EFFECT OF RATE, PLACEMENT AND SOURCE OF POTASSIUM ON YIELD AND MINERAL CONTENT OF POTATOES AND PHOSPHORUS FORMS AND EQUILIBRIA IN SELECTED PERUVIAN SOILS

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ABSTRACT

PART I

EFFECT OF RATE, PLACEMENT AND SOURCE OF POTASSIUM ON YIELD AND MINERAL CONTENT OF POTATOES

by Carlos Valverde S.

Three field experiments with potassium fertilization of potatoes were conducted: one on Hodunk sandy loam in 1967 to determine the effects of rate and placement of K, another on Hodunk sandy loam in 1968 to determine the effects of rate, source and placement of K, and the third on McBride sandy loam in 1968 to determine the effects of rate and placement of K for Russet Burbank and Sebago potatoes.

Yields of potatoes appeared to be related to the level of exchangeable soil K, since the most marked response was obtained in 1967 on Hodunk sandy loam at an exchangeable K level of 135 pounds per acre, a lesser response on Hodunk sandy loam in 1968 at a level of 160 pounds, and the least response on McBride sandy loam at a level of 200 pounds K per acre. The yields were decreased when rates of K applied were equal to or greater than 200 pounds banded or 400 pounds broadcast. The sources of K (KCl, K_2SO_4 and K_2CO_3) were all equally effective with respect to yields when the K was applied broadcast at the level of 200 pounds K per acre or less. The specific gravity and percent dry weight of potatoes decreased as rate of K increased.

The concentration of K in petioles, leaves and vines increased as the rate of K increased, while the concentration of Ca and Mg tended to decrease. On the other hand, as the potato matured, K concentration in plants decreased and Ca and Mg concentration increased.

Broadcast and banded applications of K were generally equally effective with respect to yield and chemical composition of potatoes.

When potassium fertilizer was broadcast, exchangeable K increased as the rate of K increased, but a comparison of the level of soil K after cropping and of crop removal with the rate of K application indicates that a considerable portion of applied fertilizer K was either "fixed" by the soil or leached from the plow layer.

Carlos Valverde S.

ABSTRACT

PART II

PHOSPHORUS FORMS AND EQUILIBRIA IN SELECTED PERUVIAN SOILS

A laboratory study was conducted to characterize the phosphorus fractions in nine Peruvian soils and to evaluate the phosphorus fixation and equilibria reactions in these soils. Three of the soils were from the coastal area, three from the mountains, and three from the jungle.

Phosphorus in the coastal soils was primarily calcium phosphate, and adsorption maxima and strength of adsorption, as determined using the Langmuir adsorption isotherm, were directly related to the amount of free calcium carbonate in the soils. Phosphate potential determinations indicated that phosphorus solubility in these soils was controlled mainly by octocalcium phosphate.

In a mountain soil with a neutral reaction, calcium phosphate was again the dominant form of phosphorus, but phosphorus solubility was governed by hydroxyapatite, and the strength of bonding was much higher than on the coastal soils. In two acid mountain soils, iron phosphate was the dominant form of phosphorus, with considerable amounts of

aluminum phosphate present. Phosphorus solubility was less than that of strengite until 500 ppm P had been applied, when variscite appeared to be governing phosphorus availability.

Phosphorus in strongly acid jungle soils occurred mostly as iron and aluminum phosphates, and phosphorus solubility was again less than that of strengite. In a slightly acid jungle soil, phosphorus solubility appeared to be controlled by hydroxyapatite, even though iron and aluminum phosphates appeared to be the dominant forms of phosphorus in this soil.

When that part of the total phosphorus in the soils extracted during the fractionation procedure is considered, the data indicate that the jungle soils were the most severely weathered, and that the coastal soils showed the least weathering.

EFFECT OF RATE, PLACEMENT AND SOURCE OF POTASSIUM ON YIELD AND MINERAL CONTENT OF POTATOES

AND

PHOSPHORUS FORMS AND EQUILIBRIA IN SELECTED PERUVIAN SOILS

By

Carlos Valverde Suarez

A THESIS

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This thesis is dedicated to my wife and daughter
FLOR DE MARIA and KAREN

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PART I

EFFECT OF RATE, PLACEMENT AND SOURCE OF POTASSIUM ON YIELD AND MINERAL CONTENT OF POTATOES

EFFECT OF RATE, PLACEMENT AND SOURCE OF POTASSIUM ON YIELD AND MINERAL CONTENT OF POTATOES

INTRODUCTION

Heavy rates of potassium fertilizer are generally needed to produce optimum yields of potatoes. Considerable field research has been done to evaluate the potassium status of Michigan potato soils, but relatively few of these experiments were conducted with irrigation and at current yield levels. Control of fertilizer nutrient levels and adequate evaluation of cation balance in soils becomes highly important as fertilizer rates increase and production becomes more intensive. Evaluation of nutrient levels in petioles and leaves throughout the growing season is necessary if reliable criteria are to be established for the interpretation of plant analyses.

As higher rates of potassium fertilizers are applied, the effects of the different sources of potassium need to be re-evaluated, since the effects of anions applied with potassium may be more critical at high fertilization levels. The relative effectiveness of band and broadcast applications needs to be determined at high rates of application.

The investigations reported herein were conducted to determine the effects of rate, source, and placement of potassium fertilizers on yields, specific gravity, and levels of potassium, calcium, and magnesium in potatoes grown under irrigation.

LITERATURE REVIEW

Potassium Deficiency Symptoms in Potatoes

The deficiency symptoms for K in potatoes have been fully reported (Mc Murtrey, 1948; Wallace, 1951; Cook, 1953; Houghland, 1964; Ulrich and Ohki, 1966), and may be described as follows: The growth of the plant is retarded and the stalks (haulms) are slender with the internodes somewhat shortened. The leaves lose their smooth surface, are reduced in size, and tend to be flat or to curl backward near the margins. The appearance of dark green foliage is an early sign of K shortage. Then the older leaves become yellowish, and a brown or bronze color develops, starting from the tips and margins and gradually affecting the entire leaves. Leaflets are cupped and crowded together. The lower leaves dry up and collapse prematurely. The tuber flesh is bluish and poorly developed. When a deficiency of K is severe, the plants eventually die.

Effect of Rate of Potassium on Yields

The effects of rates of K on yields of potatoes have been studied in most of the potato producing areas (Brown, 1938 and 1940; Ware, 1939; Prince *et al.*, 1940; Chucka *et al.*, 1944; Jacob *et al.*, 1949; Terman *et al.*, 1949, 1950, 1953 and 1963; Hawkins et al., 1946; Nelson and Hawkins, 1947; Lorenz et al., 1954; Harrap, 1960; Berger et al., 1961; Wilcox, 1961; Rowberry et al., 1963; Murphy and Goven, 1965 and 1966; and Laughlin, 1966). The results obtained by these authors indicate that response of potatoes to K fertilizer varies with soil type, climate conditions, and varieties used. In California, Lorenz et al. (1954) indicate that potatoes did not respond to different rates of K in most of the potato-producing areas with exception of the peat soils of San Juaquin Delta, where applications as high as 160 pounds of K per acre were needed, and the Ripperdan fine sandy loams, the only mineral soils on which yields were increased by K. Nelson and Hawkins (1947) reported that yields may be increased with applications of K greater than 120 pounds per acre in North Carolina. In Maine, Terman (1950) summarized 83 field experiments involving potassium rates conducted from 1930 to 1949, and concluded that the greatest yield response was obtained with the first 60-80 pounds of K_2O per acre. The same author (Terman, 1953) later reported significant yield increases with only 60 pounds K_2O per acre.

In Ontario, Rowberry et al. (1963) reported that potatoes growing in mineral soils responded to successive increments of a 6-12-12 fertilizer up to 1,000 pounds per acre, with no further increase when 1,500 pounds were applied. Timm and Merkle (1963), in the major potato growing area of Pennsylvania, reported increases in potato yields when 66 pounds of

K_2O per acre was applied to soils in which the exchangeable K was more than 200 pounds K per acre. Harrap (1960), at Levington in Great Britain, found that the optimum K applications for the production of good quality potatoes varied from soil to soil, and that the average optimum rate was 200 pounds K_2O per acre. Wilcox (1961) in southwestern Indiana observed linear increases in yields for rates of K_2O up to 150 pounds per acre. Higher rates of K_2O resulted in sharply decreased yields. In Michigan, Crabtree (1969) reported significant yield increases for rates of K_2O up to 180 pounds per acre.

Effect of Source of Potassium on Potato Yields

In considering the effect on yields, the literature indicates that the source of K does not usually affect potato yields. Chucka *et al*. (1944) in Maine, comparing potassium chloride (KCl), potassium sulfate (K_2SO_4), potassium nitrate (KNO_3) and potassium metaphosphate (KPO_3), reported that the yields produced were approximately the same with all sources.

Terman (1949 and 1950), comparing KCl and K_2SO_4, found that yields were not affected although variable results were obtained in individual experiments. Timm and Merkle (1963) in Pennsylvania did not find statistically significant differences in yields between either of these two sources, and stressed that soil variability, moisture content and varietal differences apparently affected potato yields as much as did the source of K. In Ontario, Rowberry et al. (1963) did not find any yield differences due to either of these sources of K except at one location in 1958 and in 1960 where yields were higher with K_2SO_4. Recently in Maine, Murphy and Goven (1965) in a three-year period found that the source of K had no significant effect on yield of tubers and in 1966 these same authors, summarizing data from 1956 to 1958, concluded that source of K did not influence yield of potatoes, but that potatoes fertilized with KCl tended to produce chips of lighter color than did those fertilized with K_2SO_4 or KNO_3.

There are some reports that potato yields on plots to which KCl was applied were higher than those from plots to which K_2SO_4 was applied (Berger et al., 1961 and Wilcox 1961). Under greenhouse conditions, using solution culture where the ions present were carefully controlled, Hart and Smith (1966) determined that at the same level of K, the percent dry weight of plant tops was higher when K_2SO_4 was used than when KCl was used. Lucas et al. (1954) reported that potato yields on organic soils in Michigan were slightly, and nearly significantly, higher when K_2SO_4 was applied than when KCl was applied. Doll and Thurlow (1965) indicate that no consistent differences in yields were obtained on mineral soils between the chloride and sulfate forms of K fertilizers.

The Effect of Rate and Source of Potassium on the Specific Gravity of Potatoes

The starch content of the potato tubers is important because the quality of the tubers is related to the dry matter content (starch, protein and other mineral constituents). Studies by many investigators indicate that the specific gravity of the tubers indirectly measures the starch content. In Germany, Scheele _et_ _al_. (1936) from 540 potato samples collected over a four year period, correlated specific gravity with dry matter and starch content and reported correlation coefficients (r) of 0.937 and 0.947, respectively. Dunn and Nylund (1945) in Minnesota reported a correlation coefficient (r) of 0.8686 between specific gravity and dry matter for 260 samples from the Red River valley.

Early in 1912, Thatchter noted that the production and storage of starch in potatoes and sugar beets was directly related to a decreasing supply of available soil K. Mulder (1956) reported that K affected the rate of tuber respiration more than N, P, Mg or Ca. Potassium-deficient tubers have considerably higher respiration rates than tubers grown with an adequate supply of K. McCollum _et_ _al_. (1958) have pointed out that for maximum activity of pyruvic kinase, magnesium (Mg) is required as well as K; this enzyme is essential for the metabolism of carbohydrates. While the above effects of K were noted for the experimental condition reported, under field conditions, increasing rates of K usually result in a reduction of the starch content and consequently the specific gravity of the tubers. The same is true with the anion associated with the K fertilizer. Houghland and Shricker (1933) in Virginia measured total starch production in more than 300 samples of potatoes tubers grown on a Norfolk sandy loam and an Arlington clay loam. These authors found that in the majority of the cases, the addition of K caused a slight depression in the starch content of the tubers, and noted that this reduction was greater when KCl was applied than when K_2SO_4 was applied.

Results of subsequent research have usually indicated that K fertilizers, particularly those containing chlorides, lower the specific gravity and that the higher the rate of application the more the specific gravity is lowered (Dunn and Nylund, 1945 - Dunn and Rost, 1948; Terman, 1949 and 1950; Harrap, 1960; Berger _et_ _al_., 1961; Wilcox, 1961; Timm and Merkle, 1963; Rowberry _et_ _al_., 1963). Murphy and Goven (1959, 1965, and 1966) reported that as the rate of K was increased from 0 to 250 pounds of K_2O per acre, the specific gravity of the tubers was decreased linearly from 1.084 to 1.070, and that the yield was increased only by the first 50-pound increment of K. When sources of K were compared, the specific gravity was higher when K_2SO_4 and KNO_3 were applied than when KCl was applied, and chips made from potatoes fertilized with KCl were higher in color than chips from potatoes fertilized with K_2SO_4. Lucas _et_ _al_. (1954) reported that potatoes grown on organic soils in Michigan contained 13 percent less starch and were 6 percent lighter in weight when KCl was applied than when the same rate of K_2SO_4 was applied.

The effect of Cl^- on the metabolism of starch formation is not clear, but Cl^- does result in a higher water content in the tubers. Numerous reports in the literature indicate that large and sometimes excessive amounts of Cl^- are readily absorbed by potatoes. (Dunn and Nylund, 1945; Dunn and Rost, 1948; Knolewles and Cowie, 1940).

Corbett and Gausman (1960) suggested that Cl may affect potato tuber's quality by affecting the uptake of phosphorus (P). Along with these findings, Hart and Smith (1966) found that P absorption at a particular stage of plant development was affected by source of K. On the other hand, Latzko (1955) indicated that invertase, amylase and / glucosidase are inhibited by Cl^- and increased by $SO_4^=$.

Fertilizer Placement for Potatoes

The potato plant does not have an extensive root system, and it has a high K requirement. Data obtained in Maine (Hawkins, 1946) revealed that during the peak period of K absorption (70 days after planting), as much as 6.4 pounds of K_2O per acre per day were absorbed.

Cummings and Houghland (1939) studied 13 different methods of K placement from 1931 to 1937 on typical potato growing areas of Arostook County, Maine; on Long Island, New York; in central New Jersey; on the eastern shore of Virginia; in northeastern Ohio and in western Michigan. Their results indicate that placement of the fertilizer in a band immediately under, above or mixed with the soil around the seed resulted in delayed emergence of the sprout and reduction in yield. The placement of the fertilizer in bands 2 inches at each side and on the lower level of the seed consistently produced relatively higher average yields than the other side placements, both those nearer and those further from the seed. The placement of the fertilizer in a band at only one side of the row gave lower yields than two bands, one on either side of the seed. In general, fertilizer concentrated in bands near the row was more effective than broadcast fertilizer. A more detailed description of the results obtained at Mancelona and Greenville in the Michigan area is given by Grantham et al. (1939); these results indicate that for equal amounts of commercial fertilizer, higher yields were obtained when the fertilizer was applied in the row than when it was applied broadcast.

In Maine on a Caribou loam, Chucka et al. (1944) compared the placement of a 6-6-12 fertilizer applied as follows at a total rate of 2,000 pounds per acre: (1) all applied in the row; (2) 1,500 pounds in the row and 500 pounds plowed down; (3) 1,000 pounds in the row and 1,000 plowed down; (4) 500 pounds in the row and 1,500 pounds on the plowsole; (5) 2,000 pounds plowed down; (6) all applied broadcast before plowing and (7) all applied broadcast after plowing. The results indicated that the fertilizer applied broadcast gave the highest yield, but not significantly higher, and that the other placements were comparable. Similar results were reported for the same area by Hawkins et al. (1944).

Berger et al. (1961) in Wisconsin compared the effects of banded and broadcast applications of KCl and K_2SO_4, on P uptake. Their results were summarized as follows:

(1) The same amount of KCl applied broadcast with banded P and nitrogen (N) banded resulted in higher P uptake than when the KCl was applied banded.

(2) In most potato trials, P uptake was higher with broadcast applications of either KCl or K_2SO_4 than with comparable row applications.

(3) Broadcasting K resulted in higher specific gravity than with row applications.

(4) K_2SO_4 is a better source of K than is KCl when applied banded in the row with the P and N fertilizer.

Nelson (1968) indicates that the modern trend on fertilizer practices is to minimize sizeable amounts at planting in favor of large amounts broadcast and plowed down. Hawkins (1965) reported that sidedressing one half of the K either as KCl or K_2SO_4 resulted in slightly better yields than when all K was applied in side bands at planting. Sidedressing three fourth's of the K when the plants were 3 to 5 inches high, without irrigation, gave larger yields than when all the K was banded at planting. Similar results were obtained with chloride, sulfate, and nitrate of K although the best yield, growth, and dry matter content was obtained with KNO_3. The same author (1964) compared applications of KCl either plowed down or broadcast after plowing with banded K at planting, and obtained better early growth and as good or slightly better yields with the plow down or broadcast applications.

Effects of Rates and Sources of Potassium on the Absorption of Potassium, Magnesium and Calcium by Potato Plants

High rates of K applied to the soils can induce Mg deficiency and lower the Ca content of plants in many crops (Stanford *et al*., 1942; Boynton and Burrell, 1944; Mehlich and Reed, 1946; Lucas and Scarseth, 1947; McColloch *et al*., 1957). More specific results of K inducing Mg deficiency in potatoes have been reported by Hovland and Caldwell (1960), Doll and Hossner (1964) and Adams and Henderson (1962). Wallace *et al*. (1942) observed that K deficiency symptoms were present on the leaves of potato plants grown on plots where K was not applied, and Mg deficiency on those grown where K was applied. Walsh and O'Donohoe (1945) reported that high rates of K induced severe Mg deficiency which was reflected in a very low content of Mg in the foliage while the tuber was affected only slightly. They also noted that the calcium (Ca) content of the foliage, and to a lesser extent in the tubers, was lowered by K fertilization.

Dunn and Rost (1948) in Minnesota reported the results of 23 field experiments which indicated that the application of K increased the K content of potatoes grown on Ulen soils and some Bearden soils and that the percentages of Ca, Mg and S were not affected by K fertilization.

Ward (1959) grew potatoes in sand culture with various levels of K ranging from complete deficiency to luxury consumption. This resulted in increasing amounts of K in all plant tissues and in decreasing amounts of Na, Ca, Mg, Fe, and Cu. In certain tissues, particularly in the leaf and stem, Mg content varied inversely with K content. The same trend was noted with Ca, but was much less pronounced. Roots and tubers did not show these effects.

Tyler _et_ _al_. (1960), reported the results of 40 field experiments and 73 field surveys from 1956 to 1960 in California and concluded that the differences in K content between K-deficient plants and those grown with sufficient K fertilizer remain small until tuber growth commences.

Also in California, Lorenz (1947) studied four treatments on a Hesperia fine sandy loam: none, 50, 100 pounds per acre of N as NH_4SO_4 with neither P or K and as a fourth treatment, 125 pounds per acre each of P_2O_5 and K with the highest rate of N. Leaf samples were first taken when the plants were about six inches high, and successive samples were taken at approximately two week intervals until harvest. From the analysis of the samples, it was concluded that the K content of both plants and tubers decreased with age of the plant and that the K application had no effect on the K content of either plants or tubers at any stage of growth.

Wilcox (1961), in Indiana, applied 0, 75, 150 and 225 pounds per acre of K_2O applied as KCl and as K_2SO_4. In order to intensify the anion effect, N was applied as ammonium sulfate [$(NH_4)_2SO_4$] with K_2SO_4 and as ammonium chloride (NH_4Cl) with KCl. The analyses of leaves sampled at prebloom stage showed that as rate of K applications was increased, K in the leaf tissue increased without any differential effect due to associated anion. The Ca and Mg content of the leaf decreased as the K rate increased. The Ca and Mg content of the leaves tended to be higher when KCl was applied than when K_2SO_4 was applied.

Laughlin (1966), in the Matanuska Valley of Alaska from 1961 to 1963, compared sources and rates of K and soil and spray applications of magnesium sulfate ($MgSO_4$). The foliage and tubers were analyzed for N, P, K, Ca and Mg. In two of the three years, K fertilizer increased the sum of the cations (K + Ca + Mg) in the tubers and decreased the dry matter, N, and P content, the Ca:Mg ratio of tubers, and the content of Mg and the sum of cations in the tops.

Hossner and Doll (1968) indicate that with a soil Mg:K ratio below 0.8 (expressed as me/100 g), K induced Mg deficiency in potatoes grown on an acid sandy podzol in Northern Michigan.

McColloch <u>et al</u>. (1957) found that an exchangeable K:Mg ratio, as lb/A, greater than 0.4 to 0.5 is suggestive of Mg deficiency in citrus. They concluded that the exchangeable K:Mg ratio appears to be a useful index in determining the need for supplemental Mg, as have other workers with other crops (Prince _et al._, 1947; Walsh and O'Donohoe, 1945).

Hovland and Caldwell (1960) explained the effect of K in inducing Mg deficiency in soils as follows:

(1) The addition of K to soils may decrease the ease of replacement of exchangeable Mg, thus lowering Mg availability to the plants.

