling (2) to be an excellent basis for determination of phosphate fixing capacity, and was chemically equivalent to direct measurement of phosphate fixing capacity by the Piper method (24).

Cole and Jackson (7) have demonstrated the formation of iron and aluminum phosphate crystals under controlled conditions simulating possible soil conditions, and related the solubility equilibirum constant of dihydroxy aluminum dihydrogen phosphate to a mechanism of phosphate fixation in soils. Precipitation of the variscite species in soils takes place in the form of its crystals as a new, separate soil phase, and therefore its precipitation is distinct from adsorption. The solubility equilibrium constant of dihydroxy aluminum dihydrogen phosphate (variscite crystal species) and dihydroxy iron dihydrogen phosphate (strengite crystal species) is pointed out by Cole and Jackson (8) to be of such magnitude as to cause formation of these species in acid soils containing reactive aluminum and iron when soluble phosphate fertilizers are added. They further state that dihydroxy dihydrogen phosphates of aluminum are sufficiently soluble to furnish phosphorus for plant growth, as has been demonstrated by Truog (34). Additional work (8) suggests that the presence of relatively soluble sources of aluminum such as gibbsite and kaolinite and, to some extent montmorillonite, may decrease the concentration of phosphorus in the soil solution to a point at which phosphorus availability becomes the limiting factor in plant growth.

Localized placement of phosphate in bands precipitates the local active aluminum and iron, and the phosphorus concentration shifts to a higher equilibrium concentration, except as calcium enters the equilibrium system, as shown by Cole and Jackson (8).

The effect of increasing OH concentration on the release of phosphorus from variscite has been shown (8) through the decrease in aluminum activity. Other anions also increase the concentration of phosphorus in solution if they decrease the effective concentration of aluminum either by the formation of stable soluble complexes or by precipitation of the aluminum. The replacement of phosphorus from precipitated phosphates of aluminum and iron by various organic anions has been demonstrated by Struthers (31) and Swenson (32), and relates phosphorus availability in soils to the formation of various organic acids during active decomposition of organic matter.

In work by Chang and Jackson (6) the distribution of soil inorganic phosphorus was found to measure the degree of chemical weathering, the chemical weathering sequence being calcium, aluminum, iron and occluded phosphate, in order. The latter category includes reductant soluble iron-phosphate and aluminum-iron phosphate occluded in iron oxide. They found that in highly weathered Latosols only a very small amount of phosphorus is present as calcium phosphate (1%) and aluminum phosphate (0-3%), with most of the phosphorus being present in the form of iron phosphate (10-13%) and occluded (reductant soluble) phosphate (66-78%).

The practice of liming acid soils results in a number of beneficial effects with respect to crop growth. One of these is considered to be an increase in the availability of soil and fertilizer phosphorus. Neller (21) points out that in acid soils lime is generally credited with the ability to make more of the added phosphate available to crops, particularly for soils high in iron and aluminum. The data consistently show that use of varied amounts of lime had no effect on the percentage uptake by oats and millet of phosphorus in currently applied superphosphate for Rutlege fine sand and sandy loam soils of Florida. In the fine sand lime caused a marked reduction in the phosphorus content of the plants. An explanation of the rather unusual effect is that lime converts the water-soluble monocalcium phosphate of superphosphate to the less soluble dicalcium phosphate and possibly in some loci to tricalcium phosphate. In additional work by Neller (21) lime had an opposite effect in Marlboro fine sandy loam in that it caused the phosphorus content of oats to be somewhat higher. This soil contains considerably more iron and aluminum than Rutlege and the lime probably resulted in formation of phosphate compounds that were more soluble than those of iron and aluminum. Albrecht and Klemme (1) report that application of limestone and superphosphate to mineral soils approximately doubled the phosphorus content of lespedeza forage over that contained in plants from soils receiving super-phosphate alone.

Work by Robertson (28) on liming Florida soils relatively low in residual phosphorus indicates on increased availability of applied phosphorus up to pH 6 to 6.5 when the sesquioxides were high, but had no effect where the sesquioxides were low. Liming these soils above 6 to 6.5 caused the percentage of phosphorus in the plant from the fertilizer to level off or decline, probably due to the formation of relatively unavailable tricalcium phosphate. Liming soils high in residual phosphorus reduced the availability of fertilizer phosphate regardless of the sesquioxide content. Uptake of phosphorus from currently applied superphosphate was highest from the soils high in sesquioxide content irrespective of rate of liming. Soil and plant analysis indicated that the differences might be due to calcium nutrition. Prince (25) has shown that it was possible to improve the availability of phosphorus in soils that fix phosphorus by adding lime. Cole and Jackson (8) suggest that the increased release to the crop of phosphorus from aluminum and iron phosphate is due at least partially to the lowered aluminum and iron activity resulting from increased pH through liming.

Personnel from the Rockefeller Foundation (29) found that twenty tons of chicken manure plus 200 kilograms of P_2O_5 per hectare on some Tarascan soils gave a much larger increase in corn production than that obtained with nitrogen and phosphorus alone.[5/] Tisdale and Nelson (33) suggest the decomposition of organic material is accompanied by the evolution of appreciable quantities of carbon dioxide which, when dissolved in water, forms carbonic acid which is capable of decomposing certain primary soil minerals over a wide pH range from calcareous to acid soils.

5/ One hectare is 10,000 square meters; therefore kilograms per hectare is approximately equal to pounds per acre.

CHAPTER III

MATERIALS AND METHODS

Soil Description

The soil of this mountain area is of the type classified by Whiteside as being very similar to the Ando soils which were first recognized in Japan.[6/] Adequate soil classification and survey data are lacking for this area. The soil formed from volcanic ash with the surface soil weathered to silt loam (Table I) and has a gently rolling topography with a few stony patches and higher hills. The soil sample used for laboratory and greenhouse studies was taken from an uncultivated site which had been cleared of coniferous forest two seasons previously and replaced with native grass.

TABLE I. SOME PHYSICAL AND CHEMICAL PROPERTIES OF THE SOIL SURFACE 25 CENTIMETERS.

SILT %	CLAY %	SAND %	O.M. %	TOTAL N %	pH
79.4	13.4	7.2	9	.20	5.5

AVAILABLE P. ppm.	AVAILABLE K. ppm.	AVAILABLE S. ppm.	C.E.C. me/100 g.	Ex.H me/100 g.	C/N

The drainage is good, the soil having rapid permeability and low ground water.[7/] The soil is high in iron and aluminum which presents a phosphorus fixation problem, and aluminum toxicities may occur. The slope

6/ Personal correspondence with Dr. E. P. Whiteside, Professor of Soil Science, Michigan State University, East Lansing, Michigan.

7/ Laboratory measurements gave an average distilled water flow of 1.74 inches per hour with 4-inch soil columns with an additional 1-inch head.

of the sampling area is approximately 8% with very little erosion. The root distribution is abundant above the hard massive "tepetate" layer at 98 centimeters (Table II). In places many "tuza" burrowing rodents are present in old fence rows. Ballados (steep sided narrow trenches) are used to keep cattle out of the cultivated fields.

Collection and Treatment of the Soil

A 100-kilogram sample of soil was collected from the top 25 centimeters of the soil profile, thoroughly mixed, and approximately 30 kilograms were placed in a metal container (10-gallon milk can). The can was sealed and shipped to Laredo, Texas, where it was vacuum fumigated with methyl bromide, and subsequently steam sterilized under 15 pounds pressure for 3 hours at Montana State College, permitting the entire volume to reach a constant temperature.[8/] The soil was then air dried, thoroughly mixed, and 300-gram aliquots placed in plastic pots with top diameters of 10 centimeters.

Experimental Design

A completely randomized greenhouse experiment was designed using 24 different treatments duplicated. The treatments consisted of 6 levels of phosphorus (0, 25, 50, 100, 200, and 400 ppm.), 2 levels of calcium (0 and 4500 ppm.), and 2 levels of potassium (0 and 50 ppm.) as a complete factorial. Nitrogen and sulfur were applied to all pots in a split application before planting and immediately following the

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8/ This was in accordance with specifications given by the United States Department of Agriculture, Plant Quarantine Division, 209 River Street, Hoboken, New Jersey.

harvest of the first crop. Total nitrogen and sulfur rates were 100 and 10 parts per two million (100 and 10 kilograms per hectare), respectively.

The phosphorus dressings, from standardized dilute phosphoric acid, were applied at the outset of the experiment. The potassium was supplied by potassium chloride dissolved in water and applied at the beginning of the study. The rate of calcium addition was sufficient to increase the pH to about 6.8. This proved to be 600 milliliters of a saturated calcium hydroxide solution which was equivalent to 9000 kilograms per hectare.

Sorghum variety Martins (Sorghum vulgare) was planted 3 seeds to a pot for each crop. The first crop was harvested 42 days after planting and the second crop 32 days after planting, at about the 7-leaf stage of growth. The crop yield data was statistically analyzed, separately for each crop, and total crop response derived by adding the individual crop responses.

Soil Analytical Procedures

All soil chemical and physical anaylses were conducted on aliquots of soil held back from the cropping phase, except the phosphorus fractionation. It was conducted on the soil after the second crop was removed and the soil air dried and mixed.

All phosphate analyses are given as parts per million P for oven-dry soil. The available phosphorus was extracted with sodium bicarbonate as described by Jackson (19, p. 163). Phosphorus fractionation was conducted according to the procedure outlined by Chang and Jackson (4). The aluminum phosphate was extracted with neutral 0.5 N ammonium fluoride and the iron phosphate subsequently extracted from the same sample with 0.1 N sodium hydroxide, both at room temperature. The calcium phosphate was then removed from the same sample with 0.5 N sulfuric acid.

The pH measurements were conducted on a 1:2 soil-water dilution, left for an hour to reach equilibrium, and determined with a Beckman Model H-2 glass electrode pH meter.

The percent organic matter was determined using the chromic acid wet digestion oxidation method by Jack (19, p. 206).

The total nitrogen determination, excluding nitrates, was conducted using the modified Kjeldahl method given by Jackson (19, p. 183).

The carbon was estimated by multiplying the percent organic matter by the coefficient 0.58, since soil organic matter is generally considered to have about 58% carbon. This was coupled with the total nitrogen value, as determined by the Kjeldahl method, to give a carbon-nitrogen ratio.

Total cation exchange capacity was determined by leaching the soil with ammonium acetate as described in the Agricultural Handbook No. 60 (26).

Mechanical analysis was accomplished by dispersing with 0.1 percent Calgon solution according to the procedure by Brown (3) and pipette samples withdrawn at the depth and time designated by Jackson (18) for silt (less than 50 microns) and clay (less than 2 microns).

Available sulphur was determined by extracting with ammonium acetate and measured by turbidity utilizing barium chloride.[9/]

The exchangeable hydrogen was removed by leaching with barium acetate and then determined titrimetrically using the procedure of Jackson (19, p. 74).

Plant Analytical Procedures

The plants were harvested at the soil level, the top material dried at 70° C., broken, placed in a beaker, ashed, and taken up in hydrochloric acid according to the procedure given by Jackson (19, p. 334). The solution phosphorus was determined by the chlorostannous reduced molybdophosphoric blue color method as described by Jackson (19, p. 144). Potassium in solution was determined by flame emission on a Model B Beckman Spectrophotometer. Solution calcium was determined by the versenate method (19, p. 64). All plant minerals are listed as concentration in parts per million of plant tissue in addition to total uptake in milligrams.

9/ Klages, M. G., Procedures in Use at the Soil Testing Laboratory, mimeographed circular No. 50, Montana State College, Bozeman, Montana. July 1963.

CHAPTER IV

RESULTS AND DISCUSSION

Crop Yield Response

The addition of phosphorus alone had an effect upon the vegetative yield of sorghum. The total crop data (Appendix, Table III) (Fig. 1) indicate that the response was somewhat erratic, but with the exception of the 100 parts per million phosphorus treatment the total yield in all cases was larger than the check with increased phosphorus applications. The phosphorus treatments were statistically significant at the 5% level for both crops and total yield (Appendix, Tables IV, V, and VI).

Potassium addition alone gave statistically significant results at the 5% level in the second and total crop analyses of variance (Appendix, Tables V and VI). In the first crop there was actually a slight decrease in yield where potassium was used (Appendix, Table III). The yield from each individual pot was very small; therefore, a genetic difference such as seed size may have affected the one duplicate of the check, which is about 50% larger than the other (Appendix, Table III). In all other cases individual pot yields were slightly larger when potassium was applied. Figure 2 indicates the sorghum growth response with varied phosphorus rates when potassium and calcium were also supplied. Figure 3 indicates the same circumstances except for the deletion of potassium.

Calcium alone, in all cases, increased the sorghum yield over that of the check. The calcium response was significant at the 5% level in both crops and in total yield (Appendix, Tables IV, V, and VI). Figures 4 and 5 indicate the lack of plant growth response where phosphorus and

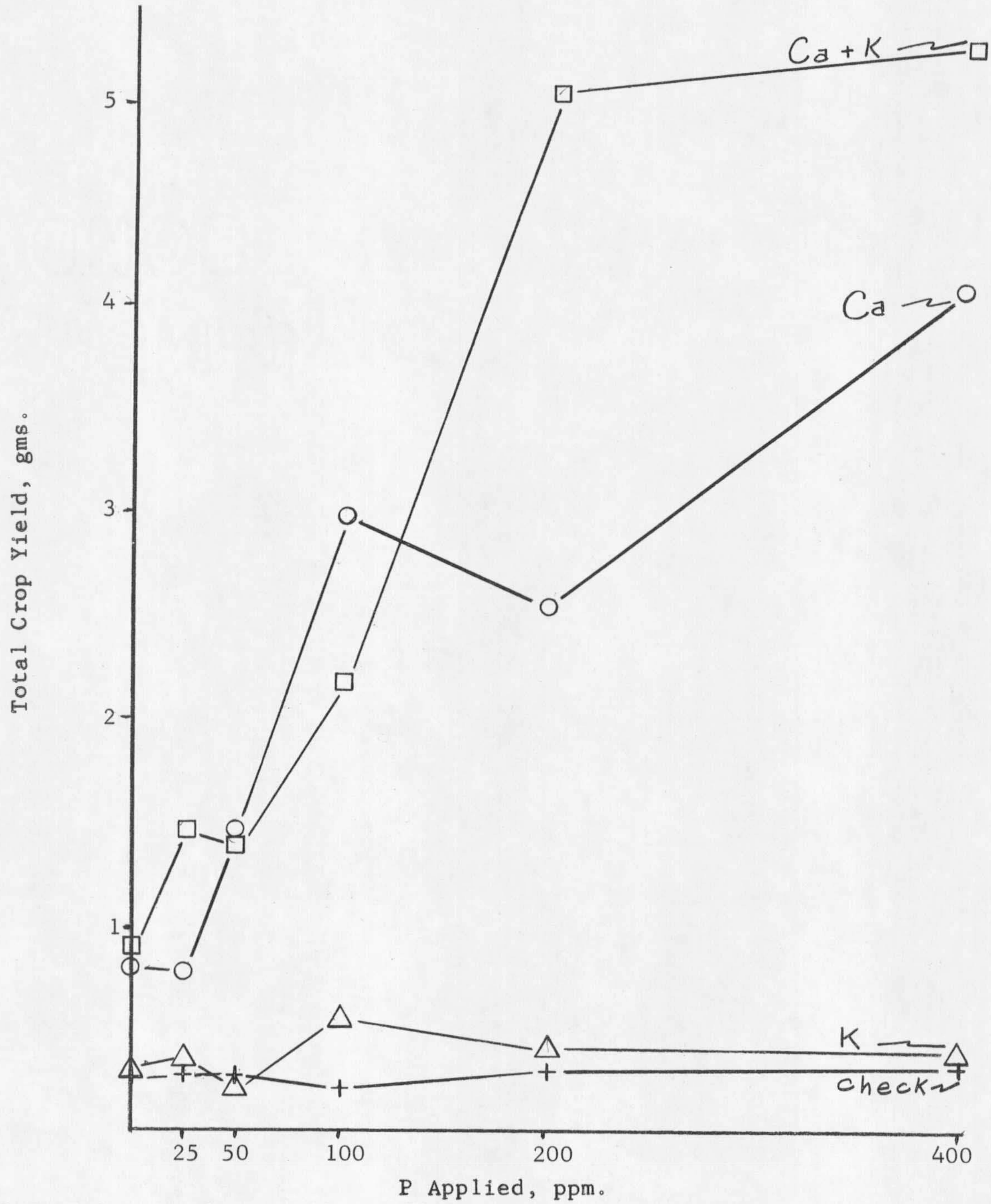


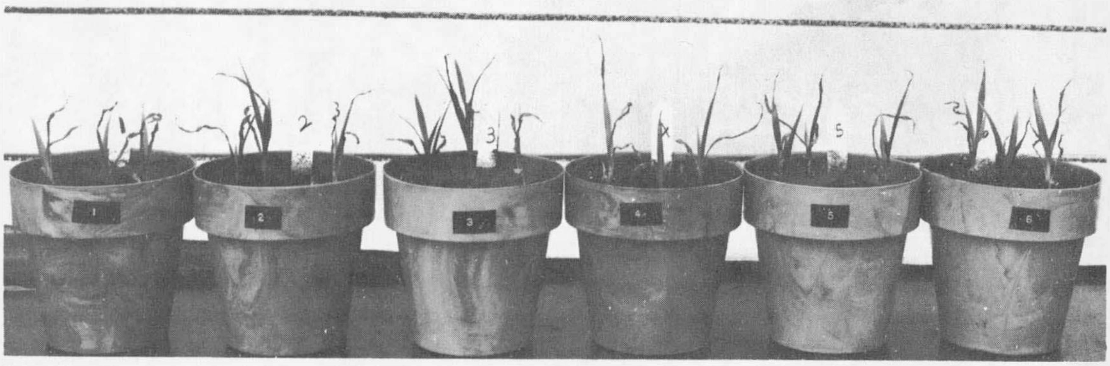
FIGURE 1. Sorghum yield as affected by phosphorus additions associated with calcium and potassium fertilization (Ca at 4500 ppm., K at 50 ppm.)