(2) Competition for exchange sites on plant roots caused by increasing levels of K, thus decreasing the rate of Mg uptake.

(3) High amounts of K in the plants may in some way prevent Mg from performing its functions.

Bear and Prince (1945) postulated that each cation has at least two functions in the plant, one which is unique to that cation and the other(s) of the type that could be performed by any of the three dominant cations--K, Ca, and Mg. Once the supply of each cation is adequate to meet the specific need for it, then there can be a wide range in ratios and quantities of cations that could be absorbed by the plant to meet its total needs.

The Relation of Exchangeable Potassium to Yields

Usually, exchangeable K is used to predict the need for K fertilizer. Bear _et al._ (1944) found that the amount of K in the exchangeable form was a reliable index to the K supplying power of the soil to alfalfa (Hardistan variety). Stanford and Kelly (1942) in Iowa found a close relationship between the yield of corn and the amount of exchangeable K in the soil. Hawkins et al. (1946), with potatoes in Maine, reported that on soils containing more than 500 pounds of exchangeable K_2O per acre, little or no increase in yield was obtained for more than 100 pounds of K_2O, which was the maximum rate used.

In one of the more comprehensive reports, Tyler et al. (1960) related K in the potato leaf petioles to exchangeable K in the soil. Soils containing 100 ppm K usually resulted in plant K values below 4 percent at late season, and the soil then was considered deficient in K. Also, potato plants growing in soils low in exchangeable (46 ppm) K showed a narrow range of K concentration at early season. By mid-season, the difference in plant K content between unfertilized plants and those which received 400 pounds of K_2O per acre was more than several fold the difference at early season, and this difference remained large the rest of the season.

Nelson and Hawkins (1947) reported that in North Carolina and in Maine, the K content of the leaves on potato plants was related to the amount of exchangeable K in the soil and to the amount of K applied. Terman (1950) concluded, after summarizing 115 experiments in Maine, that few experiments showed a yield response to more than 140-200 pounds of K_2O and these responses were on soils low in exchangeable K.

The Relation of Soil Test to the Response to Potassium Fertilizer

Crowther and Yates (1941) adopted the Mitscherlich standard curve equation with some modifications to determine response curves for the majority of arable crops in Great Britain and northern Europe. Bray (1944, 1948, and 1956) proposed the following modification of the Mitscherlich equation so that soil test values could be used in predicting the response to added increments of nutrients and to determine the rate required for maximum yield:

$$\text{Log } (A-y) = \log A - (c_1b_1 - cx)$$

where A is 100 percent or maximum yield, y is the yield or relative yield obtained at soil test value of b_1, x is the rate of nutrient required for maximum yield and c_1 and c are constants which are determined experimentally.

The constants in the Bray equation are being successfully used to determine P and K requirements for some crops, (Arnold, 1953; Bray, 1945; Melsted, 1967).

On potatoes, Smith and Sheard (1957) used the Bray technique to evaluate ten extracting procedures for soil P in trials conducted in various potato growing areas of southern Ontario, over a period of three years.

MacKay et al. (1959) reported the relationship of nitrate N to potato yields at 21 experimental locations in Canada by using the Bray's modified Mitscherlich equation. A mean value of c_1 for 58 individual tests was 0.0182. A close agreement in the mean of c_1 values was found for each of the two years, for three varieties (Kennebec, Netted Gem and Sebago), and for most of the potato soils. Large yield increase would be expected from applications of nitrogen applied to potatoes grown on soils which tested 116 ppm N for mountain soils or 64 ppm N for valley soils.

METHODS AND MATERIALS

Three field experiments were conducted to determine the effects of rate, source, and placement of potassium (K) fertilizer on yields, specific gravity, and chemical composition of potatoes. Two experiments, one each in 1967 and 1968, were conducted on Hodunk sandy loam on the M.S.U. Agricultural Experiment Station Farm at East Lansing, and one experiment in 1968 on the Montcalm Experimental Farm in Montcalm County

Field Procedure

Rate and Placement of Potassium on Hodunk Sandy Loam in 1967

The experiment on Hodunk sandy loam in 1967 was conducted to determine the effect of rate and placement of K on yields, specific gravity, and chemical composition of potatoes. The experimental area tested pH 6.0, available phosphorus (P) was 89 pounds per acre, and exchangeable calcium (Ca), potassium (K), and magnesium (Mg) were 636, 135, and 131 pounds per acre, respectively. The plots were laid out in a randomized block design with four replications, and each plot consisted of 4 rows 32 inches apart and 23 feet long. The various rates and method of application of K, applied as KCl, are given in Table 1. On all plots, 65 pounds per acre of N as NH_4NO_3 was broadcast and plowed down prior to planting, as was the broadcast K on appropriate plots. An additional 60 pounds of N and 44 pounds of P per acre as 45 percent concentrated superphosphate were banded at planting in 2 bands located 2 inches on either side of the seed piece. On appropriate plots, banded K was applied with the N and P.

Sebago potatoes (B-size whole seed) were planted May 19, 1967 and harvested November 23, 1967.

Soil samples were taken from each plot of the experiment on three different dates: (1) before fertilizers were applied in the spring, (2) on July 30, 70 days after planting, and (3) on November 9, 170 days after planting. At each sampling, at least 20 cores were taken midway between the rows on each plot.

Petiole and leaf samples were obtained as described by Tyler _et_ _al_. (1960) by taking 50 to 60 petioles and leaves from the center rows on each plot; the fourth or fifth leaf from the growing tip of the plant was sampled. Generally, the fourth leaf is the youngest fully developed leaf of the plant. The petioles comprise that portion of the plant between the stem and the base of the first leaflet, whereas the leaf samples were made up of the leaves as removed from the ends of the petioles.

The leaf and petiole samples were taken on July 28, 69 days after planting, when the plants were 14 to 18 inches high. On November 9, ten complete plants were sampled randomly from each plot, dried and weighed to calculate total nutrient uptake. Plant samples were dried in a forced-air oven at 65° C, and ground in a Wiley mill to pass 40-mesh sieve for chemical analysis.

For specific gravity determinations, 8 pounds of tubers were randomly selected from each plot, washed thoroughly, placed in a wire basket and suspended in water from a hydrometer, and specific gravity determined by the method described by Smith (1950).

To obtain tuber samples for chemical analysis, ten mature tubers were randomly selected from each plot, washed with tap water, and then rinsed with distilled water. The tubers were sliced, and a one-pound sample taken for drying so that the dry matter content could be determined. Samples were dried in a forced-air oven at 65° C until a constant weight was reached. After weighing, dried samples were ground for analysis as described above.

Rate, Source, and Placement of Potassium on Hodunk Sandy Loam in 1968

The experiment on Hodunk sandy loam in 1968 was conducted to determine the effect of source, rate, and placement of K on potato yields, specific gravity, and chemical composition. The experimental area tested pH 6.8, available P was 69 pounds per acre, and exchangeable Ca, K, and Mg were 966, 160, and 190 pounds per acre, respectively. The plots were laid out in a randomized block experiment with 4 replications as described for the 1967 experiment, except that the rows were 25 feet in length. The various potassium rates and method of placement are listed in Table 7, and potassium chloride (KCl), potassium sulfate (K_2SO_4) and potassium carbonate (K_2CO_3) were used as sources of K.

In addition to these K treatments, four additional treatments were included, three in which magnesium as $MgSO_4 \cdot 7H_2O$ was banded on plots to which each of the three sources of K were broadcast and one in which potassium-magnesium sulfate [$K_2Mg(SO_4)_2$] was banded together with supplemental K_2SO_4.

As was described for the 1967 experiment, 65 pounds of N and 44 pounds of P were banded at planting on all plots, and the banded K and Mg treatments listed in Table 7 were banded with the N and P on appropriate plots. Sebago potatoes were planted May 13, 1968, using B-size whole seed, and were harvested on October 10, 1968.

Petiole samples, obtained as described for the 1967 experiment, were taken 60, 98, and 130 days after planting, or on July 13, August 21, and September 24, respectively. For the purposes of this discussion, the petiole samples will be referred to as "early season", "mid-season", and "late season", respectively. As has been pointed out by Tyler _et_ _al_. (1960), "The length of the growing season for potatoes varies widely even within the same district due to environmental conditions, and it is advisable to classify plants and samples according to their physiological age rather than to the time since planting." They consider "early season" plants to be from 4 to 6 weeks after emergence, usually until the time of blossoming or the beginning of tuber set. "Mid-season" is from blossoming or early tuber set until the tubers are half grown, which is generally from 6 to 10 weeks after emergence. "Late season" is the time tubers are half-grown until maturity.

Tuber samples were taken at harvest for determinations of specific gravity and total dry matter content and for chemical analysis. The same procedures as described previously for the 1967 experiment were followed.

Rate and Placement of Potassium on McBride Sandy Loam in 1968

The experiment on McBride sandy loam in 1968 was conducted to determine the effect of rate and placement of K fertilizer on yield and chemical composition of Russet Burbank and Sebago potatoes. The experimental area tested pH 6.5, available P was 225 pounds, and exchangeable Ca, K, and Mg were 950, 200, and 150 pounds per acre, respectively. The plots were laid out in a split plot design with four replications; main plots were K treatments, and sub-plots were varieties. Each plot consisted of 6 rows, 32 inches wide and 50 feet long. Russet Burbank potatoes were planted in three rows of each plot, and Sebago potatoes were planted in the other three rows.

On all plots, 120 pounds of N was applied as NH_4NO_3, half of the N was broadcast before plowing and the other half was banded at planting. Concentrated superphosphate at a rate to supply 44 pounds P per acre was also banded at planting on all plots. Potassium treatments, which are listed in Table 14, were either broadcast before plowing or banded at planting with the N and P on appropriate plots. The potatoes were planted on May 1 and 2, 1968, and were harvested September 27, 1968.

Petiole samples were taken from each variety on each plot 60 and 96 days after planting, or on July 2 and August 8. The sampling procedures described previously were followed.

Laboratory Procedure

Soil Analyses

Soil samples were air-dried and ground to pass a 20-mesh sieve. Exchangeable cations (Ca, K, and Mg) were extracted with 1.0 N NH_4OAC adjusted to pH 7.0, using a 1:8 soil:solution ratio and a one-minute extraction period. Potassium in the extract was determined using a Coleman Model 21 flame photometer, and Ca and Mg were determined using a Model 290 Perkin-Elmer atomic absorption spectrophotometer; 1500 ppm La was added to the diluted extract for Ca and Mg to eliminate interference from other ions as described by Doll and Christenson (1966).

Available P was extracted for one minute using the Bray P-1 reagent (0.025 N HCl + 0.03 N NH_4F) at 1:8 soil solution ratio. Soil pH was determined in a 1:1 soil:water suspension, using a glass electrode potentiometer.

To separate the clay from Hodunk sandy loam, a sample of the soil was buffered at pH 4.8 with a sodium acetate-acetic acid buffer and then treated with H_2O_2 to destroy organic matter, followed by leaching with more buffer and then with water to remove the salts. The treated soil was suspended in water and the pH adjusted to the phenolphthalein endpoint with NaOH. Dispersion was completed by shaking the soil suspension for 48 hours on a reciprocating shaker, with periodic adjustments of the pH. The sand fraction was separated by decanting, and the clay fraction separated from the silt by sedimentation.

Oriented clay specimens were prepared for X-ray diffraction by depositing 25-30 mg of clay on ceramic plates. Specimens were then Mg-saturated and glycerol solvated. Diffraction patterns were made with a Phillips-Norelco X-ray unit using a copper source and nickle filter. Prior to heat treatments of 300° and 550° C, the specimens were K-saturated with 1 N KCl and washed free of chlorides. The X-ray diffraction patterns indicated that kaolinite was the dominant clay mineral, and that appreciable amounts of illite, vermiculite, a randomly stratified chlorite-vermiculite-montmorillonite, and quartz were present. Cation exchange capacity was 20.5 me/100 g when determined by replacing Ca with Mg, and was 11.4 me/100 g when determined by replacing K with NH_4^+. Accordingly, the vermiculite content of the clay was estimated at 5.9 percent.

Plant Analyses

For cation analyses of plant tissue, 0.5 grams of oven dry ground plant tissue was ashed in a muffle furnace at 500° C for 14 hours. After cooling, 25 ml. of 1 N HNO_3 was added, and the acid was evaporated to dryness on a hot plate over a period of 2 to 3 hours. The residue was then placed in a muffle furnace and reashed at 525° C for 10 minutes. After cooling, the residue was dissolved in 25 ml. of 1 N HCl, the resulting solution filtered into a 100 ml. volumetric flask, and Ca, K, and Mg determined in the solution as described above for the soil extract.

Statistical Analyses

All the field and laboratory analysis data from the East Lansing field experiments were subjected to analysis of variance for a completely randomized block design. The field and laboratory analysis data for the Montcalm field experiment were subjected to analysis of variance using a split plot design with the K treatment as the whole plot and potato variety as sub-plots.

Simple linear regressions were used in order to relate specific gravity to percent tuber dry matter weight, and to evaluate the effects of rate, placement, and source of K on the levels of the various nutrients in the petioles. The least significant differences (lsd) is used to denote the statistical differences between treatments.

RESULTS AND DISCUSSION

Rate and Placement of Potassium on Hodunk Sandy Loam in 1967

An experiment was conducted on Hodunk sandy loam in 1967 to determine the effects of rate and placement of K on yields, specific gravity, percent dry weight of tubers, and the K, Ca, and Mg contents of petioles, leaves, vines (or tops) and tubers of Sebago potatoes.

Yields of Potatoes

In 1967, yields of potatoes on Hodunk sandy loam were increased when K was applied (Tables 1 and 2); the highest yields were obtained when 200 pounds of K per acre was broadcast. The maximum yield, obtained when 200 pounds of K was broadcast, was significantly higher (0.01 level) than when no K was applied. When 400 pounds of K was broadcast, the yield was lower than when 200 pounds was broadcast, but it was not significantly lower. No statistically significant differences were noted between comparable rates of banded and broadcast K, but yields when K was banded were consistently lower than when similar rates were broadcast.

Specific Gravity

The specific gravity of the tubers decreased as the rate of K increased (Table 1). For both the banded and the

Table 1. Yield, specific gravity, and percent dry weight of tubers and dry weight of potato vines as affected by rate and placement of K on Hodunk sandy loam in 1967.

Pounds K per acre		Tubers				Vines
Banded	Broadcast	Yield cwt/A	Specific gravity	Percent dry wt	Pounds/A dry wt	Pounds/A dry wt
0	--	251	1.084	20.9	2,948	1,570
50	--	353	1.083	19.5	3,854	1,743
100	--	320	1.081	19.6	3,514	1,589
200	--	380	1.079	18.5	3,957	1,687
400	--	357	1.072	17.2	3,448	2,015
--	100	333	1.080	19.1	3,571	1,482
--	200	426	1.079	18.7	4,453	1,835
--	400	405	1.074	18.8	4,262	1,751
lsd (.05)		63	0.003	1.4	732	ns
(.01)		82	0.004	1.9	975	ns

Table 2. Significant differences of Sebago potato yields as related to rate and placement of K on Hodunk sandy loam in 1967.

Treatments compared	Probability level
Banded:	
No K vs K (All rates)	.01
50 vs 100 lbs and 200 lbs	ns
100 vs 200 lbs and 400 lbs	ns
200 vs 400 lbs	ns
Broadcast:	
No K vs K (All rates)	.01
100 vs 200 lbs	.01
100 vs 400 lbs	.05
200 vs 400 lbs	ns
Banded K vs broadcast K	ns
200 banded vs 200 broadcast	ns
lsd (.05)	63
lsd (.01)	82

broadcast treatments, the specific gravity was lower (0.01 level) when K was applied at a rate of 400 pounds per acre than when applied at 200 pounds.

Percent Dry Weight of Tubers

As was the case with specific gravity, the percent dry weight of tubers decreased as the rate of both banded and broadcast K was increased. The percent dry weight was significantly less when 400 pounds of K was banded than when no K was applied or when 50 or 100 pounds was banded.

Total dry matter produced per acre was directly related to tuber yields (Table 1). Thus, even though increasing the rate of K decreased the dry matter content of the tuber as measured by either specific gravity or percent dry weight, the total dry matter produced per acre was increased when the yields increased.

Yield of Vines

The vine yields, in terms of dry matter per acre, were not affected by rate or placement of K (Table 1).

Potassium Concentration in Petioles and Leaves

At mid-season (69 days after planting), the K concentration in the petioles increased with each additional increment of banded K and with each increment of broadcast K up to 200 pounds per acre (Table 3). However, the increase in petiole K when 50 and 100 pounds of banded K and 100 pounds of broadcast K were applied was not significantly higher than when no K was applied. No differences were noted in the K content of petioles between comparable banded and broadcast treatments, although petiole K when 100 and 200 pounds of K were broadcast was slightly higher than when the same rates were banded.

In the leaves, the K concentration also increased for each additional increment of applied K for both banded and broadcast treatments (Table 3), although the increased level of leaf K when 50 and 100 pounds K were applied was not significantly higher than when no K was applied. No differences were apparent when banded and broadcast treatments were compared. The concentration of K in the leaves was only about one-third of that in the petioles for all comparable treatments.

Potassium Concentration in Vines

The K concentration in potato vines increased with increasing rates of both banded and broadcast K (Table 4), although only in the 200 and 400 pound rates was the K concentration significantly higher than that when no K was applied. No differences in K concentration of the vines were noted between similar rates of banded and broadcast K.

The level of K in the vines was lower than that of either the petioles or leaves (Tables 3 and 4) on comparable treatments.

Potassium Concentration in Tubers

The K concentration in the tubers, calculated on a dry-weight basis, increased with each increment of applied K

Table 3. Potassium, calcium, and magnesium concentrations in petioles and leaves in early season (69 days after planting) as affected by rate and placement of K on Hodunk sandy loam in 1967.

		Cation content (%)					
Pounds K per acre		Petioles			Leaves		
Banded	Broadcast	K	Ca	Mg	K	Ca	Mg
0	0	6.59	1.04	0.77	1.78	1.66	0.77
50	--	7.34	1.06	0.58	2.27	1.41	0.68
100	--	7.45	0.94	0.50	2.31	1.29	0.66
200	--	8.67	0.91	0.48	2.66	1.31	0.66
400	--	10.09	0.76	0.37	3.28	1.16	0.59
--	100	7.64	0.91	0.46	2.37	1.46	0.69
--	200	9.40	0.89	0.47	2.65	1.25	0.66
--	400	9.16	0.76	0.32	2.99	1.12	0.60
lsd (.05)		2.06	.15	.19	.39	.18	.07
lsd (.01)		2.81	.21	.27	.54	.25	.10

(Table 4), and the increase when 200 and 400 pounds K were applied was significantly higher than when no K was applied. Although not statistically significant, K content of tubers tended to be higher when K was banded than when K was broadcast.

The K content of the tubers was higher than that of the vines (Table 4) for comparable treatments, but was lower than that of petioles and leaves (Table 3).

Potassium Uptake by Vines and Tubers

The uptake of K per acre by both vines and tubers increased as the rates of both banded and broadcast K increased (Table 5). The K uptake by vines was higher (0.01 level) when 400 pounds of K was applied, both banded and broadcast, than for any of the other rates of application, and the uptake of K when 400 pounds was applied was higher (0.01 level) when K was banded than when broadcast.

The uptake of K by tubers was higher than that of vines, as would be expected because of both the higher dry matter yields and the higher K content of the tubers. Recovery of applied K tended to be low, only about 20 to 25 percent of that applied when recovery is calculated as the difference between K uptake when K fertilizer was applied and K uptake when no K was applied.

Calcium Concentration in Petioles and Leaves

The Ca concentration in petioles at mid-season (69 days after planting) decreased as the rate of K increased for both banded and broadcast K applications (Table 3); however, this decrease was statistically significant only when 200 or 400 pounds K were applied. The effect of K on decreasing Ca concentrations in the petioles was similar for both banded and broadcast treatments.

The Ca concentration in the leaves also decreased with increasing rates of K for both banded and broadcast applications (Table 3). The Ca concentration in the leaves was consistently higher than that of the petioles.

Calcium Concentration of Vines

The Ca concentration of the vines decreased as the rate of K increased, but this decrease was not statistically significant except when 400 pounds of K was applied (Table 4). No differences due to placement of K were noted.

Calcium Concentration in Tubers

The Ca concentration in the tubers was not affected by any of the K treatments, and the levels found were extremely low, averaging 0.77 percent (Table 4).

Calcium Uptake by Vines and Tubers

The uptake of Ca by vines and tubers was not affected by either rate or placement of K (Table 5). The vines contained about 10 times as much Ca as the tubers.

Magnesium Concentration in Petioles and Leaves

The magnesium concentration in petioles decreased as rate of K increased (Table 3), and this decrease tended to

Table 4. Potassium, calcium and magnesium concentration in vines (150 days after planting) and tubers as affected by rate and placement of K on Hodunk sandy loam in 1967.