P ppm.	0	25	50	100	200	400
Ca ppm.	4500	4500	4500	4500	4500	4500
K ppm.	50	50	50	50	50	50

Figure 2. Sorghum growth indicating the response to various phosphorus applications coupled with potassium and calcium.

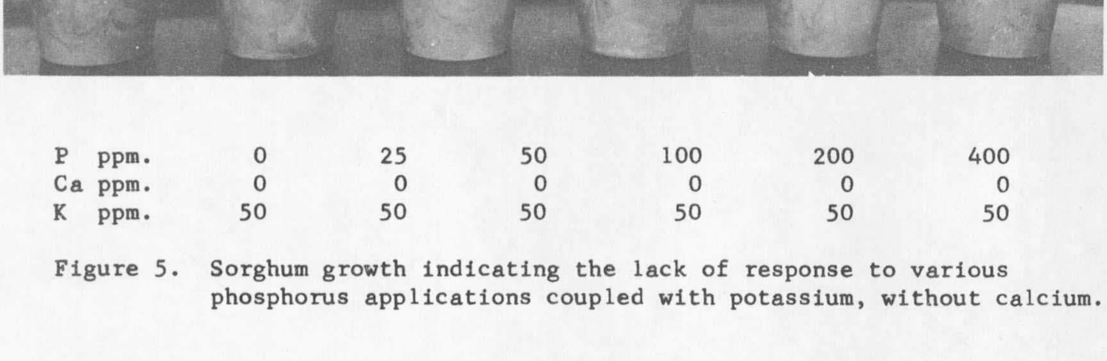
P ppm.	0	25	50	100	200	400
Ca ppm.	4500	4500	4500	4500	4500	4500
K ppm.	0	0	0	0	0	0

Figure 3. Sorghum growth indicating the response to various phosphorus applications coupled with calcium.



P ppm.	0	25	50	100	200	400
Ca ppm.	0	0	0	0	0	0
K ppm.	0	0	0	0	0	0

Figure 4. Sorghum growth indicating the lack of response to various phosphorus applications alone.



P ppm.	0	25	50	100	200	400
Ca ppm.	0	0	0	0	0	0
K ppm.	50	50	50	50	50	50

Figure 5. Sorghum growth indicating the lack of response to various phosphorus applications coupled with potassium, without calcium.

potassium were applied without calcium. The total crop yield was over 3 times greater where calcium alone was used as compared to the check (Appendix, Table III).

The phosporus potassium interaction was significant at the 5% level for the second crop and total crop, but not for the first crop (Appendix, Tables IV, V, and VI). In all cases except the low phosphorus application (0 and 50 ppm.), the addition of potassium increased the total crop yield over that of phosphorus alone (Fig. 1).

The calcium curve of Figure 1 indicates the large increase in total vegetative yield of sorghum where calcium was used with phosphorus as opposed to phosphorus applications alone. The calcium phosphorus interaction was significant at the 5% level for both crops and total yield. The total yield data (Appendix, Table III) indicate an increase of over 800% where calcium was used with phosphorus compared to phosphorus applications alone.

The potassium calcium interaction was not statistically significant at the 5% level for the individual crops (Appendix, Tables IV and V) but was for the total crop yield response (Appendix, Table VI). In all cases where potassium was applied with calcium the yields were greater than where calcium was applied alone (Appendix, Table III).

The yield response was much greater where potassium plus calcium in addition to phosphorus were used as opposed to phosphorus alone. The calcium plus potassium curve of Figure 1 indicates the magnitude of their effect upon phosphorus. The vegetative yield response is about

15 times greater where calcium and potassium were used in conjunction with phosphorus as compared to the yield obtained from the use of phosphorus alone.

Mineral Uptake and Plant Concentration

The addition of phosphorus to the soil had an effect upon the uptake and plant concentration of phosphorus (Figures 6 and 7), calcium (Figures 8 and 9) and potassium (Figures 10 and 11). In all cases added phosphorus increased the plant phosphorus concentration over the check, but at the higher phosphorus additions (from 100 to 400 ppm.) the concentration of calcium and phosphorus declined. The plant concentration does not necessarily indicate soil availability. It may indicate the plants' inability to take up additional minerals due to a fertilizer inbalance.

In all cases where potassium was added alone the concentration of phosphorus, calcium and potassium in the plants increased over the concentration of the check. This is opposite to the effect which the addition of calcium has upon the three mineral concentrations. The comparison may indicate to some extent the relative deficiencies of calcium and potassium as nutrients. Table III of the appendix indicates a much larger comparative yield response to calcium than to potassium. Therefore, with the addition of calcium the increased plant response may render other elements deficient. Or it may be a case of the physiological growth rate being such as to maintain mineral concen-

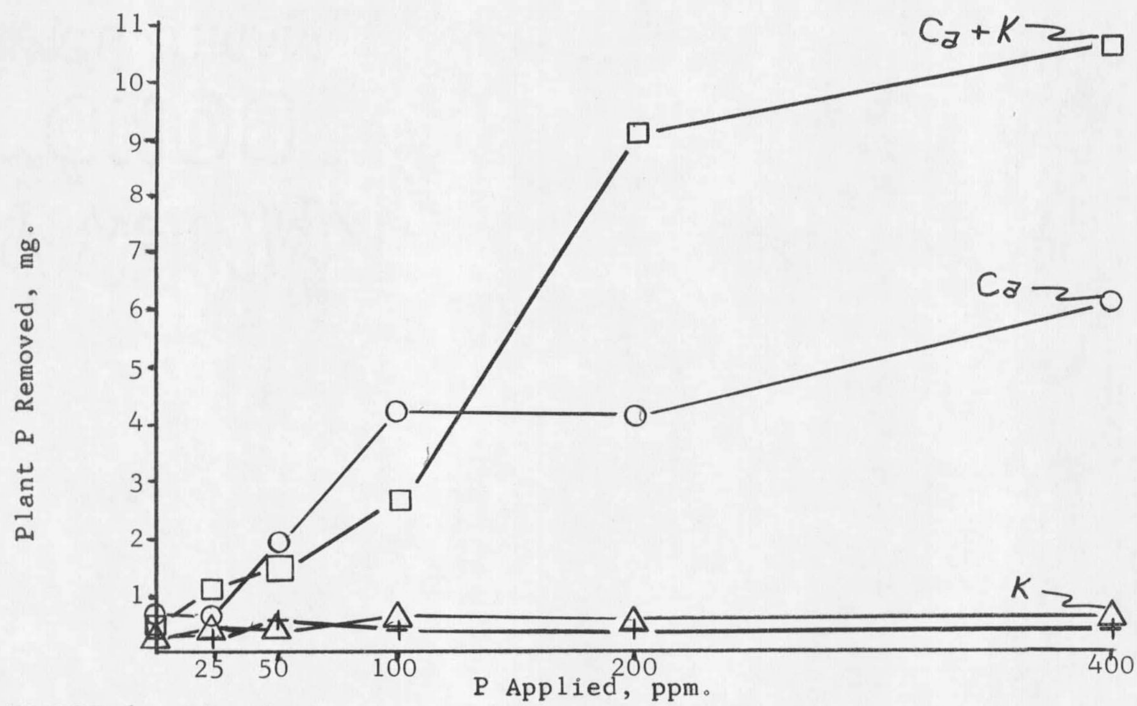


FIGURE 6. Phosphorus removed by plants corresponding to phosphorus applications related to calcium and potassium fertilization.