Pounds K per acre		Cation content (%)					
		Vines			Tubers		
Banded	Broadcast	K	Ca	Mg	K	Ca	Mg
0	--	0.51	2.26	1.01	1.58	0.07	0.11
50	--	0.92	1.99	0.91	1.72	0.12	0.12
100	--	0.85	1.93	0.84	1.91	0.07	0.12
200	--	1.42	1.90	0.78	2.14	0.07	0.12
400	--	2.48	1.63	0.71	2.46	0.06	0.12
--	100	0.86	2.09	0.93	1.88	0.07	0.11
--	200	1.12	1.89	0.81	2.08	0.06	0.11
--	400	2.14	1.71	0.74	2.25	0.06	0.12
lsd (.05)		.54	.38	.15	.25	ns	ns
(.01)		.74	.52	.21	.34	ns	ns

Table 5. Uptake of potassium, calcium and magnesium by potato vines and tubers as affected by rate and placement of K on Hodunk sandy loam in 1967.

Pounds K per acre		Uptake of K (lbs/A)			Uptake of Ca (lbs/A)			Uptake of Mg (lbs/A)		
Banded	Broadcast	Vine	Tubers	Total	Vine	Tubers	Total	Vine	Tubers	Total
0	--	8.1	46.7	54.8	35.3	2.3	37.6	15.9	3.2	19.1
50	--	15.1	67.1	82.3	35.0	4.9	39.9	16.2	4.6	20.8
100	--	14.1	67.1	81.2	31.5	2.8	34.3	13.7	4.2	17.9
200	--	24.0	84.3	108.3	32.4	2.9	35.3	13.7	4.7	18.4
400	--	50.6	84.8	135.4	32.8	2.0	34.8	14.5	4.1	18.6
--	100	13.6	66.8	80.4	30.4	2.9	33.3	13.7	3.9	17.6
--	200	20.3	92.6	112.9	34.6	2.6	38.2	15.0	4.9	19.9
--	400	36.5	96.0	132.5	30.1	2.5	32.6	12.9	5.1	19.0
lsd (0.5)		11.5	16.9	--	ns	ns	--	ns	ns	--
(0.1)		15.4	22.6	--	ns	ns	--	ns	ns	--

be relatively greater when K was broadcast than when banded, but not significantly greater.

The Mg concentration in the leaves decreased significantly as the rate of K was increased for both banded and broadcast applications of K. No differences in Mg concentration were noted due to band or broadcast placement of K. The concentration of Mg in leaves was about the same as that of the petioles when no K was applied, but the decrease in Mg when K was applied was relatively greater in the petioles than in the leaves.

Magnesium Concentration in Vines

The Mg concentration of vines decreased as the rate of K increased for both the band and the broadcast applications (Table 4). This decrease in Mg concentration was statistically significant for all rates of applied K except when 50 pounds was banded. The relative decrease in Mg concentration tended to be greater, but not significantly greater, when K was banded than when broadcast.

Magnesium Concentration in Tubers

The Mg concentration in tubers was not affected by K rate or placement (Table 4).

Magnesium Uptake by Vines and Tubers

The uptake of Mg by vines and tubers was not affected by either rate or placement of K (Table 5). The total uptake of Mg was slightly less than 20 pounds per acre, and the vines contained approximately four times as much Mg as the tubers.

Exchangeable Soil Potassium

In soil samples taken at mid-season (70 days after planting), exchangeable K was not affected when fertilizer K was banded, and the level of exchangeable K tended to be lower than that before planting (Table 6 and Figure 1). This indicates that the plants were absorbing soil K as well as banded fertilizer K. On the other hand, the level of exchangeable K on the plots where K fertilizer was broadcast increased as the rate of K increased (Table 6 and Figure 2). Whenever fertilizer K was broadcast, exchangeable K was equal to or higher than the initial exchangeable K before planting.

Exchangeable K at late season (170 days after planting) showed more variation than the initial and mid-season exchangeable K, and increased as the rate of either banded or broadcast K was increased. However, only when 400 pounds K was banded was the exchangeable K on any of the banded treatments higher than the initial level of exchangeable K. When K was broadcast, exchangeable K at 170 days was lower than the initial level only when 100 pounds was broadcast.

The total uptake of K by vines and tubers (Table 6) when no K was applied was about 30 percent greater than the decrease in exchangeable K during the season (Table 3), indicating either that a significant amount of non-exchangeable

Table 6. Exchangeable soil K, Ca, and Mg before planting, at mid-season, and late season (0, 70 and 170 days after planting respectively) as affected by rate and placement of K on Hodunk sandy loam in 1967.

Pounds K per acre		K (lbs/A)			Ca (lbs/A)			Mg (lbs/A)		
		Days after planting			Days after planting			Days after planting		
Banded	Broadcast	0	70	170	0	70	170	0	70	170
0	0	136	114	97	939	975	855	101	124	121
50	--	126	118	116	812	855	897	98	108	105
100	--	132	130	130	854	848	855	105	121	111
200	--	142	126	130	855	932	975	98	117	114
400	--	136	128	158	728	812	770	92	108	95
--	100	136	136	113	848	982	1025	108	134	127
--	200	134	144	150	855	854	855	89	117	101
--	400	134	164	179	897	813	897	101	105	105
lsd (.05)		ns	20	29	ns	ns	ns	ns	ns	ns
lsd (.01		ns	28	39	ns	ns	ns	ns	ns	ns

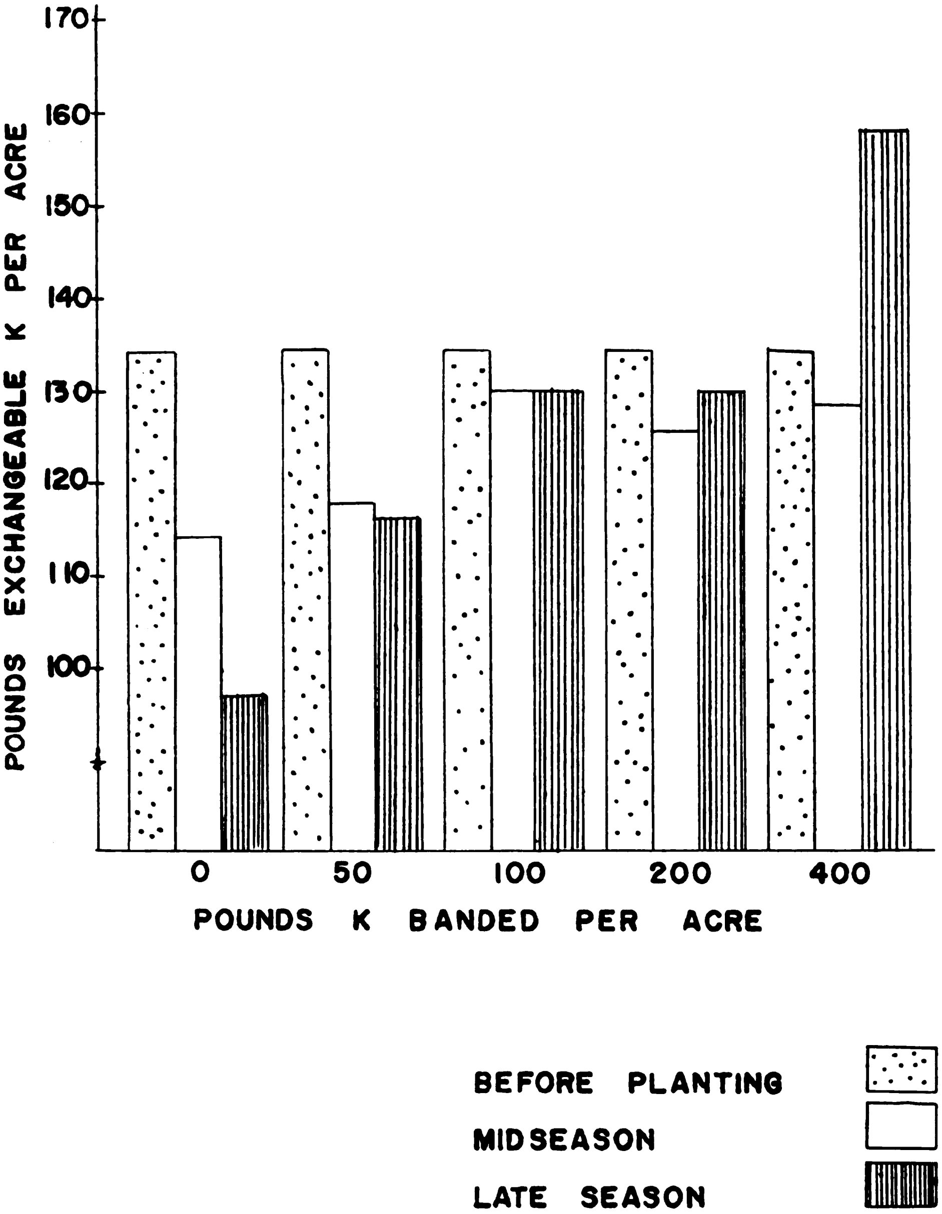


Figure 1. Exchangeable potassium before planting, at mid-season, and late season, (0, 70 and 170 days after planting, respectively) as affected by rates of K applied banded on Hodunk sandy loam in 1967.

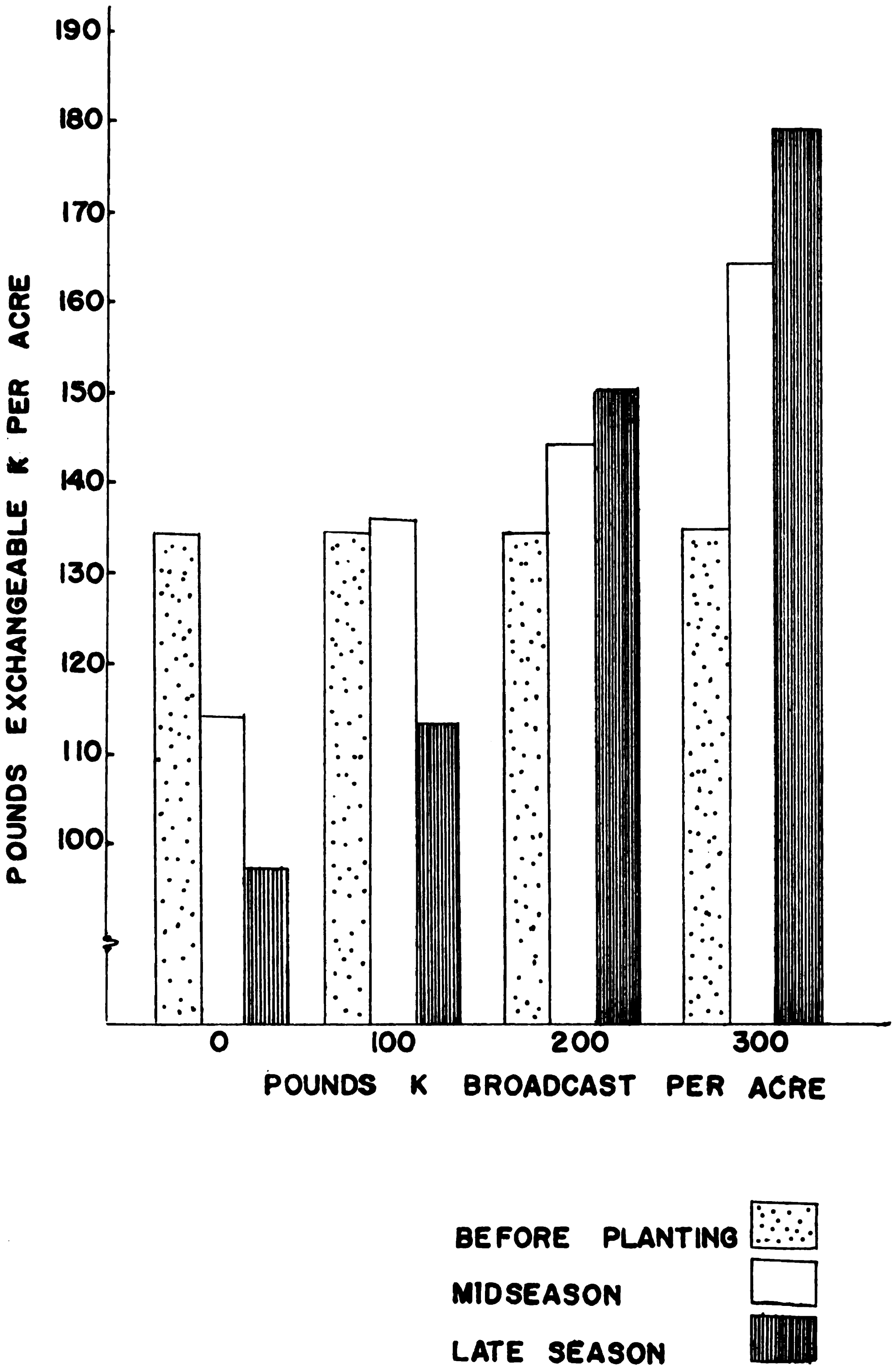


Figure 2. Exchangeable potassium (1 N NH_4OA_c pH 7.0) before planting, at mid-season, and late season (0, 70 and 170 days after planting, respectively) as affected by rates of K applied broadcast on Hodunk sandy loam in 1967.

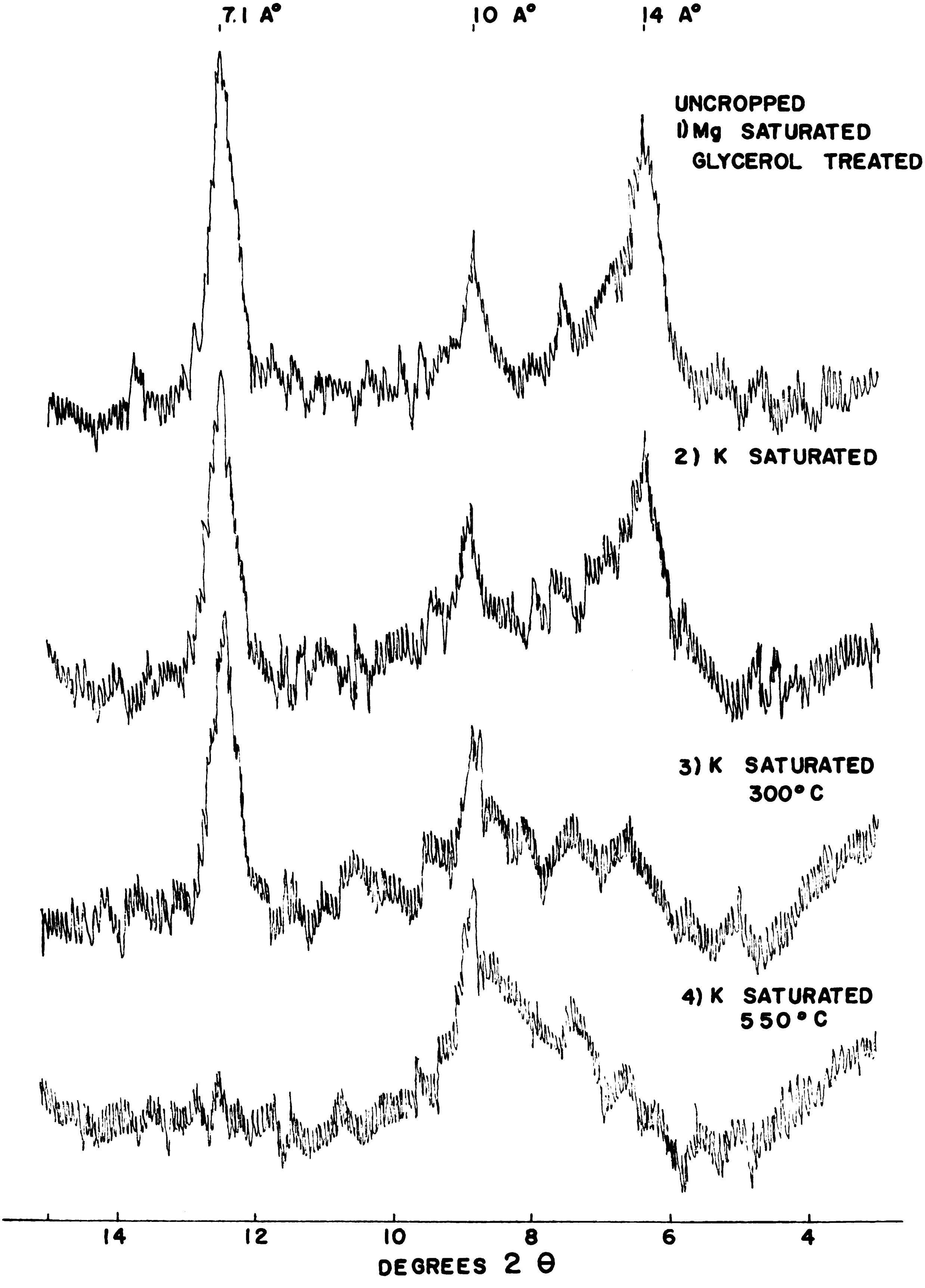


Figure 3. X-ray diffraction patterns for coarse clay (0.2 - 2.0 u) of Hodunk sandy loam soil.

K was released during the season or that a considerable portion of the K absorbed by the plant came from below the plow layer. On the other hand, when 400 pounds of K was broadcast, exchangeable K was increased by 45 pounds, and the vines and tubers contained 132.5 pounds; this leaves 22.5 pounds of the original 400 pounds which was either fixed or leached below the plot layer. This soil would be expected to fix and release K since illite and vermiculite are important clays in this soil (Figure 3).

Exchangeable Soil Calcium

Exchangeable Ca in the soil during the growing season was not affected by the K fertilizer treatments (Table 6).

Exchangeable Soil Magnesium

Exchangeable Mg during the growing season was not affected by the application of K fertilizers (Table 6).

Relation Between Yields and Soil Potassium

In order to describe the relation between yields at the initial level of soil K and the rate of K fertilizer, the Mitscherlich equation (as given by Bray, 1945) was used:

$$\text{Log } (A - y) = \text{Log } A - c_1 b_1$$

in which *A* was the maximum yield obtained (426 cwt/A or 100%), *y* the yield when no K was applied (251 cwt/A or 59%), and b_1 the level of exchangeable K prior to applying fertilizer (135 pounds/acre). The calculations are as follows:

$$c_1 = \frac{\text{Log } A - \text{Log } (A - y)}{b_1} = \frac{2.62941 - 2.24304}{135} = 0.00287$$

Using the preceding calculated value for c_1 (0.00287), the curve relating yield to exchangeable soil K was drawn (Figure 4). This curve relates yield only to level of soil K, and indicates that maximum yields would be obtained at a soil test level of about 400 pounds of exchangeable K.

In order to relate the rate of applied fertilizer K to yields, the modified Misterlich equation proposed by Bray (1945) was used:

$$\text{Log } (A - y) = \text{Log } A - (c_1 b_1 - cx)$$

in which $\underline{c}$ is the constant for fertilizer K and $\underline{x}$ is the rate of fertilizer K. The following calculations were made, equating the maximum yield (A) of 426 cwt. to 100%, equating the yield for $\underline{y}$ of 333 cwt. to 78% when $\underline{x}$ or rate of K is 100 pounds broadcast, and using the same values of 0.00287 and 135 for $\underline{c_1}$ and $\underline{b_1}$ respectively:

$$\text{Log } (100 - 78) = \text{Log } 100 - (0.00287 \times 135 - 100\ \underline{c})$$

$$0.34242 = 2.00000 - 0.38722 - 100\ c$$

$$c = \frac{0.27036}{100} = 0.00270$$

The complete equation then becomes:

$$\text{Log } (A - y) = \text{Log } A - (0.00287\ b_1 - 0.00270\ x)$$

For practical use, fertilizer recommendations were developed to calculate the amount of fertilizer needed to obtain a yield equivalent to 95% of the maximum possible yield. Calculations were made using the above equation from which:

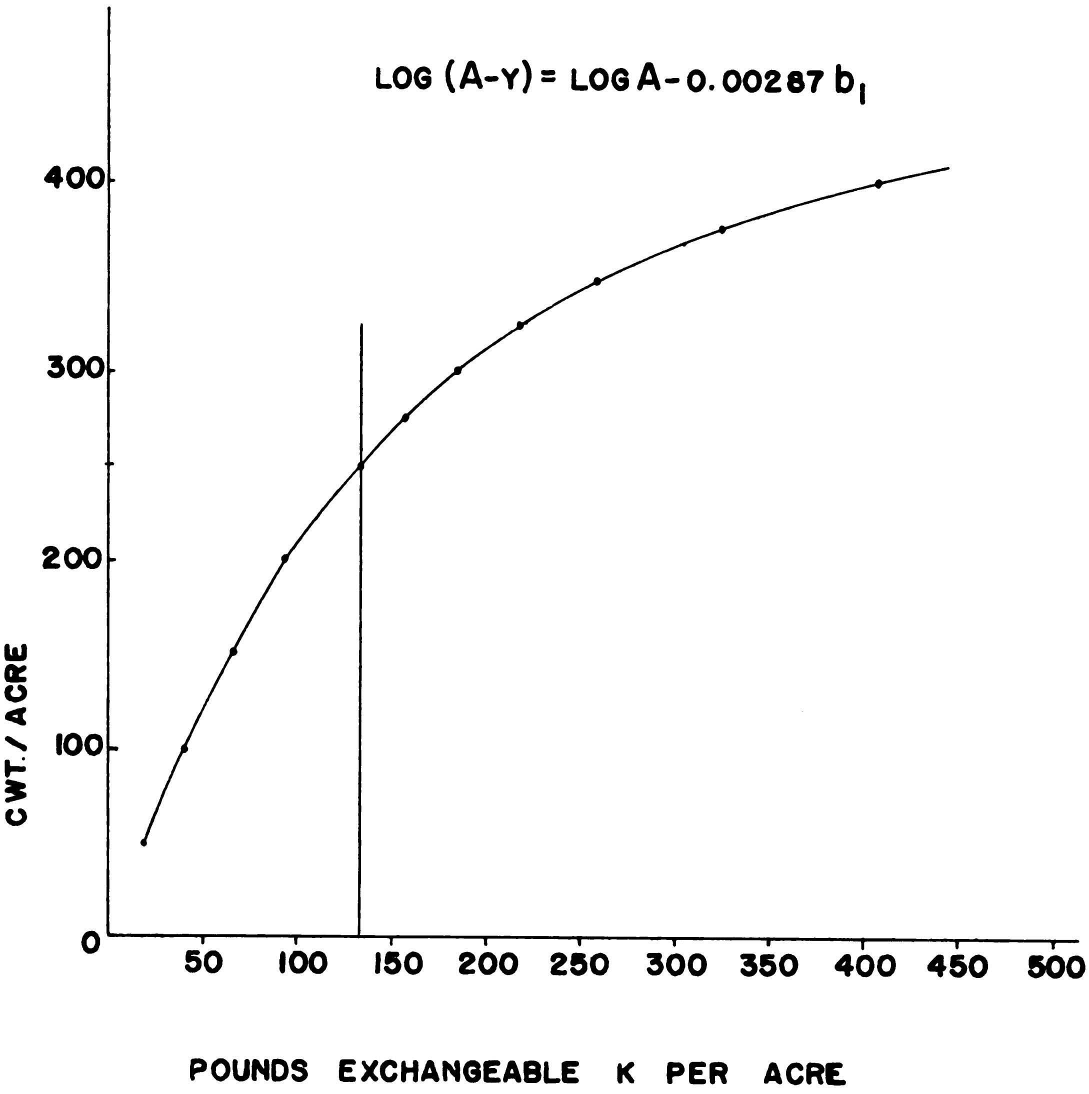


Figure 4. Mitscherlich response curve relating yield to exchangeable soil K (Hodunk sandy loam, 1967).

$$\text{Log}\ (100 - 95) = \text{Log}\ 100 - (0.00286\ b_1 - 0.00270\ x)$$

$$x = \frac{1.30103 - 0.00287\ b_1}{0.00270}$$

From this equation, the rate of fertilizer required to obtain 95 percent of the maximum yield (x) can be calculated for any soil test level (b_1), or a graph such as that shown in Figure 5 can be constructed.

The soil test calibration developed here represents the results of only one year at one location, and would not be adequate for general fertilizer recommendations. However, it does describe the response obtained at this location, and illustrates a method that can be used to calibrate soil tests.

Rate, Source, and Placement of Potassium on Hodunk Sandy Loam in 1968

Another experiment was conducted on Hodunk sandy loam in 1968 to determine the effect of the effects of rate and placement of KCl and rate of broadcast K_2SO_4 and K_2CO_3 on yields, specific gravity, and chemical composition of petioles of Sebago potatoes.

Yield of Potatoes

In 1968, the yields increased when K was applied (Table 7), and the highest yield was obtained when 200 pounds of K was broadcast as KCl. When K as KCl was banded, yields tended to be slightly lower than for the comparable broadcast treatments, although these differences were not statistically significant (Table 8).

No significant differences in yields were noted due to the different sources of K (Tables 7 and 9), but yields tended to be higher when 200 and 400 pounds K were applied as KCl than when the same rates were applied as K_2SO_4 or K_2CO_3.

When 40 pounds per acre of Mg was banded with 400 pounds of K broadcast as KCl, K_2SO_4, or K_2CO_3, yields were not different than those obtained when the same sources of K were broadcast without banded Mg. When sulfate of potash-magnesia was banded, and supplemented with K_2SO_4 so that a total of 400 pounds of K and 40 pounds of Mg were applied, yields were not different from those obtained with comparable rates of the other sources of broadcast K when Mg was applied, or when the same amount of K was banded as KCl without Mg.

Specific Gravity of Potatoes

The specific gravity decreased as the rate of K was increased (Table 7); and when KCl was applied, the specific gravity was significantly lower (0.01 level) than when K_2SO_4 or K_2CO_3 were applied.

It should be mentioned that the anion CO_3^{+2} will react with soil hydrogen ions (H^+) and form water and carbon dioxide, and thus does not add to the salt content of the soil. This may have had some effect which caused the

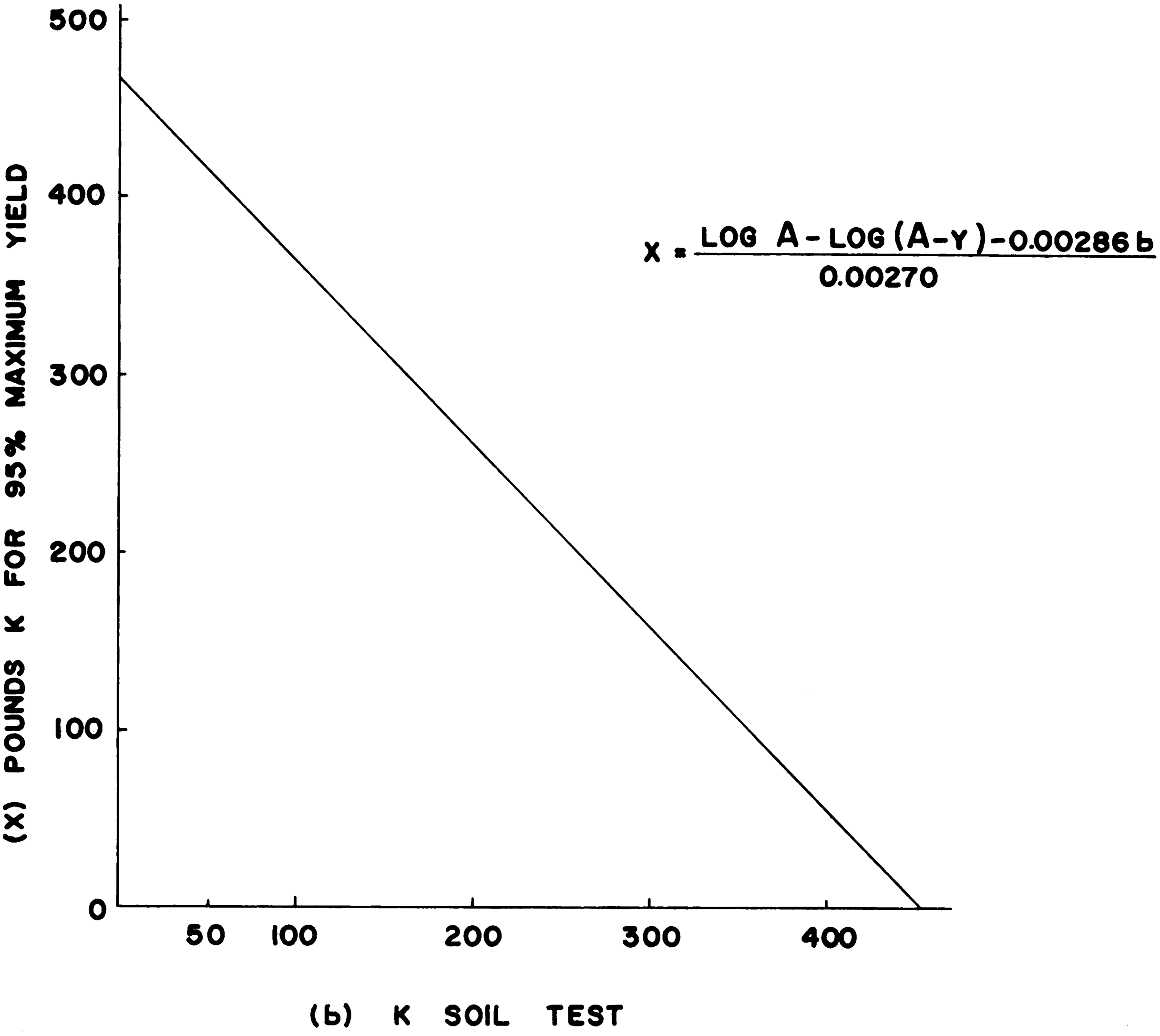


Figure 5. Relationship between soil test value and rate of K application for expected 95% maximum yield response (Hodunk sandy loam, 1967).

Table 7. Yield and specific gravity of Sebago potatoes as related to source, rate and placement of K on Hodunk sandy loam in 1968.

Source of K	Pounds K per acre		Pounds Mg per acre	Yield cwt/A	Specific gravity
	Banded	Broadcast	Banded		
None	--	--	--	404	1.083
KCl	--	100	--	426	1.083
KCl	--	200	--	477	1.079
KCl	--	400	--	459	1.077
KCl	--	800	--	435	1.075
K_2SO_4	--	200	--	426	1.082
K_2SO_4	--	400	--	416	1.079
K_2SO_4	--	800	--	441	1.079
K_2CO_3	--	200	--	434	1.083
K_2CO_3	--	400	--	454	1.079
K_2CO_3	--	800	--	438	1.082
KCl	100	--	--	416	1.083
KCl	200	--	--	441	1.082
KCl	400	--	--	450	1.080
KCl	--	400	40	469	1.077
K_2SO_4	--	400	40	417	1.076
K_2CO_3	--	400	40	417	1.081
K_2SO_4Mg	400	--	40	445	1.081
lsd (.05)				53	0.004
(.01)				70	0.005

Table 8. Significant differences of Sebago potato yields as related to rate and placement using potassium chloride (KCl) as a source of K fertilization on Hodunk sandy loam in 1968.

Comparison	Probability level
Banded:	
No K vs K (All rates)	ns
100 vs 200 lbs and 400 lbs	ns
Broadcast:	
No K vs K (All rates)	ns
No K vs 200	.01
No K vs 400	.05
No K vs 800	ns
100 vs 200 lbs and 400 lbs	ns
200 vs 400 lbs and 800 lbs	ns
lsd (.05)	53
lsd (.01)	70

Table 9. Significant differences of Sebago potato yields as affected by sources and rates of K on Hodunk sandy loam in 1968.

Comparison	Probability level
Sources:	
No K vs K sources (All sources)	ns
KCl vs K_2SO_4	ns
KCl vs K_2CO_3	ns
K_2SO_4 vs K_2CO_3	ns
Rates and Sources:	
200 lbs KCl vs 200 lbs K_2SO_4 and 200 lbs K_2CO_3	ns
400 lbs KCl vs 400 lbs K_2SO_4 and 400 lbs K_2CO_3	ns
800 lbs KCl vs 800 lbs K_2SO_4 and 800 lbs K_2CO_3	ns
200 lbs KCl vs 400 K_2SO_4	.05
Sources and Magnesium:	
400 lbs (All sources) vs 400 lbs (All sources) + 40 lbs Mg	ns
lsd (.05)	53
lsd (.01)	70

differential reaction of K_2CO_3 with respect to decreasing the specific gravity.

Potassium Concentration in Petioles

The potassium concentration in the petioles at early season (60 days after planting) increased as the rate of K increased for all the K sources (Table 10). When 200 and 800 pounds of K per acre were applied broadcast, the K concentration was lower (0.01 level) when K_2CO_3 was applied than when KCl or K_2SO_4 was applied (Figure 6).

At mid-season (98 days after planting) the K concentration was generally lower than that at early season (Table 10 and Figure 6), but the K concentration still increased with increasing rates of K.

At late season (130 days after planting) the K concentration was generally lower than that obtained at mid-season, although the K concentration still increased as the rate of K increased (Table 10).

It is interesting to note that when K_2SO_4 was the source of K, a fairly uniform increase in K concentration was noted as the rate of applied K increased at each of the three sampling dates, while K concentrations in petioles showed more variability at early and mid-season when KCl and K_2CO_3 were the sources of K. The K concentration in petioles was not affected by K placement, although K in petioles tended to be higher when K as KCl was banded at early season than when broadcast, but it tended to be lower on banded treatments at mid and late season.

Table 10. Potassium concentration (%) in petioles of Sebago potatoes in early season, mid-season and late season (60, 98 and 130 days after planting, respectively) as affected by source and rate of K on Hodunk sandy loam in 1968.

Fertilizer treatment				Potassium content (%)		
	Pounds K per acre		Pounds Mg per acre			
Source of K	Banded	Broadcast	Banded	60 days	98 days	130 days
None	--	--	--	7.72	3.89	1.98
KCl	--	100	--	9.01	5.67	2.15
KCl	--	200	--	10.55	6.52	3.05
KCl	--	400	--	10.50	8.33	5.06
KCl	--	800	--	13.01	8.39	6.62
K_2SO_4	--	200	--	10.25	6.72	3.22
K_2SO_4	--	400	--	10.60	7.48	4.03
K_2SO_4	--	800	--	12.50	8.96	5.77
K_2CO_3	--	200	--	8.61	5.89	3.29
K_2CO_3	--	400	--	10.70	7.40	4.27
K_2CO_3	--	800	--	10.55	7.96	5.31
KCl	100	--	--	9.95	5.23	2.01
KCl	200	--	--	10.75	6.55	2.76
KCl	400	--	--	12.70	8.15	4.26
KCl	--	400	40	11.80	8.33	5.24
K_2SO_4	--	400	40	10.35	7.63	4.52
K_2CO_3	--	400	40	10.30	6.61	4.05
K_2SO_4Mg	400	--	40	11.45	6.05	2.74
lsd (.05)				1.34	1.12	1.02
(.01)				1.79	1.50	1.30

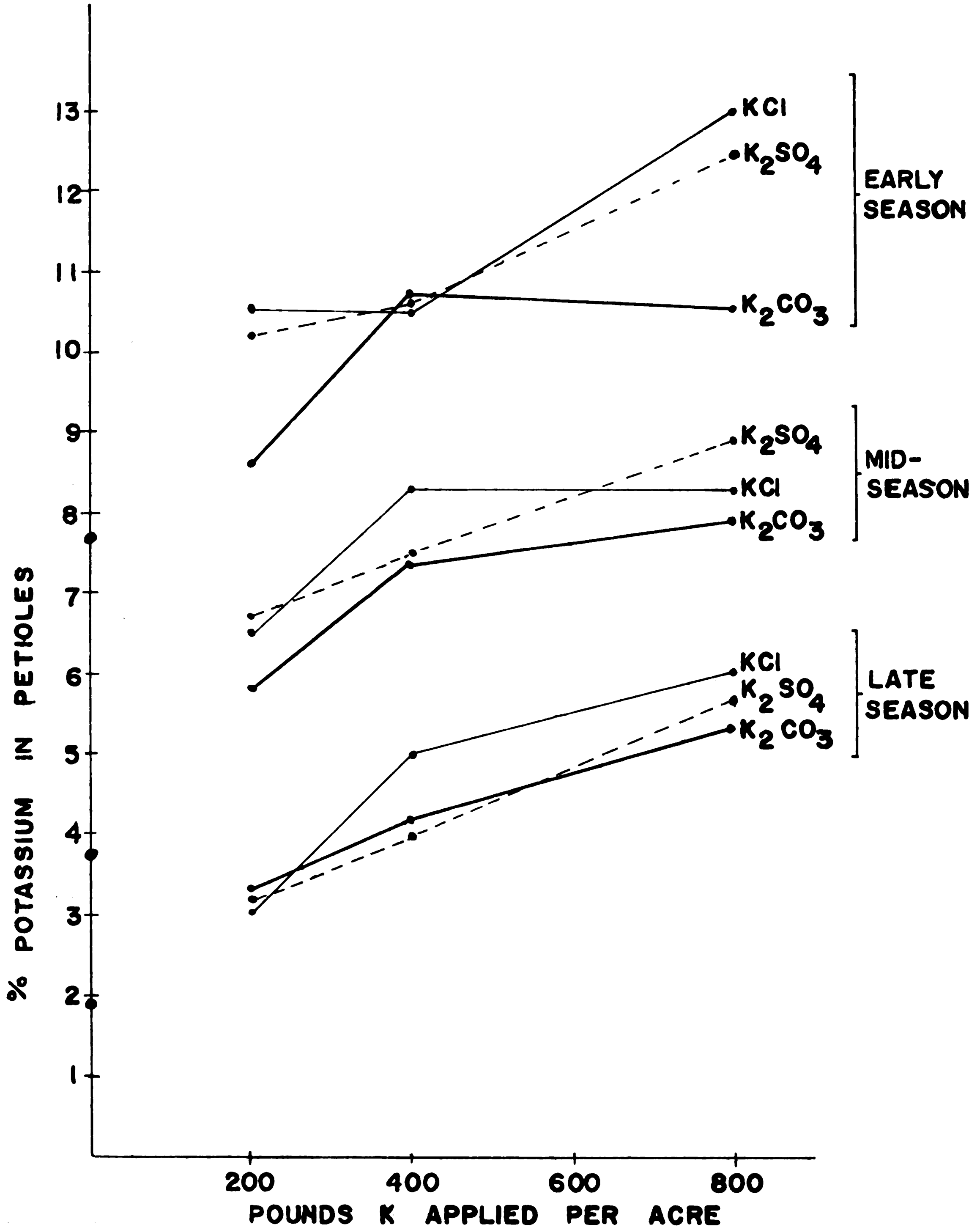


Figure 6. Effect of rate and source of K on the K concentration in petioles at early season, mid-season and late season.

Applying Mg in the fertilizer band did not affect K in petioles except that K was lower when sulfate of potash-magnesia, supplemented by K_2SO_4, was banded.

Potassium Concentration in Tubers

The K concentration of the tubers tended to increase when K fertilizers were applied (Table 11), but no differences due to the different sources of K were noted.

No differences in K concentration in the tubers were noted between banded and broadcast applications of KCl, or when Mg was applied.

Calcium Concentration in Petioles

The Ca concentration in petioles at the early season sampling (60 days after planting) was decreased when K fertilizers were applied, but at the mid- and late season samplings (98 and 130 days after planting), Ca concentration was not affected, even though it tended to be lower in mid-season when K was applied (Table 12).

The Ca concentration in the petioles at early season was lowest when K_2SO_4 was applied, but no differences were noted between KCl and K_2CO_3. When KCl was banded, Ca in petioles tended to be lower than when KCl was broadcast, but this difference was not statistically significant. Applying Mg in the fertilizer band did not affect Ca concentration in petioles.

Table 11. Percent of potassium, calcium, and magnesium in mature tubers as affected by source and rates of K on Hodunk sandy loam in 1968.

Source of K	Pounds K per acre		Pounds Mg per acre	Tubers, content in (%)		
	Banded	Broadcast	Banded	K	Ca	Mg
None	--	--	--	1.52	0.04	0.12
KCl	--	100	--	1.59	0.03	0.16
KCl	--	200	--	1.96	0.03	0.24
KCl	--	400	--	1.91	0.03	0.20
KCl	--	800	--	2.36	0.03	0.19
K_2SO_4	--	200	--	2.27	0.03	0.25
K_2SO_4	--	400	--	1.99	0.04	0.21
K_2SO_4	--	800	--	2.44	0.04	0.29
K_2CO_3	--	200	--	1.98	0.03	0.23
K_2CO_3	--	400	--	2.02	0.04	0.23
K_2CO_3	--	800	--	2.00	0.04	0.20
KCl	100	--	--	1.73	0.02	0.21
KCl	200	--	--	1.85	0.05	0.21
KCl	400	--	--	2.26	0.04	0.22
KCl	--	400	40	2.45	0.03	0.21
K_2SO_4	--	400	40	2.11	0.04	0.12
K_2CO_3	--	400	40	1.72	0.04	0.14
K_2SO_4Mg	400	--	40	2.02	0.03	0.26
lsd (.05)				.45	ns	ns
(.01)				.57	ns	ns

Table 12. Calcium concentration (%) in petioles of Sebago potato in early season, mid-season, and late season (60, 98 and 130 days after planting, respectively) as affected by source and rate of K on Hodunk sandy loam in 1968.