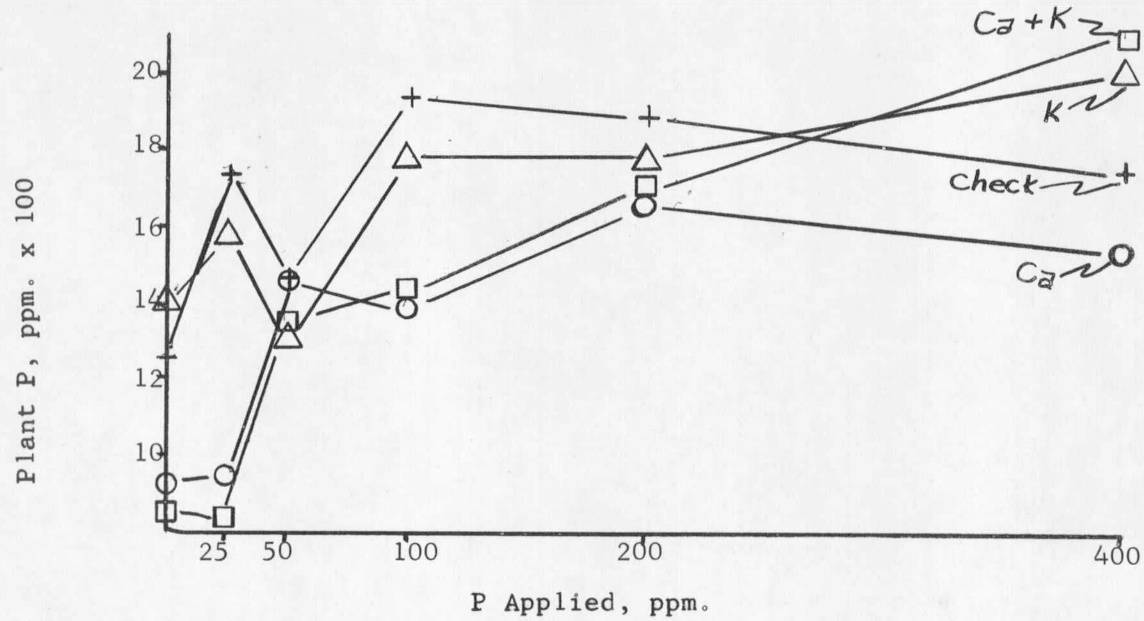


FIGURE 7. Concentration of phosphorus in plants corresponding to phosphorus applications related to calcium and potassium fertilization.

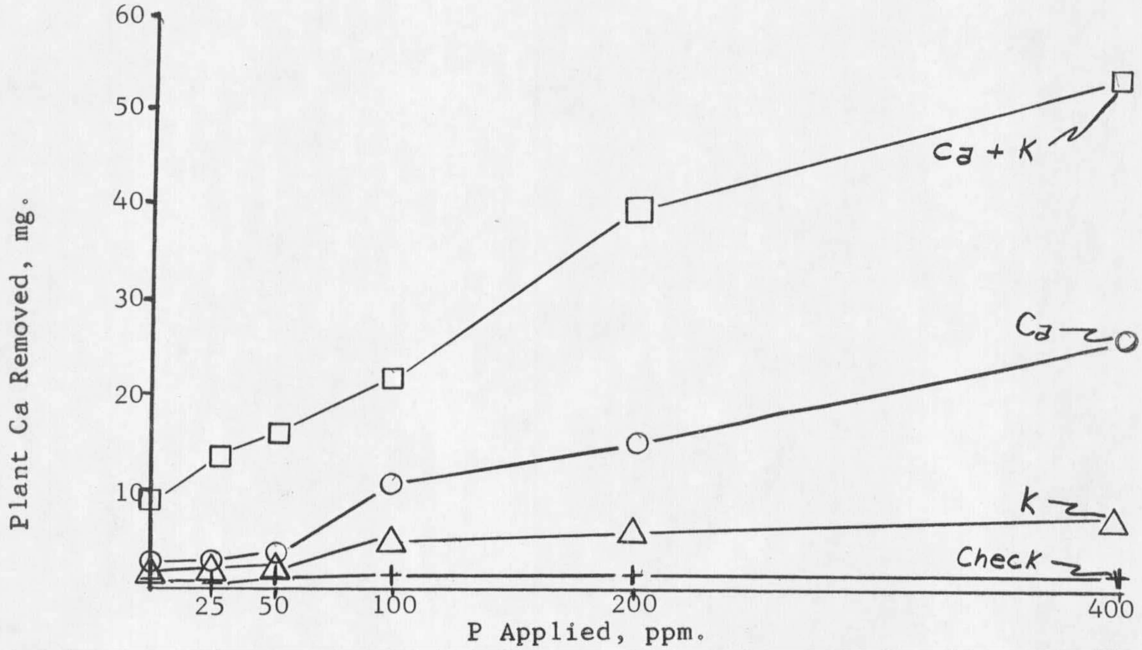


FIGURE 8. Calcium removed by plants corresponding to phosphorus applications related to calcium and potassium fertilization.

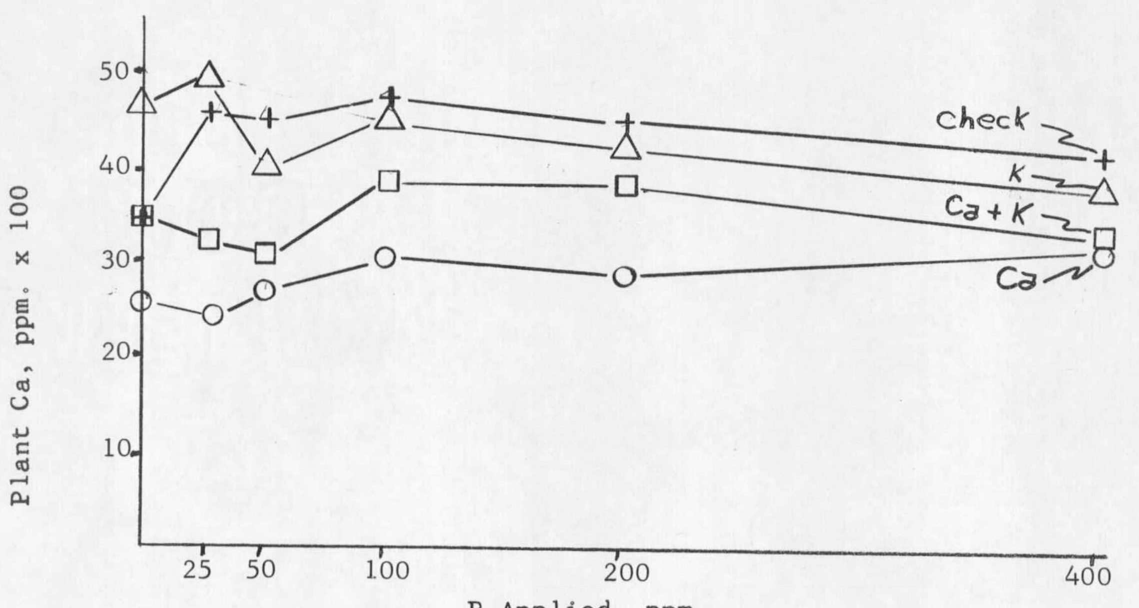


FIGURE 9. Concentration of calcium in plants corresponding to phosphorus applications related to calcium and potassium fertilization.

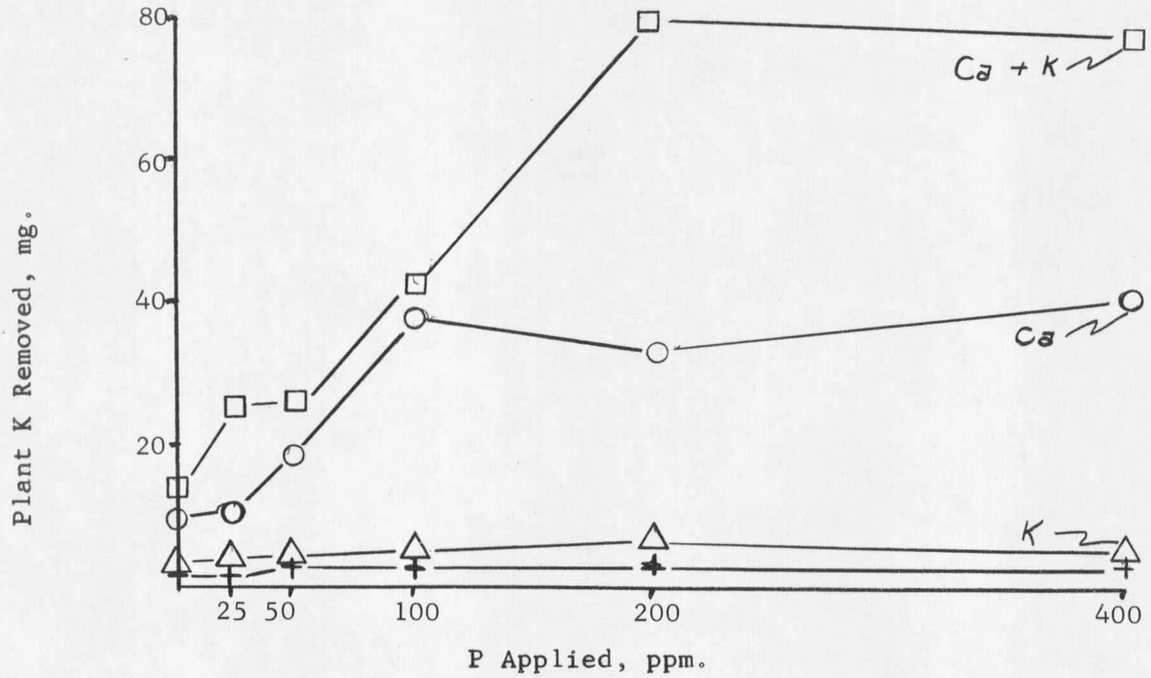


FIGURE 10. Potassium removed by plants corresponding to hposphorus applications with and without Ca and K.