Source of K	Pounds K per acre		Pounds Mg per acre	Calcium content (%)		
	Banded	Broadcast	Banded	60 days	98 days	130 days
None	--	--	--	1.77	1.42	1.17
KCl	--	100	--	1.57	1.18	1.39
KCl	--	200	--	1.60	1.33	1.34
KCl	--	400	--	1.33	1.23	1.28
KCl	--	800	--	1.38	1.18	1.28
K_2SO_4	--	200	--	1.28	1.24	1.28
K_2SO_4	--	400	--	1.09	1.08	1.34
K_2SO_4	--	800	--	1.09	1.09	1.22
K_2CO_3	--	200	--	1.62	1.28	1.28
K_2CO_3	--	400	--	1.47	1.23	1.45
K_2CO_3	--	800	--	1.28	1.14	1.39
KCl	100	--	--	1.41	1.48	1.28
KCl	200	--	--	1.24	1.13	1.39
KCl	400	--	--	1.09	1.18	1.17
KCl	--	400	40	1.19	1.23	1.28
K_2SO_4	--	400	40	1.28	1.08	1.45
K_2CO_3	--	400	40	1.28	1.28	1.34
K_2SO_4Mg	400	--	40	1.19	1.19	1.28
lsd (.05)				.28	ns	ns
(.01)				.35	ns	ns

Calcium Concentration in Tubers

The Ca concentration in the tubers was not affected by either rate or source of K fertilizer (Table 11).

Magnesium Concentration in Petioles

The Mg concentration in petioles decreased as the rate of K increased at each of the three sampling dates except at the late season sampling when 100 pounds of K was applied as KCl (Table 13).

At the early season sampling, Mg in petioles tended to be higher when KCl was applied than when K_2SO_4 or K_2CO_3 was applied, except when 200 pounds of K was applied as K_2CO_3 (Figure 7).

When KCl was banded at planting, Mg in petioles tended to be lower, but not significantly lower, than when KCl was broadcast. Applying 40 pounds of Mg fertilizer in the band at planting did not affect Mg levels in petioles.

At the mid-season sampling, Mg levels in petioles were consistently higher than at the early season sampling, and Mg concentrations in the petioles decreased as the rate of K was increased. When K_2SO_4 was applied, Mg in petioles was lower than when KCl or K_2CO_3 was applied.

Again, Mg in petioles appeared to be slightly higher, but not significantly higher, when KCl was banded than when KCl was broadcast. The levels of Mg in petioles were not increased when Mg fertilizer was banded at planting.

At the late season sampling, Mg in petioles was higher than for all comparable treatments at the mid-season

Table 13. Magnesium concentration (%) in petioles of Sebago potato in early season, mid-season and late season (60, 98 and 130 days after planting, respectively) as affected by source and rate of K on Hodunk sandy loam in 1968.

Source of K	Pounds K per acre		Pounds Mg per acre	Magnesium content (%)		
	Banded	Broadcast	Banded	60 days	98 days	130 days
None	--	--	--	0.99	1.02	1.55
KCl	--	100	--	0.83	1.08	1.66
KCl	--	200	--	0.65	1.03	1.48
KCl	--	400	--	0.63	0.82	1.37
KCl	--	800	--	0.47	0.67	1.25
K_2SO_4	--	200	--	0.58	0.90	1.21
K_2SO_4	--	400	--	0.56	0.66	1.06
K_2SO_4	--	800	--	0.39	0.56	0.90
K_2CO_3	--	200	--	0.80	1.02	1.18
K_2CO_3	--	400	--	0.53	0.77	0.99
K_2CO_3	--	800	--	0.44	0.65	0.89
KCl	100	--	--	0.76	1.29	1.71
KCl	200	--	--	0.49	1.01	1.39
KCl	400	--	--	0.37	0.82	1.40
KCl	--	400	40	0.60	0.91	1.37
K_2SO_4	--	400	40	0.57	0.64	1.04
K_2CO_3	--	400	40	0.61	0.84	1.16
K_2SO_4Mg	400	--	40	0.52	0.92	1.49
lsd (.05)				.27	.29	.28
(.01)				.36	.37	.37

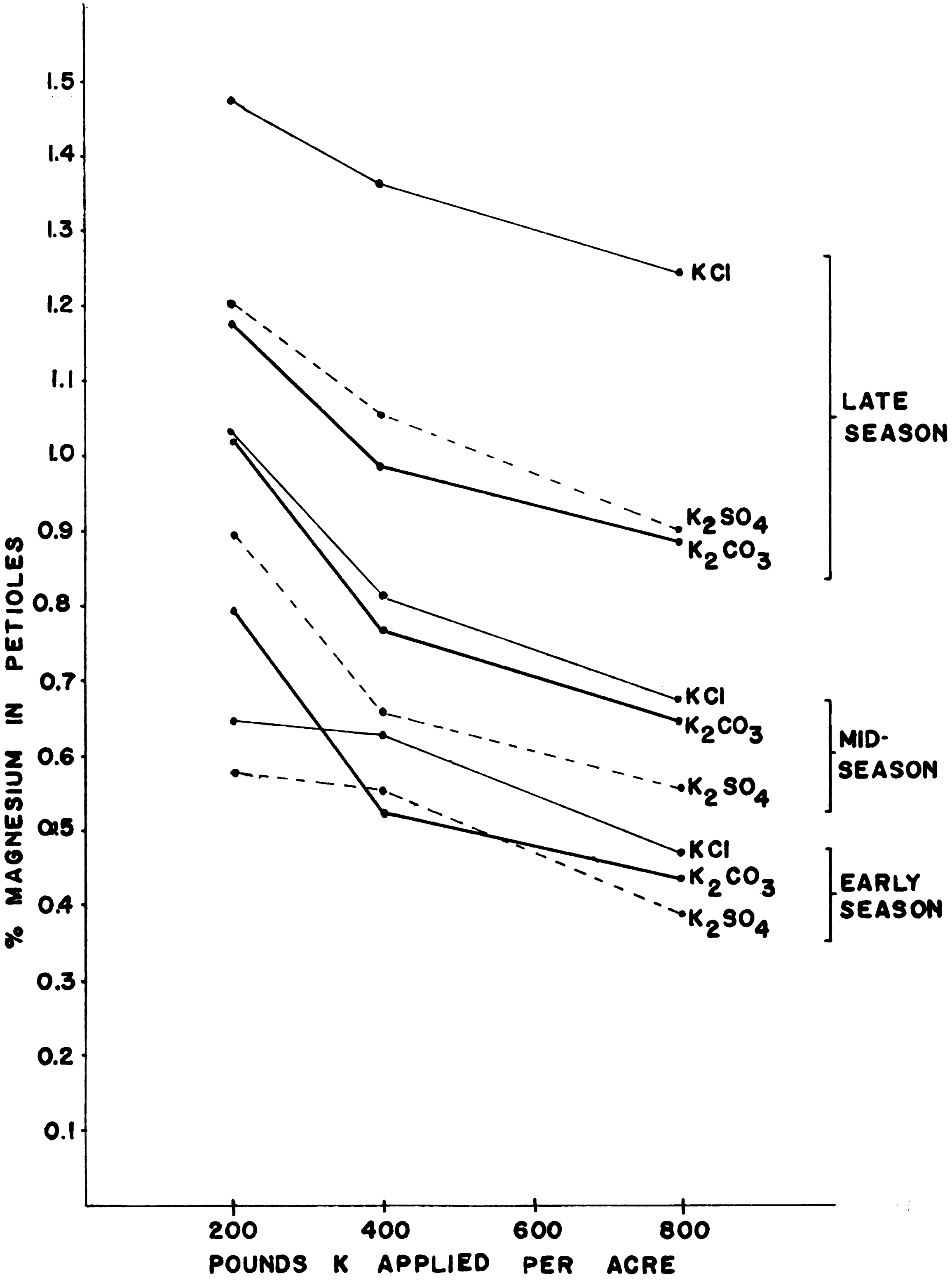


Figure 7. Effect of rate and sources of K in the Mg concentration in petioles at early season, mid-season and late season.

sampling, and Mg levels again decreased as the rate of K fertilizer increased. The level of Mg in petioles was markedly higher when KCl was applied than when K_2SO_4 or K_2CO_3 was applied. No differences in petiole Mg levels were apparent between banded and broadcast applications of KCl. Petiole Mg was not increased when Mg fertilizers were banded at planting. At no time was the uptake of Mg either increased or decreased when sulfate of potash-magnesia was used as a source of K and Mg.

It was apparent that at the late season sampling, the anion accompanying the K in the fertilizer affected the Mg concentration in the petioles, and the differences found in the decrease of Mg in petioles due to the different K sources were relatively greater than at the earlier samplings.

Magnesium Concentration in Tubers

The Mg concentration in tubers was not affected by rate or source of K fertilizer (Table 12).

Rate and Placement of Potassium on McBride Sandy Loam in 1968

The experiment on McBride sandy loam in 1968 was conducted to determine the effects of rate and placement of K on yields, and the Ca, K, and Mg concentrations in petioles of Sebago and Russet Burbank potatoes.

Yield of Potatoes

The yields of both Sebago and Russet Burbank potatoes were increased when K fertilizer was applied (Table 14), but statistical analyses of the data do not indicate that these differences are significant.

The highest yield of Sebago potatoes was obtained when 100 pounds of K was banded at planting, and the highest yield of Russet Burbank potatoes was obtained when 200 pounds of K was banded. Higher yields were obtained with Sebago potatoes than with Russet Burbank potatoes.

Potassium Concentration in Petioles

At the early season sampling (60 days after planting), K in the petioles of Sebago potatoes was increased only when 200 pounds of K was banded at planting and when 400 pounds K (300 pounds broadcast plus 100 banded) was applied (Table 15). In Russet Burbank petioles, K was increased by all rates of applied K except when 50 pounds was applied (either broadcast or banded). No consistent differences were noted between banded and broadcast applications of K, but K in petioles of Sebago potatoes tended to be slightly higher when K was banded. No differences were apparent between the K content of Sebago and Russet Burbank potatoes, although the difference in K content between the low and the high rates of K seemed to be greater in Russet Burbanks.

At mid-season (96 days after planting), the K concentration in petioles of both varieties was lower than at the

Table 14. Yield of Sebago and Russet Burbank potatoes as affected by rate, placement and time of K on McBride sandy loam in 1968.

Pounds K per acre			Sebago	Russet Burbank
Broadcast	Banded	Total	Yield cwt/A	Yield cwt/A
0	0	0	268	218
0	50	50	304	247
0	100	100	324	250
0	150	150	316	246
0	200	200	318	272
300	100	400	294	252
50	0	50	316	262
100	0	100	317	248
200	0	200	307	250
lsd (.05)			ns	ns
lsd (0.5) treatment x variety			ns	ns

Table 15. Potassium concentration (%) in petioles of Sebago and Russet Burbank potatoes in early and mid-season (60 and 96 days after planting, respectively) as affected by rate, placement and time of K on McBride sandy loam in 1968.

Pounds K per acre			Potassium content (%)			
			Sebago		Russet Burbank	
Broadcast	Banded	Total	60 days	96 days	60 days	96 days
0	0	0	10.20	6.56	9.21	5.99
0	50	50	10.13	6.01	9.98	6.92
0	100	100	10.26	7.33	10.50	7.58
0	150	150	9.93	7.09	10.89	7.97
0	200	200	11.97	8.24	13.64	8.99
300	100	400	11.41	8.93	11.82	10.12
50	0	50	9.65	6.62	10.00	7.22
100	0	100	10.00	7.09	10.99	8.65
200	0	200	10.02	6.87	11.59	9.24
Mean			10.47	7.25	10.89	8.05
lsd (.05)			.93	.73	.93	.73
(.01)			1.26	.99	1.26	.99
lsd (.05) treatment x variety			ns	.46	ns	.46
(.01)			ns	.63	ns	.63

early season sampling, and differences in K content due to K fertilizer treatment were more marked. The K content in petioles of both varieties was increased when K was applied except when 50 pounds K (either banded or broadcast) was applied to Sebago potatoes. No differences were noted between broadcast and banded applications of K. Except when no K was applied, petiole K was higher in Russet Burbank potatoes than in Sebago potatoes.

The differences in K concentration at early season and mid-season indicate that the petiole K concentration is related to the potato variety, and that these differences due to variety tend to increase as the plant matures. Also, at mid-season, the highest petiole K concentration in the Sebago variety was obtained when the K was banded, and in the Russet Burbank variety, the highest petiole K was obtained when the K was broadcast. These tendencies could very well be the effects of differences in the root systems of the two varieties and/or in their ability to absorb K from the soil.

Calcium Concentration in Petioles

The Ca concentration of the petioles was not affected by rate or placement of K at either the early or mid-season sampling date for either variety (Table 16). The petiole Ca in both varieties was higher at mid-season than early season. No differences were noted in petiole Ca between the two varieties at the early season sampling, but petiole

Ca in Russet Burbanks at mid-season was higher than that of Sebagos.

Magnesium Concentration in Petioles

The Mg concentration in the petioles of the Sebago and Russet Burbank varieties was not affected by either rate or placement of fertilizer K at either the early or the mid-season sampling (Table 17). However, the data tended to be extremely variable; at mid-season, petiole Mg tended to decrease in both varieties as the rate of K was increased, especially in the Sebago variety. When these results are compared with those of the two experiments on Hodunk sandy loam, the differences obtained here are greater than significant differences on the other experiments.

The Mg in petioles of both varieties increased about sevenfold from the early to the mid-season sampling. The Mg concentration in petioles of both varieties at early season appears to be at or near the deficiency level, especially for the Sebago variety. Doll and Hossner (1964) reported Mg deficiency in Sebago potatoes when Mg concentration in petioles was less than 0.15 percent.

Table 16. Calcium concentration (%) in petioles of Sebago and Russet Burbank potatoes, in early and mid-season (60 and 96 days after planting, respectively) as affected by rate placement and time of K on McBride sandy loam in 1968.

Pounds K per acre			Calcium content (%)			
			Sebago		Russet Burbank	
Broadcast	Banded	Total	60 days	96 days	60 days	96 days
0	0	0	0.62	0.95	0.67	0.95
0	50	50	0.67	1.00	0.59	1.22
0	100	100	0.62	0.84	0.67	1.17
0	150	150	0.67	0.84	0.73	0.78
0	200	200	0.67	0.84	0.56	0.84
300	100	400	0.56	0.89	0.56	0.78
50	0	50	0.72	0.89	0.73	1.11
100	0	100	0.67	0.84	0.78	0.89
200	0	200	0.78	1.06	0.62	1.06
Mean			0.65	0.90	0.68	1.02
lsd (.05)			ns	ns	ns	ns
lsd (.05) treatment x variety			ns	ns	ns	ns

Table 17. Magnesium concentration (%) in petioles of Sebago and Russet Burbank potatoes, in early and mid-season (60, and 96 days after planting, respectively) as affected by rate, placement and time of K on McBride sandy loam in 1968.

Pounds K per acre			Magnesium content (%)			
			Sebago		Russet Burbank	
Broadcast	Banded	Total	60 days	96 days	60 days	96 days
0	0	0	0.09	1.10	0.18	1.28
0	50	50	0.07	1.13	0.14	1.60
0	100	100	0.09	0.79	0.12	1.40
0	200	200	0.11	0.72	0.23	1.26
0	250	250	0.16	0.77	0.12	1.23
300	100	400	0.13	0.50	0.16	0.84
50	0	50	0.13	0.93	0.18	1.40
100	0	100	0.10	0.70	0.16	1.10
200	0	200	0.15	0.96	0.17	0.98
Mean			0.11	0.83	0.17	1.23
lsd (.05)			ns	ns	ns	ns
lsd (.05) treatment x variety			ns	ns	ns	ns

SUMMARY AND CONCLUSIONS

EFFECT OF RATE, PLACEMENT AND SOURCE OF POTASSIUM ON YIELD AND MINERAL CONTENT OF POTATOES

Three field experiments with potassium fertilization of potatoes were conducted: one on Hodunk sandy loam in 1967 to determine the effects of rate and placement of K, another on Hodunk sandy loam in 1968 to determine the effects of rate, source and placement of K, and the third on McBride sandy loam in 1968 to determine the effects of rate and placement of K for Russet Burbank and Sebago potatoes.

Yields of potatoes appeared to be related to level of exchangeable soil K, since the most marked yield response was obtained in 1967 on Hodunk sandy loam at an exchangeable K level of 135 pounds per acre, a lesser response on Hodunk sandy loam in 1968 at a level of 160 pounds, and the least response on McBride sandy loam at a level of 200 pounds K per acre. However, even though the potatoes were irrigated at all three locations, both yields and relative response to K fertilizers appeared to be affected by climatic conditions as well as level of soil K.

Yields were not affected by the placement of the K ertilizer, so that broadcast K appeared to be as effective as did banded K. No significant yield differences were noted between sources of K, although the highest yield was obtained when KCl was applied on Hodunk sandy loam in 1968. No differences were noted between Russet Burbank and Sebago potatoes with respect to relative response to K fertilizer, although actual yields were higher when Sebago potatoes were grown than when Russet Burbanks were grown.

Exchangeable soil K on Hodunk sandy loam in 1967 decreased during the growing season on plots to which no fertilizer K was applied. The level of exchangeable K on plots to which K fertilizer was broadcast increased as the rate of K increased; when 400 pounds K was broadcast, exchangeable K at harvest was 45 pounds more than the initial level before planting. The level of exchangeable soil K was not increased by band K applications except when 400 pounds K was applied, and when lower rates of banded K were applied, exchangeable soil K was less than that before planting, indicating that substantial amounts of native soil K as well as fertilizer K were being absorbed by the plants.

In general, the specific gravity and the percent dry weight of the potatoes decreased as the rate of K fertilizer was increased. When KCl was applied, the specific gravity decreased more than when K_2SO_4 and K_2CO_3 were applied, and specific gravity tended to be highest when K_2CO_3 was applied. Specific gravity and percent dry weight were significantly correlated ($r = 0.70$).

The concentration of K in petioles, leaves, vines, and tubers generally increased as the rate of K increased. The K concentrations were neither significantly or consistently affected by the placement (band or broadcast) of K fertilizer. No consistent differences in K concentration were noted due to source of K, although K frequently tended to be higher when KCl was applied and lowest when K_2CO_3 was applied. Russet Burbank petioles tended to be higher in K than Sebago potatoes. This varietal difference may have been due to either a difference in root systems of the two varieties, or to the smaller size of the Russet Burbank plants which resulted in a greater accumulation of K in the plant.

The concentration of K in the petioles was much higher at the early season samplings, and then decreased rapidly for the remainder of the growing season. This illustrates the need for evaluating the K status of the plant on the basis of physiological age if petiole analyses are to be used.

In 1967 on Hodunk sandy loam, the total uptake of K per acre (vines + tubers) varied from 55 pounds per acre when no K was applied to 135 pounds when 400 pounds K was applied. For maximum yields, about 110 pounds K was required. These figures are lower than other previously reported data (Rudgers, 1967).

The Ca concentration in petioles, leaves, and vines generally tended to decrease as the rate of K fertilizer was increased, especially at the early season sampling date. Placement of K did not affect Ca concentration in the plants. In the tubers, Ca concentration was not affected by rate of K. No significant differences in Ca concentration were noted due to source of K or potato variety. In 1967 on Hodunk sandy loam, the total uptake of Ca by vines and tubers was about 36 pounds per acre. The Ca concentration in petioles tended to increase as the potato plant matured.

The Mg concentration of the petioles, leaves, and vines generally decreased as the rate of K was increased. No consistent differences in Mg concentration were noted due to placement of K fertilizer. The Mg concentration of tubers was not affected by K fertilization. The Mg concentration of potato petioles tended to increase as the plants matured. On McBride sandy loam in 1968, Mg in petioles at the early season sampling was at or near previously reported deficiency levels. The Mg concentration in petioles was not affected by source of K fertilizer. Total uptake of Mg (vines + tubers) was about 20 pounds per acre in 1967.

These experiments can be briefly summarized as follows:

1. The relative response of potatoes to K fertilizer was related to the level of soil K, although actual yields were also affected by climatic factors.
2. Yields were decreased when rates of K applied were equal to or greater than 200 pounds banded or 400 pounds broadcast. Chemical analyses of the plants

indicate that this decrease in yield may be related to a suppression of Mg uptake at high levels of K.

3. Specific gravity and percent dry weight of potatoes decreased as the rate of K increased.
4. Concentration of K in petioles, leaves, and vines increased as the rate of K increased, while the concentration of Ca and Mg tended to decrease.
5. Broadcast and banded applications of K were generally equally effective with respect to yield and chemical composition of the potatoes.
6. As the potatoes matured, K concentration in plants decreased, and Ca and Mg concentrations increased.
7. When fertilizer K was banded, levels of exchangeable K before and after cropping indicated that native soil K as well as fertilizer K was being absorbed by the plant. No detectable effect of banded K on level of exchangeable K between the rows was observed except when 400 pounds K per acre was banded.
8. When fertilizer K was broadcast, exchangeable K increased as the rate of K increased, but a comparison of the level of soil K after cropping and of crop removal with the rate of K application indicates that a considerable portion of applied fertilizer K was either "fixed" by the soil or leached from the plow layer.

9. The total uptake (vines + tubers) of K ranged from 55 to 135 pounds K per acre, and the average uptake of Ca and Mg was 36 and 20 pounds per acre, respectively. These data are much lower than those previously reported from Michigan.

BIBLIOGRAPHY

PART I

Adams, F., and Henderson, J. B. 1962. Magnesium availability as affected by deficient and adequate levels of potassium and lime. Soil Sci. Soc. Amer. Proc. 26:65-68.

Baum, E. L., Heady, E. O., Blackmore, J. 1956. Methodological Procedures in the Economic Analysis of Fertilizer Use Data. The Iowa State College Press, Iowa.

Bear, F. E., Prince, A. L., and Malcolm, J. L. 1944. The potassium supplying power of 20 New Jersey soils. Soil Sci. 58:139-149.

Berger, K. C., Potterton, P. E., and Hobson, E. L. 1961. Yield, quality and phosphorus uptake of potatoes as influenced by placement and composition of potassium fertilizers. Amer. Potato J. 38:272-285.

Black, C. A. 1968. Soil-Plant Relationships, John Wiley Sons Inc., New York.

Boynton, D., and Burrell, A. B. 1944. Potassium: Induced magnesium deficiency in the McIntosh apple tree. Soil Sci. 58:441-454.

Bray, R. H. 1944. Soil-Plant Relations: I. The quantitative relation of exchangeable potassium to crop yields and to crop response to potash additions. Soil Sci. 58:305-324.

Bray, R. H. 1945. Soil-Plant Relations: II. Balanced fertilizer use through soil test for potassium and phosphorus. Soil Sci. 60:463-473.

Bray, R. H. 1948. Correlation of soil test with crop response to added fertilizers and fertilizer requirement. In Diagnostic Techniques for Soils and Crops. Amer. Potash Inst., Washington, D.C.

Bray, R. H. 1948. Requirements for successful soil tests. Soil Sci. 66:83-89.

Brown, B. A. 1938. Fertilizer for Potatoes. Conn. Agric. Exp. Sta. Bull. 223.

Brown, B. A. 1944. Soil Fertility Experiments with Potatoes. Amer. Potato J. 21:163-169.

Carolus, R. L. 1933. Some significant variations in the chemical composition of the plant associated with a malnutrition trouble of potatoes. Amer. Potato J. 10:147-165.

Chucka, J. A., Hawkins, A., and Brown, B. E. 1944. Potash source. Fertilizer placement. Maine Agric. Exp. Sta. Rept. of Progress, Bull. 426, pp. 247 and 248.

Cook, R. L., and Millar, C. E. 1953. Plant nutrient deficiencies. Michigan Agric. Exp. Sta Special Bull. 353, p. 34.

Corbett, E. G., and Gausman, H. W. 1960. The interaction of chloride with sulfate and phosphate in the nutrition of potato plants (solanum tuberosum). Agron. J. 52:94-96.

Crowther, E. M., and Yates, F. 1941. Fertilizer policy in wartime: the fertilizer requirements of arable crops. Empire J. Exp. Agric. 9:77-97.

Cummings, G. A., and Houghland, G. V. C. 1939. Fertilizer placement for potatoes. U.S.D.A. Tech. Bull., 669.

Doll, E. C., and Christenson, D. R. 1966. Routine soil test determination of magnesium using an atomic absorption spectrophotometer. Quart. Bull. Mich. Agric. Exp. Sta., East Lansing, Mich. 49:216-220.

Doll, E. C., and Hossner, L. R. 1964. Magnesium deficiency as related to liming and potassium levels in acid sandy podzols. 8th Intern. Congress of Soil Sci., Bucharest, Romania. 4:907-912.

Doll, E. C., and Thurlow, D. L. 1965. Soil management and fertilization for potatoes grown on mineral soils. Mich. Agric. Exp. Sta. Res. Report 31.

Dunn, L. E., and Nylund, R. E. 1945. The influence of fertilizers on the specific gravity of potatoes grown in Minnesota. Amer. Potato J. 22:275-288.

Dunn, L. E., and Rost, C. O. 1948. Effect of fertilizers on the composition of potatoes in the Red River Valley of Minnesota. Soil Sci. Soc. Amer. Proc. 13:374-379.

Grantham, G. M., Millar, C. E., and Mick, A. H. 1939. Soil management for potatoes. Michigan Agric. Exp. Sta. Spec. Bull., 299.

Harrap, F. E. G. 1960. Some aspects of the potash nutrition of the potato. J. Sci. Food Agric. 11:293-298.

Hart, T. G., and Smith, O. 1966. Effects of levels and sources of potassium on absorption of phosphorus by potato plants. Amer. Potato J. 43:217-235.

Hawkins, A. 1965. New ways of fertilizing potatoes. Amer. Potato J. 42:76-77.

Hawkins, A., Chucka, J. A., and Brown, B. E. 1944. Fertilizer ratio test. Maine Agric. Exp. Sta. Rept. of Progress Bull. 438, p. 548.

Hawkins, A., Chucka, J. A., and Brown, B. E. 1946. Rate of potash test. Maine Agric. Exp. Sta. Rept. of Progress Bull. 442, p. 162.

Hossner, L. R., Doll, E. C., and Thurlow, D. L. 1968. Effect of magnesium fertilization on yield and magnesium uptake by potatoes (Manuscript in press).

Houghland, G. V. C. 1964. Nutrient deficiencies in the potato. Hunper Signs in Crops a Symposium. Chapter IV. David McKay Co., New York, pp. 223-225.

Houghland, G. V. C., and Shricker, F. A. 1933. The effect of potash on starch in potatoes. J. Amer. Soc. Agron. 25:334-340.

Hovland, D., and Caldwell, A. C. 1960. Potassium and magnesium relationship in soils and plants. Soil Sci. 89:92-96.

Jackson, M. L. 1958. Soil Chemical Analysis. Prentice Hall, Inc., Englewood Cliffs, New Jersey.

James, W. D. 1930. Studies of the physiological importance of the mineral elements in plants. I. The relationship of potassium to the properties and functions of leaves. Ann. Botany. 44:173-198.

Jones, J. O., and Plant, W. 1942. Note on the composition of leaves from potato manurial experiment. Annual Rept. Agric. Hort. Res. Sta., Long Ashton, Bristol, Eng. 44-45.

Knolewles, F., and Cowie, G. A. 1940. Some effects of fertilizer interactions on growth and composition of the potato plant. J. Agric. Sci. Camb. 30:159-181.

Latzko, E. 1955. Relations between chloride and sulfate nutrition, intensity of assimilation, enzyme activity, carbohydrate metabolism, and quality of potatoes. Z. Pflanzenernahr. Dung. Bodenk. 68:49-55.

Laughlin, W. M. 1966. Effect of soil applications of potassium, magnesium sulfate and magnesium sulfate spray on potato yield; composition and nutrient uptake. Amer. Potato J. 43:403-411.

Lorenz, O. A. 1947. Studies on potato nutrition. III. Chemical composition and uptake of nutrients by Kern County potatoes. Amer. Potato J. 24:281-293.

Lorenz, O. A., Bishop, J. C., Hoyle, B. J., Zobel, M. P., Minges, P. A., Doneen, L. D., and Ulrich, A. 1954. Potato fertilizer experiments in California. Calif. Agric. Exp. Sta. Bull. 744.

Lucas, R. E., and Scarseth, G. D. 1947. Potassium, calcium, and magnesium balance and reciprocal relationship in plants. J. Amer. Soc. Agron. 39:887-896.

Lucas, R. E., Wheeler, E. J., and Davis, J. F. 1954. Effect of potassium carrier and phosphate-potash ratios on the yield and quality of potatoes grown on organic soils. Amer. Potato J. 31:349-352.

MacKay, D. C., MacEachern, C. R., and Bishop, R. F. 1959. The relation of soil test values to fertilizer response by the potato. I. Nitrate production and crop yield. Can. J. Soil Sci. 39:144-150.

McColloch, R. C., Bingham, I. T., and Aldrich, D. G. 1957. Relation of soil potassium and magnesium nutrition of citrus. Soil Sci. Soc. Amer. Proc. 21:85-88.

McCollum, R. E., Hageman, R. H., and Tyner, E. H. 1958. Influence of potassium on pyruvic kinase from plant tissue. Soil Sci. 86:324-331.

Mc Murstrey, Jr., J. E. 1948. Visual symptoms of malnutrition in plants. Diagnostic Techniques for Soils and Crops. p. 276. Amer. Potash Inst., Washington 6, D.C.

Mehlich, A., and Reed, J. F. 1946. The influence of degree of saturation potassium level, and calcium additions on removal of calcium, magnesium and potassium. Soil Sci. Soc. Amer. Proc. 10:87-93.

Melsted, S. W. 1967. Growth curves and soil test correlations. Mimeograph Article. Univ. of Illinois.

Mortland, M. M. 1959. Potassium supplying power of Michigan soils. Michigan Fertilizer Conference Proceedings.

Mulder, E. G. 1959. Effect of the mineral nutrition of potato plants on the biochemistry and physiology of the tubers. Neth. J. Agric. Sci. 4:333-356.

Murphy, H. J., Goven, M. J. 1965. Influence of source of potash on yield specific gravity, and surface russeting of the Russet Burbank variety in Maine. Amer. Potato J. 42:192-194.

Murphy, H. J., Goven, M. T. 1966. The last decade in 38 years of potash studies for potato fertilizers in Maine. Amer. Potato J. 43:122-127.

Nelson, W. L. and Hawkins, A. 1947. Response of Irish potatoes to phosphorus and potassium on soils having different levels of these nutrients in Maine and North Carolina. J. Amer. Soc. Agron. 39:1053-1067.

Pierre, W. H., and Bower, C. A. 1943. Potassium absorption by plants as affected by cationic relationships. Soil Sci. 55:23-36.

Prince, F. S. 1940. Response of potatoes to fertilizers. New Hampshire Agric. Exp. Sta. Bull. 324:3-18.

Rowberry, R. G., Sherrell, C. G., and Johnston, G. R. 1963. Influence of rates of fertilizer and sources of potassium on the yield, specific gravity and cooking quality of Katahdin potatoes. Amer. Potato J. 40:177-181.

Rudger, L. A. 1967. The evaluation of various magnesium carriers when applied with mixed fertilizers. M.S. Thesis, Michigan State University.

Salmon, R. C. 1963. Magnesium relationships in soils and plants. J. Sci. Fd. Agric. 14:605-610.

Scheele, C. V., Swensson, G., and Rasmusson, J. 1936. Determination of the starch and dry matter content of potatoes by means of specific gravity. Landw. Vers. Sta. 127:67-69.

Shickluna, J. C. 1962. The relationship of pH, available phosphorus, potassium and magnesium to soil management groups. Mich. Agr. Exp. Sta. Quart. Bull. 45:136-147.

Smith, O. 1950. Using the potato hydrometer in choosing potatoes for chipping. Natl. Potato Chip Inst. Potatoes Article 12:1-2.

Smith, J. A., and Sheard, R. W. 1957. Evaluation and calibration of phosphorus soil test methods for predicting fertilizer requirements of potatoes. Can. J. Soil Sci. 37:134-142.

Stanford, G., Kelly, J. B., and Pierre, W. H. 1942. Cation balance in corn grown on high lime soils in relation to K deficiency. Soil Sci. Soc. Amer. Proc. 6:335-341.

Terman, G. L. 1949. Effect of source of potash in the fertilizer on yield and starch content of potatoes. Amer. Potato J. 26:291-299.

Terman, G. L. 1950. Effect of rate and source of potash on yield and starch content of potatoes. Maine Agric. Exp. Sta. Bull. 481.

Terman, G. L., Carpenter, P. N., and Cunningham, C. E. 1953. Relation of soil and fertilizer potassium to dry matter content and yield of potatoes. Soil Sci. 75:449-458.

Terman, G. L., Carpenter, P. N., and Junkins, S. C. 1949. Nutrient content of potato plants as affected by fertilizer treatment and other factors. Soil Sci. Soc. Amer. Proc. 14:137-141.

Thatchter, R. W. 1912. The Chemistry of Plant Life. New York, Mc Graw-Hill Book Co.

Timm, H., and Merkle, F. G. 1963. The influence of chlorides on yield and specific gravity of potatoes. Amer. Potato J. 40:1-8.

Tyler, K. B., Lorenz, O. A., and Fullmer, F. S. 1960. I. Plant and soil analyses as guides in potato nutrition. California Agric. Expt. Sta. Bull. 781.

Ulrich, A., and Ohki, K. A. 1966. Diagnostic criteria for plants and soils. Edited by Homer Chapman. University of California, Div. of Agric. Sci. p. 369.

Wallace, T. 1951. The Diagnosis of Mineral Deficiencies in Plants by Visual Symptoms. A colour atlas and guide. Her Majesty's Stationary Office, London. V.5, p. 72.

Walsh, T., and O'Donohoe, R. I. 1945. Magnesium deficiency in some crop plants in relation to the level of potassium nutrition. J. Agric. Sci. 35:254-263.

Ward, G. M. 1959. Potassium in plant metabolism. II. Effect of potassium upon the carbohydrate and mineral composition of potato plants. Can. J. Plant Sci. 39:246-252.

Ware, L. M. 1939. Fertilizer requirements of the potato on different soils of Alabama. Amer. Potato J. 16:255-266.

Wilcox, G. E. 1961. Effect of sulfate and chloride sources and rates of potassium on potato growth and tuber quality. Amer. Potato J. 38:215-220.

PART II

PHOSPHORUS FORMS AND EQUILIBRIA IN SELECTED PERUVIAN SOILS

PHOSPHORUS FORMS AND EQUILIBRIA
IN SELECTED PERUVIAN SOILS

INTRODUCTION

The soils of Peru vary as much as those of any country in the world because of the large differences in climate, topography, parent material, and vegetation in the different parts of the country. A comprehensive review of the soils of Peru has been given by Drossdoff _et_ _al_. (1960). The formation of unavailable forms of phosphorus is known to occur when fertilizer phosphorus is applied, so that phosphorus fixation is significant in both alkaline and acid soils.

Insofar as the writer knows, no comprehensive study has been conducted with Peruvian soils to characterize the fixation of applied phosphorus and to determine the chemical forms of soil phosphorus which govern its availability to plants.

It is of considerable importance, therefore, to characterize the phosphorus fractions and to evaluate the phosphorus fixation and equilibria reactions in Peruvian soils. The study reported here was conducted to: (1) characterize the different phosphorus fractions in selected coastal, mountain, and jungle soils of Peru, and (2) study the capacity of these soils to fix added phosphorus by means of adsorption isotherms, and (3) identify the compounds formed when added P is fixed by these soils by means of phosphate potentials and solubility diagrams.

LITERATURE REVIEW

Phosphorus Fixation in Soils

The exact mechanism(s) involved in the fixation of phosphorus (P) by soils is not well understood, but the following three possibilities have been suggested: (a) adsorption of P by the soil complex, (b) the P in solution is precipitated thus becoming a part of the solid phase (oldest theory), and (c) P immobilization due to microbial uptake.

Since little is known about the role of the microorganisms in P immobilization and since their role in mineral soils does not appear of great importance, no discussion of microbial action will be included.

Absorption of P by Clay Minerals

Kelley and Midgley (1943), Scarseth (1935), and Stout (1939) all indicated a possible reversible exchange reaction between phosphate and hydroxyls at the edges of the clay lattices. Murphy (1939) indicated that finely ground kaolinite showed a very high retention of P, with the maximum absorption occurring at pH 4. His conclusions were supported by the decrease in P retention with increasing pH and the release of P when soils were extracted with dilute NaOH.

Black (1942), Coleman (1945), Ellis and Truog (1955) and Coleman (1960) all indicated that the fixation of P by clay minerals is a result of the alteration of the clay crystal by the P solution releasing of free Al^{+3} and Fe^{+3} which then precipitates the phosphates.

Fixation of P by hydrated oxides of Fe and Al can result from a simple substitution of P for hydroxyl ions.

The theory that P is fixed by a system in which cations are the linking force has been suggested. Ravikovitch (1934) indicated that a H_2PO_4-Ca-Clay system could be formed. Wild (1953) found an increase in P fixation by clay either with monovalent or divalent cations, which could indicate that the added P can react directly with Ca adsorbed on the clay surfaces or with the surface ions of $CaCO_3$ in neutral or alkaline soils (Cole *et al.* 1953).

Chemical Precipitation of P

The chemical precipitation of P is the oldest theory of P fixation and has been described by Bradfield *et al.* (1935) who postulated three separate mechanisms that could overlap each other. At pH 2 to 5, the retention is chiefly due to the gradual dissolution of iron and aluminum oxides, which then are reprecipitated as phosphates. At pH 4.5 to 7.5, P is fixed on the surface of clay particles, and at pH 6 to 10, P is precipitated by divalent cations in the soil solution.

Aluminum and iron phosphates could be present in the soil as the isomorphus series variscite (aluminum phosphate), redondite (Ferrian-variscite), barrandite (aluminum-strengite), or strengite (iron phosphate), (Freed and Shapiro, 1960).

In neutral or alkaline soils, P can be precipitated by Ca in soil solution (Midgley, 1940; Freed and Shapiro, 1960). The nature of the intermediate CaP compounds formed are not clearly defined but they are of the apatite structure $(CaF)Ca_4(PO_4)_3$. Henwall (1957) indicated that apatite is quite stable, and permits unusual types of substitutions that could involve a large number of ions.

Determination of the Fixing Capacity of the Soils

Determinations of the P-fixing capacity of soils are usually made by either (1) measuring the decrease in the concentration of aqueous P in equilibrium with soils, or (2) measuring the amount of P extracted from soils equilibrated with P compounds. Both principles are based upon the concept that P concentrations at the interface between the liquid and the solid system, a phenomenon called adsorption. Although adsorption is not clearly defined as a specific P fixation mechanism, the amount of P taken up by soils is proportional to the concentration.

It has been postulated by Russell and Prescott (1961), Davis (1935), and Kurtz et al. (1946) that the adsorption of phosphorus by soils can be described by the equation of Freundlich.

$$\frac{x}{m} = KC^{n}$$

Although the Freundlich isotherm is applicable to large amounts of absorbed P, it is not possible to calculate adsorption maximum. Olsen and Watanabe (1957), therefore, proposed the use of the Langmuir adsorption isotherm, based in the kinetic theory of gases and used to describe gas absorption on solids (Langmuir, 1918).

The equation as used in soils is:

$$\frac{x}{m} = \frac{Kbc}{1} + Kc$$

where x/m = mg of P absorbed per 100 g of soil, b = absorption maximum, c = equilibrium P concentration in moles per liter, and K = a constant related to the bonding energy of the absorbent for the absorbate. A linear form of the equation is given by:

$$\frac{c}{x/m} = \frac{1}{kb} + \frac{c}{b}$$

in this form the slope = 1/b, and the intercept = 1/kb, or K = slope/intercept.

Olsen and Watanabe (1957), by using the Langmuir isotherm, calculated the maximum absorption of P by acid as well as by alkaline soils; they indicated that the acid soils retained more P per unit of surface area and also held the P with a greater bonding energy than alkaline soils.

The use of the Langmuir isotherm in soils of the Latin-American tropics has been reported by Fassbender (1966).

Forms of Inorganic Phosphorus in Soils

Three different procedures have been used to characterize the forms of inorganic soil P: (1) direct observations using X-ray diffraction techniques, infrared spectroscopy, electron microscopy, or DTA analysis, (2) the use of phase diagrams based upon solubility product concepts; and (3) extraction with different chemical solutions.

Direct Observations

The real contribution of the use of direct observations appears to be questionable quantitatively, because of the difficulty of separating the P forms of the soils and the actual danger of altering the P compounds by any physical separation. Perhaps the most interesting use of this technique in identifying the composition of products formed by the addition of different fertilizers has been performed by Lindsay *et al*. (1962), who identified more than 30 crystalline products of variable composition as well as colloidal precipitates in soils from Tennessee, Iowa and Arizona.

Phase Solubility Diagrams

The use of solubility criteria of pure P compounds to identify forms of P in soils has been used by Aslyng (1954), Clarke and Peech (1955), Larsen and Court (1961), and

Lindsay and Moreno (1960). Aslyng (1954) plotted P potential ($\frac{1}{2}$pCa + pH_2PO_4) against lime potential (pH - $\frac{1}{2}$pCa) of soils and constructed a phase diagram for comparison with known CaP compounds. He found that when large amounts of superphosphate are added, dicalcium and/or octocalcium phosphate are initially formed in calcareous soils, and that these compounds are then slowly converted to a more basic CaP, presumably hydroxyapatite. Clarke and Peech (1955) represented the solubilities of CaP in a single solubility diagram in which pH_2PO_4 + $\frac{1}{2}$pCa and pH - $\frac{1}{2}$pCa were used as coordinates; when a $CaCO_3$ solid phase was present, the chemical potential of lime (pH - $\frac{1}{2}$pCa) depended upon the partial pressure of CO_2 in the atmosphere, leading them to conclude that monocalcium phosphate cannot persist in soils and that hydroxyapatite is the probable predominant solid phase in neutral and alkaline soils.