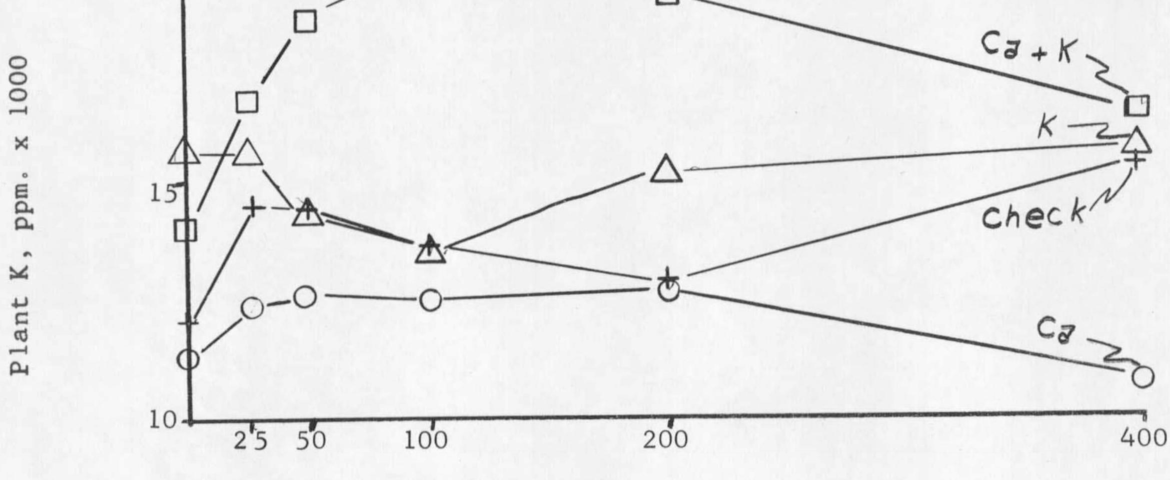


FIGURE 11. Concentration of potassium in plants corresponding to phosphorus applications with and without Ca and K.

trations at a minimum.

The effect of potassium phosphorus interaction appears to be erratic (Figures 7, 9 and 11). In all cases the plant concentration of phosphorus, calcium and potassium increased over the check when potassium was added. As additional increments of phosphorus were applied the concentrations of calcium and phosphorus first rose and then dropped, probably not beyond the realm of error.

When calcium was applied without the addition of phosphorus the mineral concentrations of calcium, potassium and phosphorus in the plant were decreased below the check. Figure 7 suggests that the effect of calcium was the overall lowering of plant phosphorus concentration, especially for phosphorus additions less than 25 parts per million. This may be explained by the ability of added calcium to provide better growing conditions, possibly due to the increase in pH, thus rendering phosphorus deficient. This may also be true for calcium and potassium concentrations (Figures 9 and 11).

When potassium was applied in addition to calcium the concentration of calcium and potassium stayed the same or increased (Figures 9 and 11). The reverse was true for the phosphorus concentration (Figure 7). This was probably due to increased availability of calcium and potassium due to the additions and the relative phosphorus deficiency due to increased growth.

The application of potassium and calcium in addition to phosphorus increased the plant concentration of potassium above that for phosphorus alone (Figure 11). This suggests, even though there is an increase in crop yield with potassium and calcium additions, potassium may have been deficient under phosphorus additions alone. Calcium concentrations within the plant are lower when calcium and potassium plus phosphorus are applied as opposed to phosphorus alone (Figure 9). This may be explained by the relatively large increase in yield when the three nutrients were added as compared to phosphorus alone (Appendix, Table III). Although there was more actual calcium available, the increase in growth more than compensated for the increase in available calcium. The plant phosphorus concentrations were lower when calcium and potassium were applied for all phosphorus applications except the largest (400 ppm. P). This may be due to the improved growing conditions associated with the addition of calcium and potassium. Therefore phosphorus may have been a limiting variable when other deficiencies are corrected until 400 parts per million of phosphorus were added.

The total plant removal (mg.) of potassium, calcium and phosphorus remained essentially constant with increasingly larger additions of phosphorus when calcium and potassium were withheld (Figures 6, 8 and 10). This indicates that phosphorus alone has very little effect on the removal of these elements and that some elements, in addition to phosphorus, are limiting.

Potassium alone had an effect upon the plant removal of phosphorus, calcium and potassium that was very similar to phosphorus alone (Figures 6, 8 and 10). This also indicates that potassium alone is not limiting or not the only limiting variable.

The addition of calcium alone had very little effect upon the total plant removal of calcium and phosphorus (Figures 6 and 8). Only a slight increase in the plant removal of potassium could be attributed to the application of calcium alone (Figure 10). This may indicate calcium has a slightly more important role in improving growing conditions on this soil as a single element, but is still not the single controlling variable.

The addition of both potassium and phosphorus had the effect of increasing the plant removal of phosphorus, calcium and potassium above phosphorus or potassium alone (Figures 6, 8 and 10), thus attributing a greater crop response to this interaction than either separately.

The effect of calcium upon phosphorus response is indicated by the calcium curves of Figures 6, 8 and 10. In all application combinations of calcium and phosphorus the plant removal of calcium, phosphorus and potassium was greater than calcium alone or any phosphorus treatment alone. The three elemental removal curves are indicative of the strong calcium-phosphorus interaction. The combinations were more effective in the removal of these elements than either phosphorus or calcium alone.

In all cases where potassium was applied with calcium, the removal of calcium, potassium and phosphorus by the plants was the same or greater than with either calcium or potassium alone (Figures 6, 8 and 10). The total phosphorus uptake was not increased by the potassium-calcium interaction alone, which indicates that neither calcium nor potassium was effective in releasing native soil phosphorus.

Either potassium or calcium, when applied with phosphorus, increased the total plant removal of phosphorus, calcium and potassium (Figures 6, 8 and 10). In practically all cases, the most effective combination for the removal of the three plant elements was potassium, calcium and phosphorus. The total phosphorus, calcium and potassium removal curves resemble the total yield curve (Figure 1) but not the curves showing the concentration of these elements in the plant.

Phosphorus Fractionation

The inorganic phosphorus existed largely as aluminum phosphate (30 ppm.) and calcium phosphate (32 ppm.), iron phosphate (11 ppm.) being much lower in the unfertilized soil (Appendix, Table X).

The application of phosphorus alone had an effect upon the formation of all three discrete forms of soil phosphorus. The aluminum phosphate increased to the greatest extent, more than doubling in content between the 0 and 25 parts per million phosphorus application and 400 parts per million (Appendix, Table X and Figure 12). This possibly indicates that a large amount of free aluminum is present in the soil to combine with added phosphorus. Iron and calcium phosphates formed to a lesser degree, indicating the probable lack of calcium for reaction and the slower formation of iron phosphate.

Neither potassium nor calcium without addition of phosphorus had much effect upon the formation of any of the three forms of phosphate (Appendix, Table X). This would be expected as the soil was probably too low in available phosphate to form any of the extracted forms without phosphorus additions.

The effect of potassium along with the phosphorus treatments had no measurable effect upon the formation of aluminum, calcium or iron phosphates.

The addition of calcium with phosphorus increased the calcium phosphate. At the high phosphorus rate (400 ppm.) the calcium phosphate was slightly greater when calcium was applied than when phosphorus was applied alone (Appendix, Table X). There was no appreciable change in the concentrations of aluminum or iron phosphate. The preferential formation of calcium phosphate would be expected under these conditions.