The use of the solubility product principle is based on the assumption that a crystalline solid phase exists in the soil as a result of the equilibrium attained between P and the other reactive ions in the soil solution. These other reactive ions are Fe^{+3}, Al^{+3}, Ca^{+2}, Mg^{+2}, K^+, NH_4^+, H^+, OH^- and F^-. Lindsay and Moreno (1960) developed a solubility diagram which includes the activity isotherms for variscite, ($AlPO_4 \cdot 2H_2O$), strengite ($FePO_4 \cdot 2H_2O$), fluorapatite [$Ca_{10}(PO_4)_6F_2$], hydroxyapatite [$Ca_{10}(PO_4)_6(OH)_2$], octocalcium phosphate [$Ca_4H(PO)_3 3H_2O$], and dicalcium phosphate dihydrate ($CaHPO_4 \cdot 2H_2O$). The activity isotherms of these compounds are represented on a simple solubility phase diagram in which pH_2PO_4 is plotted against pH. The assumption is made that the activities of Al^{+3} is limited by the solubility of gibbsite, the activity of Fe^{+3} is limited by strengite, the activity of F^- by fluorite and that of Ca^{+2} is limited by a 0.005 M Ca concentration. Then by plotting the value for pH_2PO_4 and pH, it is possible to locate a point for a given soil and determine the forms of P controlling P solubility in the soil, assess the relative stabilities of these compounds and predict the transformations of fertilizer P when applied to the soil.

Soil Phosphorus Fractions

Soil P exists in the following inorganic forms: calcium phosphates, aluminum phosphates, iron phosphates and occluded and reductant-soluble phosphates.

Kittrick and Jackson (1956) have indicated that availability of P depends on the chemical form of various surface P compounds in the soil.

The different inorganic P forms in soils have been fractionated to determine the chemical forms of the native soil P as well as to study the fate of applied P fertilizer before and after cropping. The fractionation of the soil P was studied by Fraps (1906), Dean (1938), and Williams (1950), but in their procedures FeP and AlP are combined in the same fraction. Since Turner and Rice (1954) found that neutral ammonium fluoride dissolves AlP but not FeP, many extractants have been developed to characterize a specific P fraction. For instance, it is assumed that the P extracted from soils by the Bray and Kurtz method (1945) must be largely AlP. Chang and Jackson (1957) developed a soil P fractionation procedure which uses different extraction solutions to permit the fractionation of inorganic P into AlP, FeP, CaP, reductant soluble FeP and occluded FeP and AlP. This method has been extensively used: (1) to follow the weathering process of the phosphates in soils (Hsu, 1960; Chang and Jackson, 1958; Chang and Chu, 1961) and (2) to determine the fate of applied P to soils and its availability to plants, (Hanley, 1962; Melton, 1964; Smith, 1965; Alban _et al_., 1964; Susuki _et al_., 1963). It appears that in soils the weathering sequence of the phosphorus compounds follow the order CaP, AlP, FeP and occluded P (Chang and Jackson, 1958). In acid and calcareous soils of Taiwan, Chu and Chang (1960) found that the AlP fraction was not a dominant form in any of the paddy soils studied, Sen Gupta and Cornfield (1962, 1963) studied P in calcareous soils and found a decrease in the P fractions in the order inert P, apatites, non-apatites, CaP, AlP, FeP and easily replaceable P. They also found that none of the P forms correlated with $CaCO_3$ content in the soils studied. Many studies have been conducted that indicate that AlP and FeP are quite abundant in acid soils and CaP in alkaline or calcareous soils (Chai Moo Cho and Caldwell, 1959; Chang and Juo, 1963; Chu and Chang, 1960; Dahnke and Malcolm, 1964; Henwall, 1957; Kurtz, 1953; and Olsen, 1962; Fassbender *et al*., 1968).

The fractionation procedure of Chang and Jackson has been criticized in the light of subsequent findings concerning the effects of the various extractants on pure compounds and on soils; specially in regard to the differentiation between FeP and AlP (Fife, 1959a, 1959b, 1962 and 1963; Khin and Leeper, 1960; Saunders, 1953; and Smith, 1965); thus dicalcium phosphate and some FeP may be dissolved by the neutral 0.5*N* NH_4F, measuring the amounts of AlP. Fife (1959) indicated that raising the pH of the NH_4F solution to pH 8.00 or above would decrease the concentration of the fluoroferrate complex formed. Glenn *et* al. (1959) found a negligible amount of FeP removed by the NH_4F solution at pH 8.00 or above. It is also possible that the extraction of CaP with 0.5*N* H_2SO_4 following extractions with NH_4F and HaOH may dissolve some of the occluded phosphate (Khin and Leeper, 1960). The suggestion was made before by Glenn *et al*. (1950) that the reductant soluble and occluded FeP and AlP be extracted after the removal of FeP with 0.1*N* NaOH and before extracting CaP with 0.5*N* H_2SO_4.

Although the P-fractionation procedure of Chang and Jackson has been criticized, it is without any doubt useful in helping to characterize the P forms in the soil and thus has contributed greatly to the understanding of the chemistry of soil P.

METHODS AND MATERIALS

Nine representative Peruvian soils were selected for a study involving the characterization of soil P and applied P; three of these soils were from the coastal area, three from the mountains, and three from the high jungle. The location and characterization of these soils is given in Table 1. In order to fix known amounts of P, duplicate 500 g samples of each soil were placed in plastic containers, and rates of 0, 50, 100, 200, and 500 ppm P added by applying the appropriate amount of a solution of H_3PO_4 which contained 2500 ppm P. After the P was added, enough distilled water was added to give approximately a 1:1 soil:water suspension, the mixture was thoroughly mixed, and dried in a forced-air oven at 50^o C. The samples were rewetted, mixed, and dried 20 times, and soil samples for analyses were taken after the 1st, 5th, 10th, 15th, and 20th drying cycles.

Phosphorus Adsorption Capacity

Langmuir adsorption isotherms were determined for each soil as described by Olsen and Watanabe (1957). A series of equilibrating solutions was prepared which contained from 1 to 12 x 10^{-4} M KH_2PO_4, each adjusted to pH 7.0 with KOH. Five grams of soil (to which no P had been added) was

Table 1. Texture, pH, $CaCO_3$, organic matter, Olsen P, exchangeable cations (Ca, Mg and K) and cation exchange capacity (CEC) of nine Peruvian soils.

											Exchangeable cations		
No	Location	Area	Sand	Clay	Silt	Texture	pH	$CaCO_3$	O.M	P	Ca	Mg	K	C.E.C.
			------%	-------	-------			----%	----	ppm	--me/100	g---		me/100 g
4	Lambayeque	Coast	17.6	40.4	42.0	Silty clay	8.1	5.48	2.4	10	13.5	4.8	0.96	19.2
6	Casagrande	Coast	37.6	30.4	32.0	Clay loam	8.2	2.64	2.2	8	12.4	4.5	0.80	17.7
8	La Molina	Coast	47.6	14.4	38.0	Loam	8.1	T	1.6	7	14.4	2.1	0.40	16.9
222	Casablanca	Mountain	45.6	20.4	24.0	Loam	4.6	-	5.1	11	3.2	2.8	0.52	6.5
223	Cajabamba	Mountain	45.6	28.4	26.0	Sandy clay loam	5.0	-	2.5	1	3.6	1.4	0.34	5.3
224	Huancayo	Mountain	39.6	14.4	46.0	Loam	7.2	-	1.9	13	8.4	1.6	0.42	10.4
315	San Ramon	Jungle	73.6	14.4	12.0	Sandy loam	4.8	-	2.0	1	2.2	0.5	0.16	2.8
316	Satipo	Jungle	59.6	16.4	24.0	Sandy loam	6.3	-	2.7	2	5.4	1.6	0.14	7.1
322	Tingo Maria	Jungle	-	-	-	Clay	4.4	-	0.9	1	1.2	0.6	0.20	2.1

shaken with 100 ml. of the appropriate equilibrating solution for 24 hours on a reciprocating shaker, and then centrifuged until the supernatant liquid was clear. On some soils, centrifuging did not clarify the solution; on these soils, sufficient 1 N KCl was added to the supernatant liquid, after decanting, to flocculate the suspended material.

Phosphorus in the supernatant liquid was determined by the phosphomolybdenum blue method in sulfuric acid, using $SnCl_2$ as the reducing agent. This procedure is described by Jackson (1958) and is referred to by him as Phosphorus Method I.

The linear expression of the Langmuir isotherm

$$\frac{c}{x/m} = \frac{1}{kb} + \frac{c}{b}$$

was used as is described in page 89 in the Literature Review

Phosphorus Potential

The phosphorus potential was determined essentially as described by Lindsay and Moreno (1960) and Withee and Ellis (1965). Fifteen g of soil was agitated in 50 ml. of 0.01 M $CaCl_2$ for 24 hours on a reciprocating shaker, and the pH of the suspension was determined using a glass electrode potentiometer. The solution was then centrifuged, and P in the supernatant solution determined as described above. In another aliquot, Ca was determined by means of versenate titration, using murexide (ammonium purpurate) as an indicator (Jackson, 1958).

Fractionation of Soil Phosphorus

Soil phosphorus was fractionated by the procedure of Chang and Jackson (1957) as modified by Glenn *et al.* (1959) in that the pH of the NH_4F extractant was increased to 8.2, and the reductant-soluble P (Na_2SO_4-extractable) was removed after FeP (NaOH-extractable) and before CaP (H_2SO_4-extractable). Phosphorus in the reductant-soluble fraction was not determined, so only data for bound P (NH_4Cl-extractable), AlP (NH_4F-extractable), FeP, and CaP are given.

For each soil, two samples were fractionated: one to which no P was added and which was taken after the first drying cycle, and the other one to which 500 ppm P had been added and which was taken after the twentieth drying cycle.

Total Phosphorus in Soils

The total P content of each soil was determined by fusing a sample with Na_2CO_3 as described by Jackson (1958), and P in solution after the fused sample was dissolved in 0.1 N HCl was determined as described above.

RESULTS AND DISCUSSION

Phosphorus Adsorbing Capacity

The values for the maximum adsorption of P obtained using the Langmuir isotherm varied greatly between the different soils, as would be expected from the chemical analyses given in Table 1. Typical regressions for three of the soils are shown in Figure 1.

Coastal Soils

The Lambayeque soil had the highest adsorption capacity of the calcareous coastal soils (Table 2). The results of Cole *et al.* (1953) would suggest that P in this soil and in the Casagrande soil was probably adsorbed on free $CaCO_3$, since both of these soils contain free $CaCO_3$. The adsorbing capacity of the La Molina soil was lower than that of the other two coastal soils, and it does not contain free $CaCO_3$. Olsen (1953) reported that P adsorbed from dilute solution by calcareous soils is probably all exchangeable with P^{32}. This implies that P is adsorbed in a monolayer and that the concentration of this adsorbed P is likely to be within the range of concentrations that follow the Langmuir isotherm. Based upon the magnitude of the energy-of-adsorption constant $\underline{K}$ (derived from the slope and intercept of the regression equation), the Casagrande soil adsorbed P with a greater

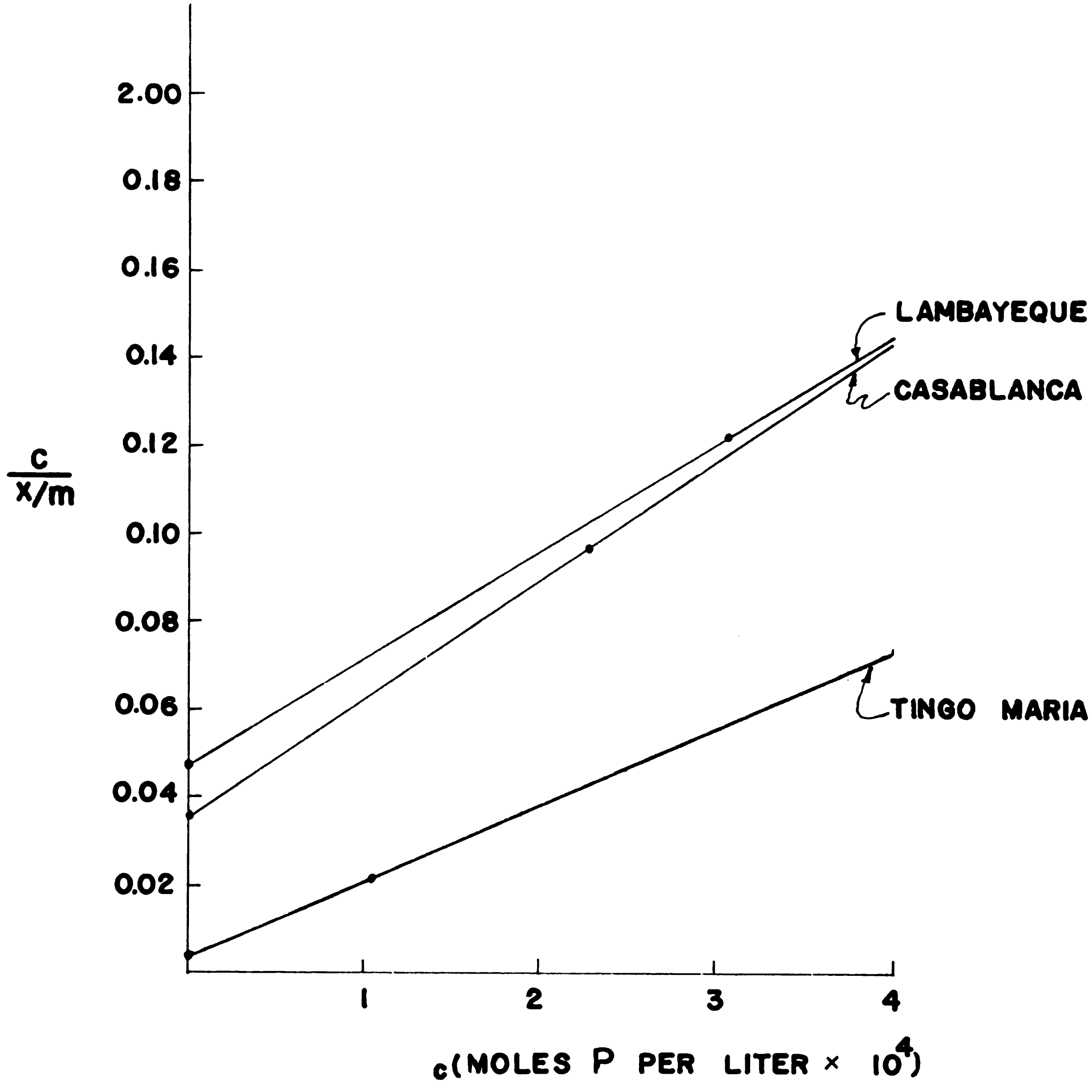


Figure 1. Langmuir isotherm regressions for Lambayeque, (coast); Casablanca, (mountain); and Tingo Maria, (jungle) soils.

Table 2. Phosphorus adsorption data for the coastal, mountain and jungle soils of Peru.

Location	pH	$y = c/x/m$ $x = c$, moles P per liter x 10^4	Simple correlation coefficient (r)	Adsorption maximum mg/100 g r/l/kb	Energy of adsorption K
Lambayeque	8.1	$y = 0.0486 + 0.0244\ x$	0.982 **	40.18	0.502
Casagrande	8.2	$y = 0.0704 + 0.0464\ x$	0.987 **	21.27	0.658
La Molina	8.1	$y = 0.1948 + 0.0777\ x$	0.947 **	12.19	0.398
Casablanca	4.6	$y = 0.0368 + 0.0271\ x$	0.983 **	36.27	0.735
Cajabamba	5.0	$y = 0.0222 + 0.0236\ x$	0.994 **	42.15	1.063
Huancayo	7.2	$y = 0.0359 + 0.0641\ x$	0.984 **	15.36	1.785
San Ramon	4.8	$y = 0.0419 + 0.1516\ x$	0.975 **	28.04	0.830
Satipo	6.3	$y = 0.1910 + 0.0513\ x$	0.933 **	18.20	0.260
Tingo Maria	4.4	$y = 0.0042 + 0.0177\ x$	0.995 **	56.23	4.199

** Highly significant (0.01 level).

bonding energy than the Lambayeque or the La Molina soils. The K values obtained are within the range of those reported by Olsen and Watanabe (1957).

Mountain Soils

The Casablance and Cajabamba soils had a higher adsorbing capacity for P than the Huancayo soil (Table 2). Both of these soils are acid soils in which Al and Fe would be expected to be important in the fixation of added P. Kurtz et al. (1946) and Low and Black (1950) suggest that P fixation takes place in two stages, a rapid initial reaction followed by a second relatively slow reaction. The predominant ions involved in P fixation in the acid Casablance and Cajabamba soils are probably Al and Fe, while Ca is probably the predominant ion in the Huancayo soil, since this soil has more exchangeable Ca and the pH is neutral.

Jungle Soils

The Tingo Maria soil had a maximum adsorbing capacity of 56.23 mg P per 100 g soil, as compared with 28.04 and 18.20 for the San Ramon and Satipo soils, respectively (Table 2). The magnitude of the adsorption maxima values for the San Ramon and Tingo Maria soils is higher than those reported by Fassbender (1966) for three strongly acid soils of Costa Rica, by Olsen and Watanabe (1957) for acid Davidson clay, and by Woodruff and Kamprath (1965) for acid soils in North Carolina. Comparing the acid Tingo Maria and San Ramon soils, the higher adsorption capacity of the Tingo Maria soil is probably due to the higher clay content which would result in a greater surface area for P adsorption and fixation.

According to the findings of Coleman et al. (1960), the amount of P removed from solution by soils correlates with the amount of exchangeable Al in the soil, and because of the low pH of the San Ramon and Tingo Maria soils, this may explain the higher level of P adsorption on these soils. Because of severe weathering under conditions of high rainfall and temperature, it is possible that the actual fixing capacity of the Tingo Maria soil could be even higher than that obtained using the Langmuir isotherm, since P fixation has been shown to increase with time (Hsu and Rennie, 1962; Fassbender, 1966).

The Satipo soil gave a P adsorption maximum of 18.2 mg P per 100 g soil. This could be a reflection of the low content of clay and the slightly acid reaction of this soil.

The K values of 4.199, 0.830, and 0.260 for the Tingo Maria, San Ramon, and Satipo soils, respectively, are in agreement with those reported for soils of similar pH values by Olsen and Watanabe (1957).

Phosphorus Potential

The soil reaction (pH), the negative logarithm of the phosphate ion activity (pH_2PO_4), the phosphate potential ($pH_2PO_4 + \frac{1}{2}pCa$) and the lime potential ($pH - \frac{1}{2}pCa$) for the coastal, mountain, and jungle soils are given in Tables 3, 4, and 5, respectively.

In general, the pH_2PO_4 and the phosphate potential, $pH_2PO_4 + \frac{1}{2}pCa$, decreased as the rate of applied P increased, which indicates that there is an increase in the solubility of the compound or compounds controlling the phosphate ion activity and phosphate potential in the soils. The decrease in pH noted when high rates of P were added, particularly in the La Molina, Cajabamba, Huancayo, San Ramon, and Tingo Maria soils, is probably related to a lower buffering capacity of these soils as compared to the other soils, so that the pH was leached when P was added as H_3PO_4.

The forms of P in the untreated soils vary considerably (Figure 2), as shown by the phosphate solubility diagram constructed as described by Lindsay and Moreno (1960). These differences are primarily due to differences in soil pH between the various soils. The data plotted in Figure 2 indicate that the alluvial soils of the coast--Lambayeque, Casagrande, and La Molina--and the Huancayo soil from the mountains are saturated with respect to hydroxyapatite and undersaturated with respect to octocalcium phosphate. Meanwhile, the acid soils of the mountain and jungle, except for the Satipo soil, are undersaturated with respect to fluorapatite and strengite. The value plotted for the pH_2PO_4 of the Tingo Maria soil is a calculated value, since it was not possible to detect any P in the equilibrium solution after the soil was treated with 0.01 M $CaCl_2$. Data for the

Table 3. The pH, pH_2PO_4, phosphate potentials and lime potentials of the coastal soils, as affected by the application of P and after wetting and drying 20 times.