Applied Phosphorus Recovery

The amount of phosphorus removed from the soil by plant uptake and chemical extraction appeared to be affected by phosphorus additions (Table XI). The total amount of phosphorus removed increased with each additional increment of phosphorus. This would be expected due to a greater supply of available phosphorus. Along with the increased removal there was also an increase in the unaccounted for phosphorus. The phosphorus recovery data of Table XI (Appendix) further indicate that the amount unaccounted for decreased somewhat for the phosphorus treatments receiving calcium. It is logical to assume, although there is no data to substantiate it, that increases in phosphorus additions may have also increased the amount of water soluble phosphate, and possibly some phosphorus may have been occluded which wasn't measured. The decrease in the unaccounted for phosphorus due to the addition of calcium can be attributed in part to an increase in the removal of phosphorus by the plants.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Greenhouse experimental results indicate that the formation of various discrete chemical forms of phosphate are related to phosphorus additions and possibly calcium interactions in this Ando-like, slightly acid soil.

Upon the addition of phosphorus and calcium, aluminum phosphates form to a larger degree than iron or calcium phosphates.

Indications are that low crop yields are due to a combination of deficiencies rather than to the deficiency of any one nutrient element. For the rates and fertilizer elements studied it appears that a combination of phosphorus, calcium and potassium in addition to nitrogen and sulfur are needed for increased yields.

No attempt was made to reach optimum yields on the one hand or stay within economical fertilizer applications on the other. Therefore, it is pointed out that further investigations are needed.

The author realizes the dangers encountered in assuming answers to soil fertility problems. It is with this in mind that further studies are recommended. More levels of calcium and potassium would be an improvement. A study on the possibility of an aluminum toxicity may be of benefit. The added phosphorus may result not only in a phosphorus nutritional improvement, but it may be alleviating an aluminum toxicity.

APPENDIX

TABLE II. SOIL PROFILE DESCRIPTION

HORIZON	DEPTH CM.	BOUNDARY	COLOR (MOIST)	TEXTURE	STRUCTURE	pH	SPECIAL FEATURE
A_1	0-36	abrupt smooth	5 YR 2/2-3/2	silt loam	weak to moderate, fine medium granular	5.5-5.6	
B_1	36-75	clear smooth	5 YR 3/4	loam	medium course granular to weak fine medium sub-angular blocky		
B_2	75-98	abrupt wavy	7.5-5 YR 4/4	loam	moderate, medium strong subangular blocky		some dark coatings
R	98-115		2.5 Y + yellow + orange	fine grained lava (?)	massive		channels of loose materials
A_{1b}	115-123		5 YR 2/2-3/2	loam			
B_1	123-130+		7.5 YR 3/2	loam			

TABLE III. TREATMENTS APPLIED TO THE EXPERIMENTAL POTS AND THE CORRESPONDING FIRST CROP, SECOND CROP, AND TOTAL CROP YIELD RESPONSE.

TREATMENT	PARTS PER MILLION ADDED TO SOIL			FIRST CROP YIELD		SECOND CROP YIELD		TOTAL CROP YIELD
	P	Ca	K	Gms.		Gms.		Gms.
1	0	0	0	.0450	.0685	0.0493	0.0644	0.2272
2	25	0	0	.0379	.0368	0.0873	0.0727	0.2347
3	50	0	0	.0472	.0530	0.0717	0.0566	0.2285
4	100	0	0	.0361	.0432	0.0610	0.0574	0.1977
5	200	0	0	.0452	.0505	0.0653	0.0849	0.2459
6	400	0	0	.0661	.0371	0.0919	0.0812	0.2763
7	0	4500	0	.1021	.1436	0.2651	0.2640	0.7748
8	25	4500	0	.1205	.1335	0.1768	0.3513	0.7831
9	50	4500	0	.2464	.2848	0.5975	0.2995	1.4282
10	100	4500	0	.2980	.3610	1.0494	1.2850	2.9934
11	200	4500	0	.3268	.3203	1.0231	0.8637	2.5339
12	400	4500	0	.7943	.4443	1.3525	1.4723	4.0634
13	0	0	50	.0491	.0345	0.0671	0.1084	0.2591
14	25	0	50	.0510	.0443	0.0803	0.0932	0.2688
15	50	0	50	.0429	.0468	0.0497	0.0740	0.2134
16	100	0	50	.0561	.0421	0.2235	0.1571	0.4788
17	200	0	50	.0463	.0438	0.2229	0.0864	0.3994
18	400	0	50	.0499	.0665	0.1389	0.0993	0.3546
19	0	4500	50	.1415	.1494	0.2834	0.2987	0.8730
20	25	4500	50	.2763	.1551	0.3316	0.7083	1.4713
21	50	4500	50	.2469	.2722	0.3624	0.4873	1.3688
22	100	4500	50	.2723	.6140	0.6533	0.6232	2.1628
23	200	4500	50	.6842	.3404	1.6836	2.3763	5.0845
24	400	4500	50	.7907	.8817	1.7126	1.9261	5.3111

TABLE IV. ANALYSIS OF VARIANCE - FIRST CROP VEGETATION WEIGHT IN GRAMS

SOURCE OF VARIATION	D.F.	S.S.	M.S.	F	F 5%
Treatments	23	2.14219	0.09314	14.42	1.98
P	5	0.48235	0.09647	11.85	2.62
K	1	0.03303	0.03303	4.06	4.26
Ca	1	1.09855	1.09855	134.96	4.26
P x K	5	0.02178	0.00436	0.54	2.62
P x Ca	5	0.45695	0.09139	11.23	2.62
K x Ca	1	0.03193	0.03193	3.92	4.26
P x K x Ca	5	0.01860	0.00372	0.46	2.62
Error	24	0.19538	0.00814		
Total	47	2.33757			

TABLE V. ANALYSIS OF VARIANCE - SECOND CROP VEGETATION WEIGHT IN GRAMS

SOURCE OF VARIATION	D.F.	S.S.	M.S.	F	F 5%
Treatments	23	15.44382	0.67147	34.77	1.98
P	5	3.61847	0.72369	37.48	2.62
K	1	0.18796	0.18796	9.73	4.26
Ca	1	6.90273	6.90273	357.47	4.26
P x K	5	0.70414	0.14083	7.29	2.62
P x Ca	5	1.45872	0.29174	15.11	2.62
K x Ca	1	0.07438	0.07438	3.85	4.26
P x K x Ca	5	2.49742	0.49948	25.87	2.62
Error	24	0.46341	0.01931		
Total	47	15.90723			

TABLE VI. ANALYSIS OF VARIANCE - TOTAL CROP VEGETATION WEIGHT IN GRAMS

SOURCE OF VARIATION	D.F.	S.S.	M.S.	F	F 5%
Treatments	23	28.21482	1.22673	83.45	1.98
P	5	6.48931	1.29786	88.29	2.62
K	1	0.38787	0.38787	26.38	4.26
Ca	1	13.50737	13.50737	918.86	4.26
P x K	5	0.85188	0.17038	11.59	2.62
P x Ca	5	5.88014	1.17603	80.00	2.62
K x Ca	1	0.19447	0.19447	13.23	4.26
P x K x Ca	5	0.90378	0.18076	12.30	2.62
Error	24	0.35268	0.01470		
Total	47	28.56750			

TABLE VII. CONCENTRATION OF PHOSPHORUS IN PLANTS AND PHOSPHORUS REMOVED FROM THE SOIL BY THE VEGETATIVE GROWTH OF SORGHUM, ASSOCIATED WITH VARIOUS FERTILIZER TREATMENTS.

TREATMENT	P IN PLANT, ppm.			P REMOVED, mg.		
	1st CROP AVERAGE	2nd CROP AVERAGE	TOTAL CROP AVERAGE	1st CROP	2nd CROP	TOTAL CROP
1	1170	1335	1252	.130	.152	.282
2	2178	1289	1734	.163	.189	.352
3	1610	1230	1420	.162	.177	.339
4	2198	1607	1948	.172	.190	.362
5	1996	1758	1877	.191	.282	.473
6	2056	1425	1740	.200	.247	.447
7	0768	1062	915	.183	.562	.745
8	744	1097	920	.207	.579	.786
9	1376	1512	1444	.489	1.356	1.845
10	1281	1497	1389	.815	3.644	4.459
11	1587	1772	1679	1.028	3.343	4.371
12	1364	1716	1540	1.664	4.847	6.511
13	1522	1279	1400	.125	.224	.349
14	1754	1411	1582	.163	.245	.408
15	1288	1332	1310	.116	.165	.281
16	1904	1674	1789	.183	.637	.820
17	2130	1448	1789	.192	.448	.690
18	2306	1719	2012	.276	.409	.685
19	679	758	718	.197	.441	.688
20	829	851	840	.341	.885	1.226
21	1495	1146	1346	.513	.974	1.487
22	1274	1601	1438	1.034	2.044	3.078
23	1538	1880	1709	1.570	7.633	9.203
24	2014	2184	2099	3.325	7.947	11.272

TABLE VIII. CONCENTRATION OF CALCIUM IN PLANTS AND CALCIUM REMOVED FROM THE SOIL BY THE VEGETATIVE GROWTH OF SORGHUM, ASSOCIATED WITH VARIOUS FERTILIZER TREATMENTS.

TREATMENT	Ca IN PLANT, ppm.			Ca REMOVED, mg.		
	1st CROP AVERAGE	2nd CROP AVERAGE	TOTAL CROP AVERAGE	1st CROP	2nd CROP	TOTAL CROP
1	3492	3526	3509	0.399	0.400	0.799
2	4572	4486	4529	0.342	0.718	1.060
3	4492	4522	4507	0.447	0.580	1.027
4	4631	4738	4684	0.361	0.561	0.922
5	4005	4766	4386	0.380	0.716	1.096
6	3917	4323	4120	0.399	0.748	1.147
7	2393	2847	2620	0.637	1.506	2.143
8	2204	2632	2418	0.570	1.390	1.960
9	2634	2849	2742	0.463	2.556	3.019
10	3078	2976	3027	2.148	7.942	10.090
11	2790	2930	2860	1.796	13.471	15.267
12	3250	3141	3196	3.420	22.343	25.763
13	4699	4733	4716	0.409	0.831	1.240
14	5029	4927	4978	0.476	1.684	2.161
15	3705	4286	3996	0.333	2.216	2.549
16	4063	4078	4070	0.399	3.768	4.167
17	4209	4396	4302	0.380	5.128	5.508
18	3566	4023	3794	0.408	6.086	6.494
19	3473	3618	3546	1.007	8.192	9.199
20	3159	3354	3256	1.330	11.680	13.010
21	2899	3192	3046	1.492	14.392	15.884
22	3742	4017	3880	2.707	19.520	22.227
23	3577	4068	3822	3.686	36.035	39.721
24	2892	3608	3250	4.823	49.164	53.987

TABLE IX. CONCENTRATION OF POTASSIUM IN PLANTS AND POTASSIUM REMOVED FROM THE SOIL BY THE VEGETATIVE GROWTH OF SORGHUM, ASSOCIATED WITH VARIOUS FERTILIZER TREATMENTS.

TREATMENT	K IN PLANT, ppm.			K REMOVED, mg.		
	1st CROP AVERAGE	2nd CROP AVERAGE	TOTAL CROP AVERAGE	1st CROP	2nd CROP	TOTAL CROP
1	11,664	12,639	12,152	11.350	1.437	2.787
2	14,207	14,724	14,466	1.060	2.352	3.412
3	14,709	13,958	14,334	1.475	1.781	3.256
4	12,538	14,590	13,564	.995	1.728	2.723
5	11,729	14,058	12,894	1.135	2.112	3.247
6	16,078	14,858	15,468	1.609	2.567	4.176
7	11,164	11,278	11,221	2.799	7.063	9.862
8	12,351	12,582	12,466	3.148	6.714	9.862
9	12,595	12,538	12,566	6.700	11.213	17.913
10	12,440	12,624	12,532	8.199	29.493	37.692
11	12,887	12,617	12,752	8.327	23.707	32.034
12	10,009	11,216	10,612	9.942	31.738	41.680
13	15,788	15,444	15,616	1.280	2.800	4.080
14	15,512	15,482	15,497	1.465	2.710	4.175
15	13,772	14,556	14,164	1.235	2.106	3.341
16	13,127	13,894	13,510	1.265	3.975	5.240
17	15,192	15,154	15,173	1.365	5.674	7.039
18	15,474	15,503	15,524	1.805	3.670	5.475
19	13,920	13,854	13,887	4.055	8.083	12.138
20	17,596	16,148	16,872	7.558	16.785	24.343
21	18,236	18,364	18,300	9.461	15.557	25.018
22	19,693	19,660	19,676	17.298	25.106	42.404
23	18,788	18,773	18,780	18.877	75.764	94.641
24	14,930	17,746	16,338	24.837	64.490	89.327

TABLE X. EXTRACTED SOIL PHOSPHORUS FRACTIONS, ASSOCIATED WITH FERTILIZER ADDITIONS.

TREATMENT	MINERAL ADDITION, ppm.			PHOSPHORUS REMOVAL, ppm.		
	P	Ca	K	Aluminum	Iron	Calcium
1	00	0	0	30	11	32
2	25	0	0	30	12	32
3	50	0	0	36	13	36
4	100	0	0	36	17	38
5	200	0	0	42	16	36
6	400	0	0	68	21	35
7	0	4500	0	38	12	28
8	25	4500	0	27	14	30
9	50	4500	0	32	16	32
10	100	4500	0	32	20	36
11	200	4500	0	44	18	37
12	400	4500	0	70	21	39
13	0	0	50	29	11	27
14	25	0	50	28	14	27
15	50	0	50	32	15	28
16	100	0	50	34	14	26
17	200	0	50	58	20	30
18	400	0	50	60	28	37
19	0	4500	50	17	16	30
20	25	4500	50	36	16	31
21	50	4500	50	32	15	26
22	100	4500	50	34	18	29
23	200	4500	50	47	17	26
24	400	4500	50	82	16	32

TABLE XI. APPLIED PHOSPHORUS RECOVERY BY PLANTS AND CHEMICAL EXTRACTIONS, EQUILIBRATED BY SETTING THE NO PHOSPHORUS TREATMENT AT ZERO AND DETERMINING THE DIFFERENCE BETWEEN PHOSPHORUS ADDED AND PHOSPHORUS REMOVED.

TREATMENT	P ADDED	P REMOVED, mg.		TOTAL	INCREASE OVER CHECK	P UNACCOUNTED FOR, mg.
		Plant	Al, Fe, & Ca			
1	0.0	0.28	21.9	22.18	0.00	0.00
2	7.5	0.35	22.2	22.55	0.37	7.13
3	15.0	0.34	25.5	25.84	3.66	11.34
4	30.0	0.36	27.3	27.66	5.48	24.52
5	60.0	0.47	28.2	28.67	6.49	53.51
6	120.0	0.45	37.2	37.65	15.47	104.53
7	0.0	0.74	20.4	21.14	0.00	0.00
8	7.5	0.79	21.3	22.09	0.95	6.55
9	15.0	1.84	24.0	25.84	4.70	10.30
10	30.0	4.46	26.4	30.86	9.72	20.28
11	60.0	4.37	29.7	34.07	12.93	47.07
12	120.0	6.51	39.0	45.51	24.37	95.63
13	0.0	0.35	20.1	20.45	0.00	0.00
14	7.5	0.41	20.7	21.11	0.66	6.84
15	15.0	0.38	22.5	22.78	2.33	12.67
16	30.0	0.82	22.2	23.02	2.57	24.43
17	60.0	0.69	32.4	33.09	12.64	47.36
18	120.0	0.68	37.5	38.18	17.73	102.27
19	0.0	0.69	18.9	19.59	0.00	0.00
20	7.5	1.23	24.9	26.13	6.54	0.96
21	15.0	1.49	21.9	23.39	3.80	11.20
22	30.0	3.08	24.3	27.38	7.79	22.21
23	60.0	9.20	27.0	36.20	16.61	43.39
24	120.0	11.27	39.0	50.27	30.68	89.32

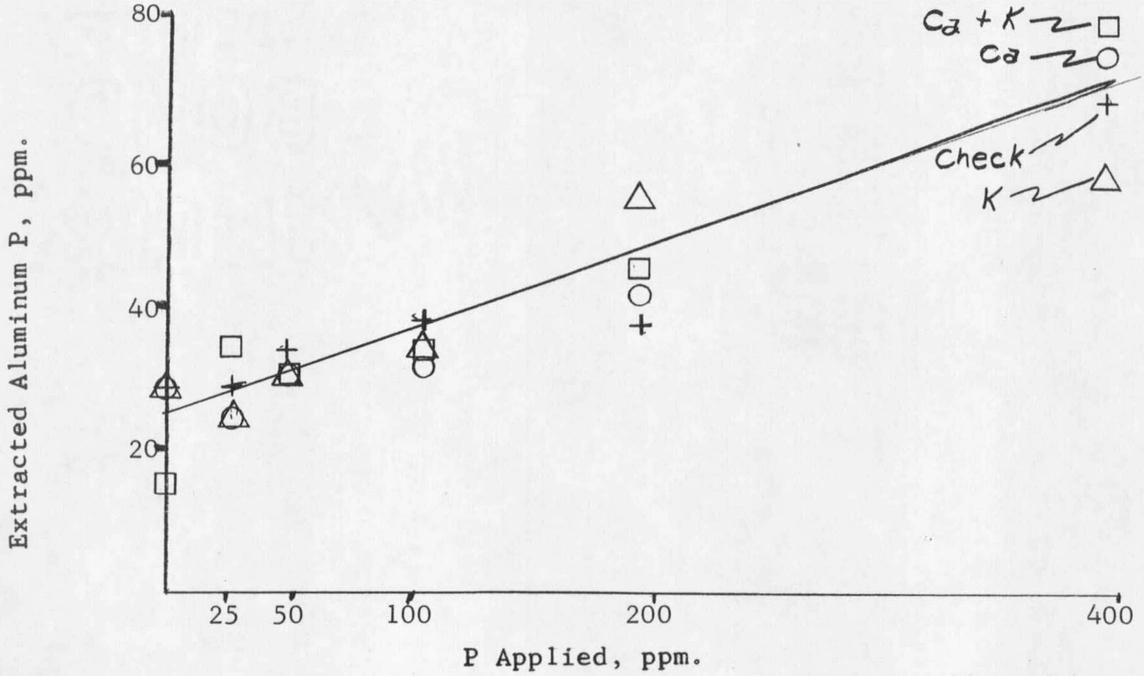


FIGURE 12. Aluminum phosphate extracted from the soil as affected by phosphorus additions associated with calcium and potassium fertilization.

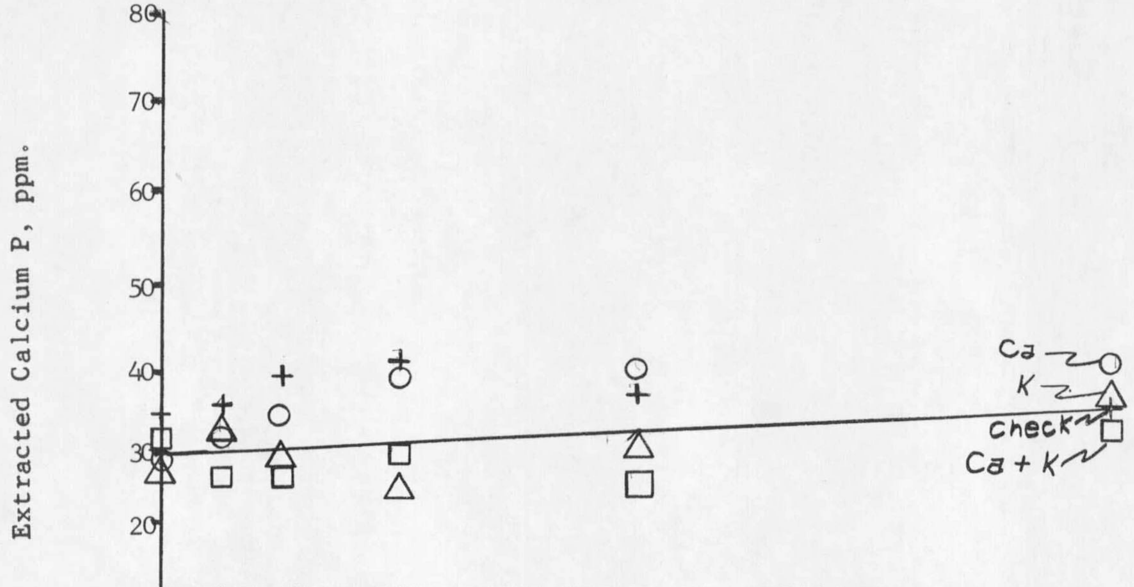


FIGURE 13. Calcium phosphate extracted from the soil as affected by phosphorus additions associated with calcium and potassium fertilization.

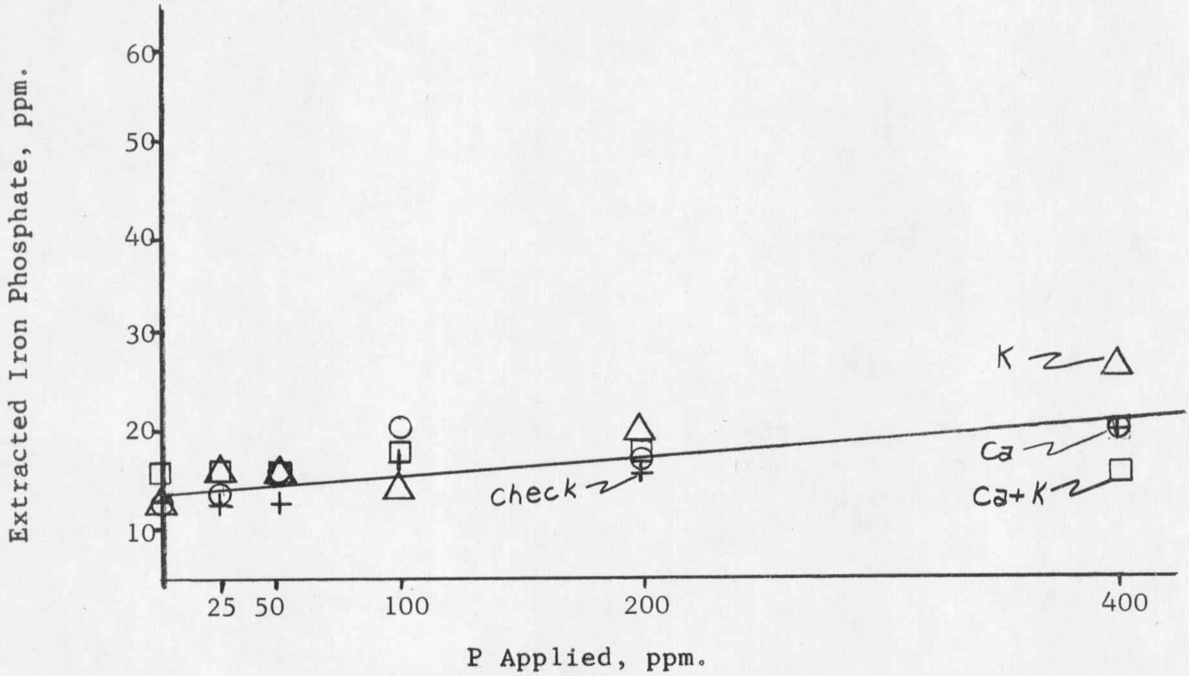


FIGURE 14. Iron phosphate extracted from the soil as affected by phosphorus additions associated with calcium and potassium fertilization.

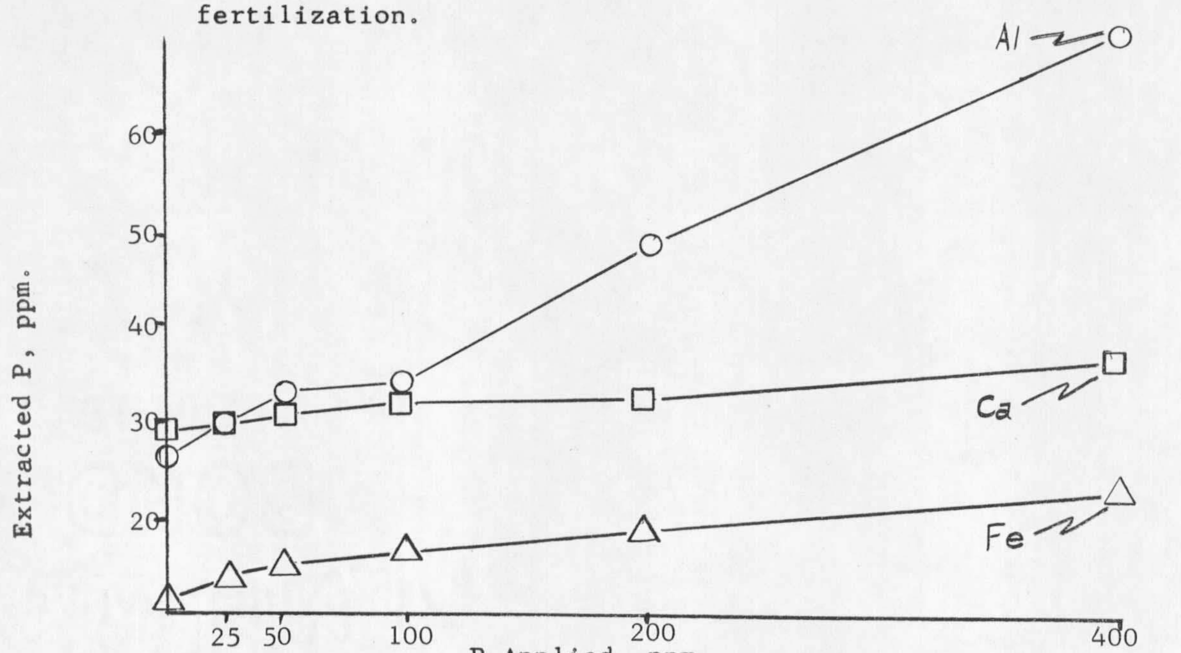


FIGURE 15. Average calcium, aluminum, and iron phosphate extracted from the soil corresponding to phosphorus additions associated with calcium and potassium fertilization.

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