Location	Applied P ppm	pH	pH_2PO_4	pH_2PO_4 + ½pCa	pH - ½pCa
Lambayeque	0	8.0	7.15	8.21	6.93
	50	8.0	6.81	7.41	7.39
	100	8.0	6.44	7.03	7.40
	200	8.0	6.33	7.33	6.99
	500	8.0	6.07	7.07	7.00
Casagrande	0	8.3	7.61	8.67	7.24
	50	8.3	7.07	8.11	7.25
	100	8.3	6.67	7.69	7.27
	200	8.3	6.34	7.36	7.28
	500	8.3	5.83	6.84	7.29
La Molina	0	8.3	7.65	8.70	7.24
	50	8.2	7.12	8.15	7.16
	100	8.2	6.93	7.95	7.18
	200	8.0	5.24	6.25	6.99
	500	7.4	5.24	6.25	6.40

Table 4. The pH, pH$_2$PO$_4$, phosphate potentials and lime potentials of the mountain soils as affected by the application of P and after wetting and drying 20 times.

	Applied P			pH$_2$PO$_4$ +	
Location	ppm	pH	pH$_2$PO$_4$	½pCa	pH − ½pCa
Casablance	0	5.0	7.17	8.23	3.91
	50	5.0	6.99	8.10	3.89
	100	5.0	6.58	7.67	3.91
	200	5.0	6.38	7.45	3.92
	500	4.9	5.75	6.80	3.84
Cajabamba	0	5.6	7.90	9.02	4.48
	50	5.6	7.30	8.39	4.50
	100	5.6	7.20	8.29	4.51
	200	5.6	6.47	7.54	4.52
	500	5.3	5.42	6.47	4.24
Huancayo	0	7.7	7.08	8.14	6.63
	50	7.6	6.63	7.68	6.55
	100	7.6	6.35	7.37	6.57
	200	7.4	5.82	6.83	6.39
	500	7.0	4.94	5.95	5.99

Table 5. The pH, pH_2PO_4, phosphate potentials and lime potentials of the jungle soils, as affected by the application of P, and after wetting and drying 20 times.

Location	Applied P ppm	pH	pH_2PO_4	$pH_2PO_4 + \frac{1}{2}pCa$	$pH - \frac{1}{2}pCa$
San Ramon	0	5.1	7.60	8.71	3.97
	50	5.1	7.42	8.53	3.98
	100	5.1	7.20	8.29	4.00
	200	5.1	6.59	7.67	4.02
	500	4.8	5.83	6.90	3.74
Satipo	0	6.7	7.51	8.59	5.61
	50	6.7	7.29	8.35	5.63
	100	6.7	6.68	7.74	5.64
	200	6.7	6.01	7.04	5.66
	500	6.6	5.17	6.19	5.57
Tingo Maria*	0	4.2	7.89	8.99	3.10
	50	4.2	7.89	8.99	3.12
	100	4.2	7.89	8.99	3.13
	200	4.2	7.89	8.99	3.17
	500	4.0	6.36	7.40	2.95

* In this soil to calculate the values pH_2PO_4, $pH_2PO_4 + \frac{1}{2}pCa$ for 0, 50, 100 and 200 ppm P added, it was assumed that the P of the equilibrium solution was 0.001 ppm since it was not possible to detect P in the equilibrium solution.

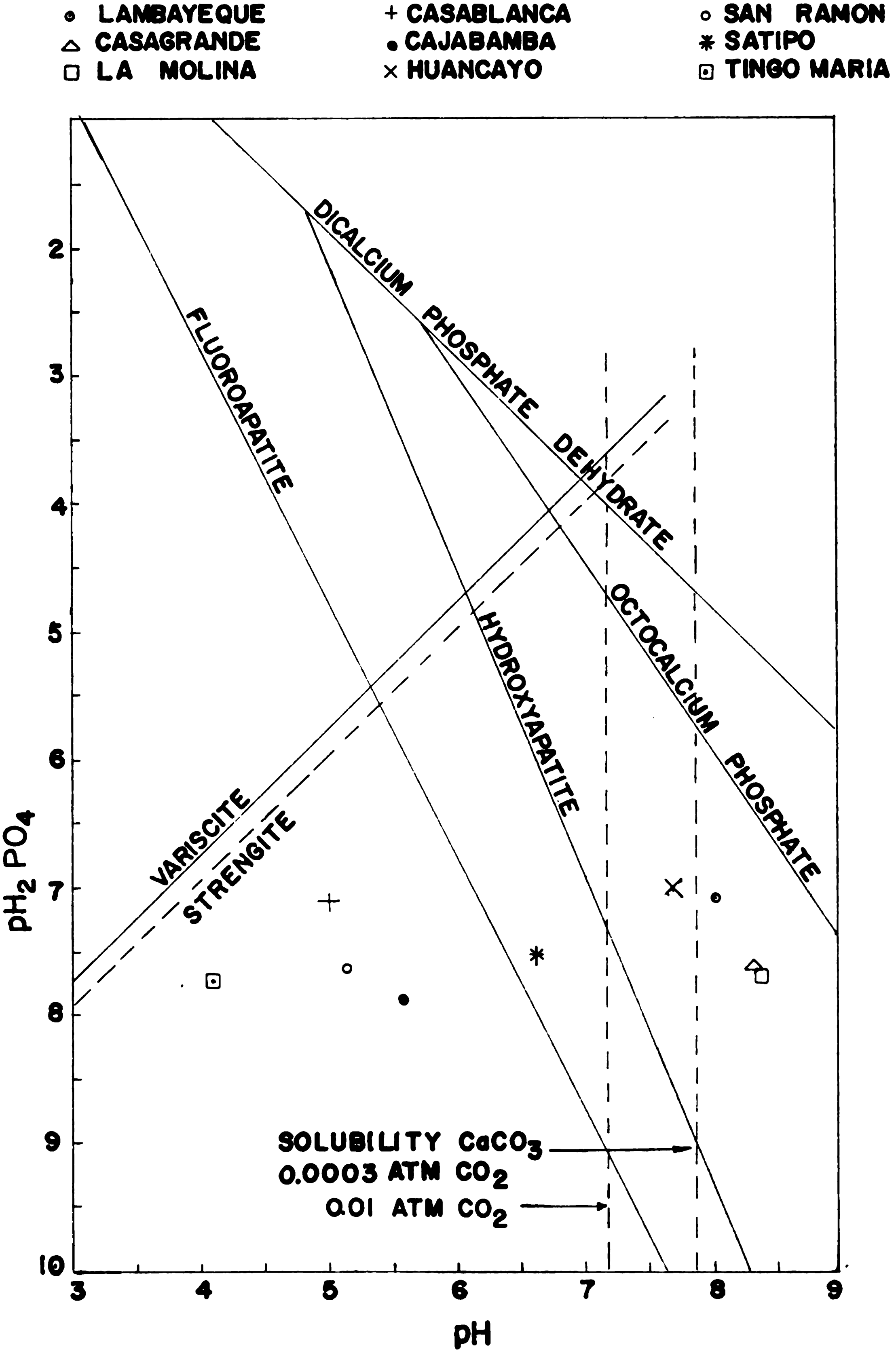


Figure 2. Phase diagram for phosphate compounds in selected Peruvian soils as determined by the phosphate solubility diagram of Lindsay and Moreno (1960).

Satipo soil indicate oversaturation with respect to fluorapatite and undersaturation with respect to hydroxyapatite.

Coastal Soils

In calcareous soils, the use of the phosphate potential ($pH_2PO_4 + \frac{1}{2}pCa$) and the lime potential ($pH - \frac{1}{2}pCa$) as proposed by Aslyng gives the most precise evaluation of the solubility of soil P compounds (Aslyng, 1954; Weir and Soper, 1963; Withee and Ellis, 1965). In general, P in these soils is more soluble than octocalcium phosphate, but less soluble than dicalcium phosphate (Figure 3). Note that the P potentials decrease as the level of P applied increases, and that all the soils were oversaturated with respect to octocalcium phosphate, especially when 200 and 500 ppm P were added.

Mountain Soils

The P solubility data from the mountain soils are plotted on the phase diagram shown in Figure 4, constructed as described by Lindsay and Moreno (1960), since two of the mountain soils (Casablanca and Cajabamba) are acid. The pH_2PO_4 values for these two acid soils decreased as the level of applied P increased; when 200 ppm P or less was applied, the soils are undersaturated with respect to both strengite and fluorapatite. When 500 ppm P was added, both soils became oversaturated with respect to strengite, and the Casablanca soil was oversaturated with respect to variscite. This would indicate that P solubility in these

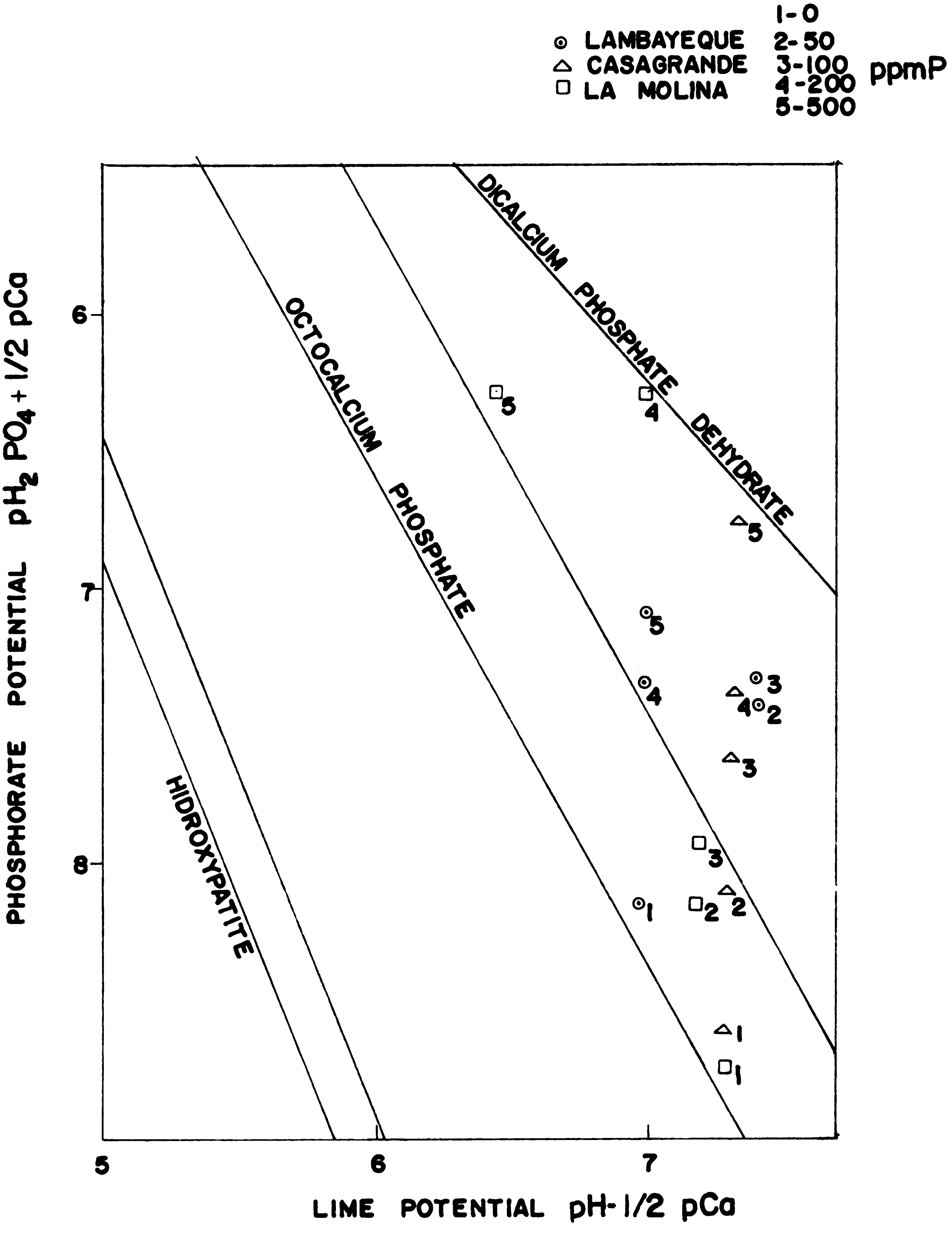


Figure 3. Phosphate and lime potentials of the coastal soils in relation to those of pure calcium phosphates, as affected by P application and after wetting and drying 20 times.

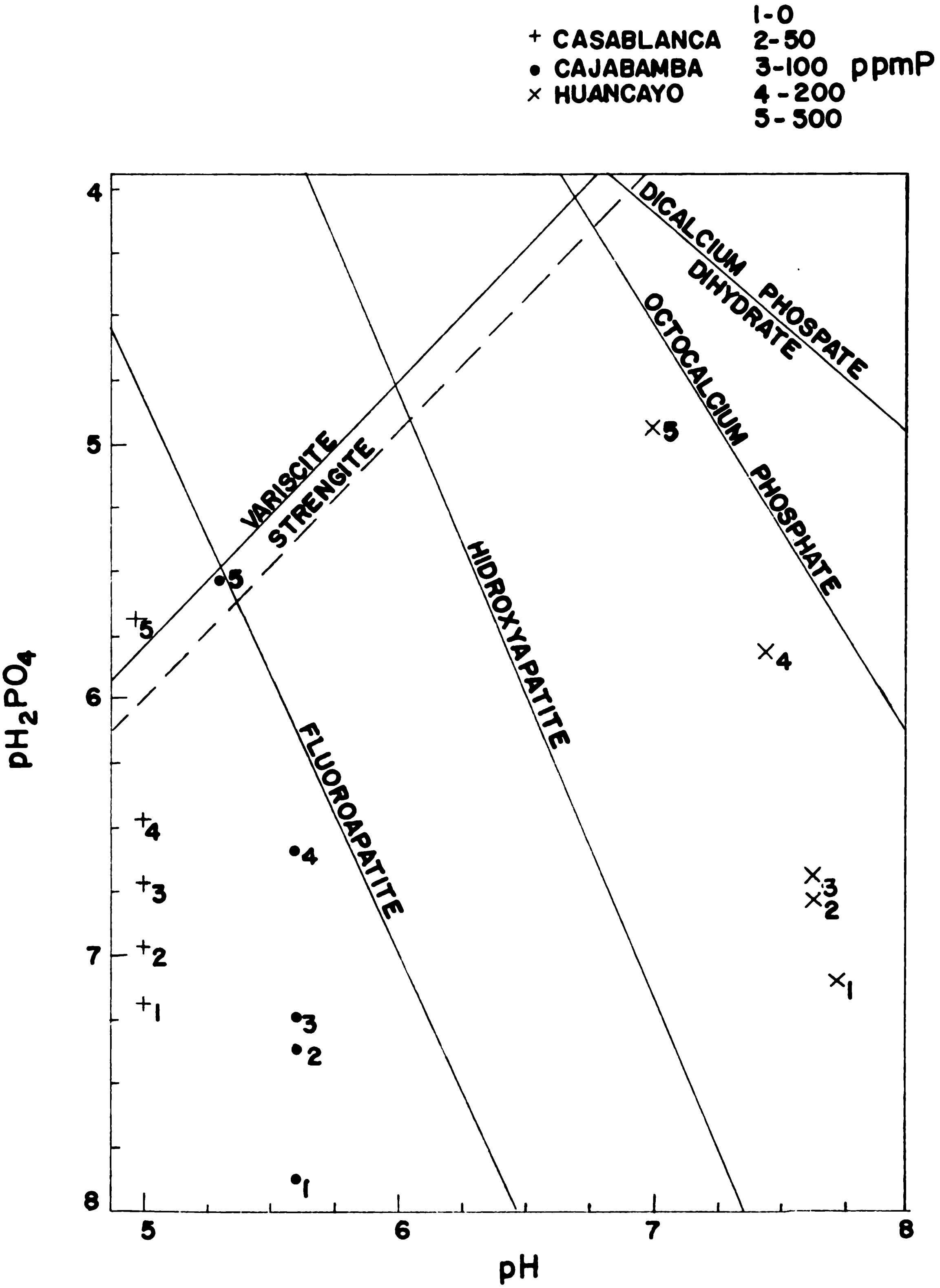


Figure 4. Solubility phase diagram of Lindsay and Moreno (1960) for the mountain soils, as affected by the application of P and after wetting and drying 20 times.

two soils is related to variscite and strengite rather than fluorapatite. Because of the high pH, P in the Huancayo soil was oversaturated with respect of octocalcium phosphate.

Jungle Soils

In the San Ramon soil, P activity appears to be governed principally by strengite (Figure 5); for even though the addition of P up to 200 ppm decreased the pH_2PO_4, not until 500 ppm P was added was the soil oversaturated with respect to variscite.

In the slightly acid Satipo soil, P activity appeared to be governed by fluorapatite and hydroxyapatite. In the Tingo Maria soil, the P concentration in the equilibrium solution could be measured only when 500 ppm P had been added. The P compound that apparently governs P solubility is apparently strengite except when the highest rate of P is applied.

Fractionation of Soil Phosphorus

The CaP, AlP, and FeP fractions were determined for each of the nine soils on samples to which no P had been added and on samples to which 500 ppm P had been added. All samples were taken after the samples had been wetted and dried 20 times.

Coastal Soils

In the coastal soils, CaP was the dominant P fraction, although appreciable amounts of AlP were present. The

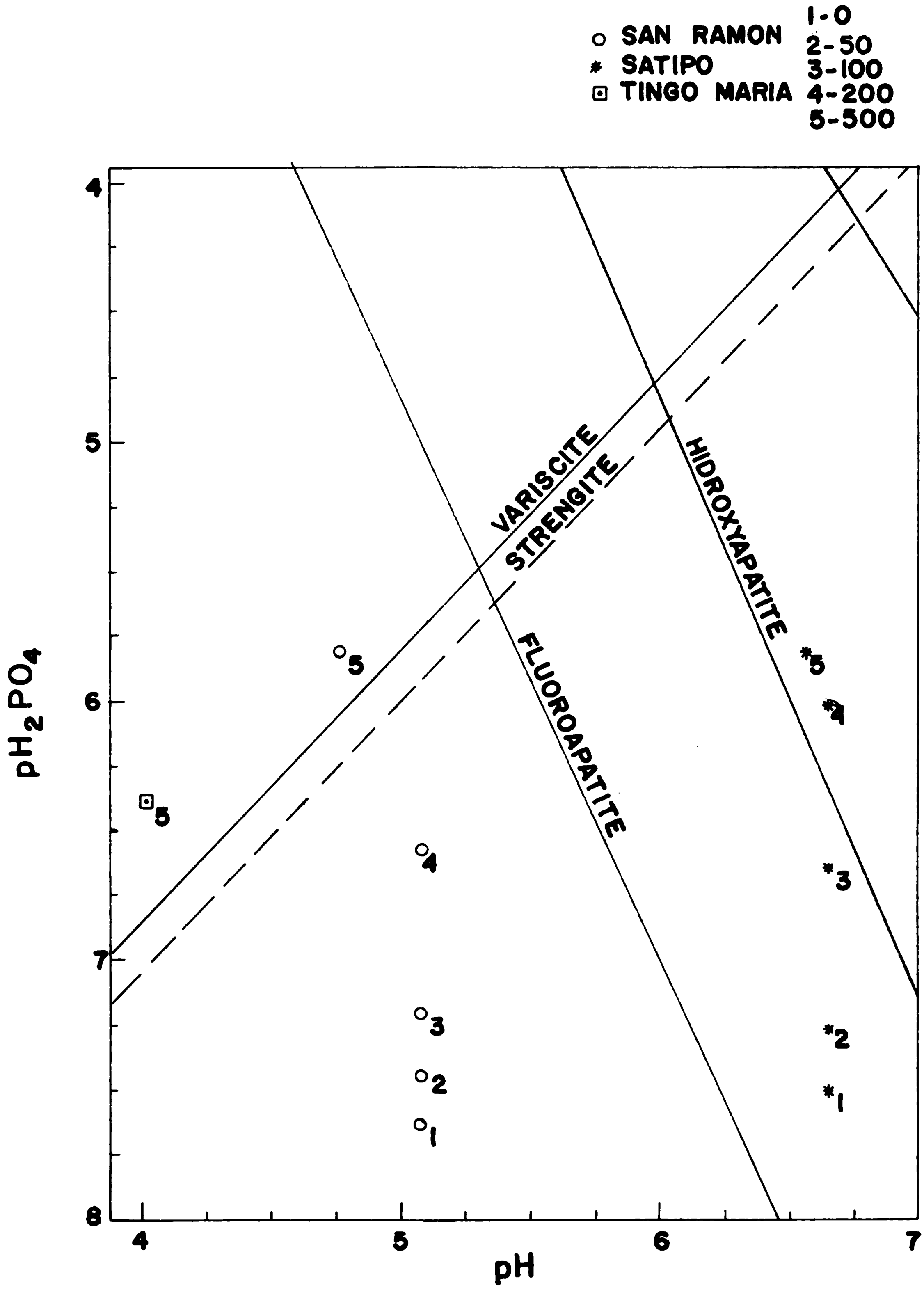


Figure 5. Solubility phase diagram of Lindsay and Moreno (1960) for the jungle soils, as affected by the application of P and after wetting and drying 20 times.

bound P (or exchangeable P) and FeP fractions accounted for a very small portion of the total extracted P (Table 6). From 50 to 60 percent of the total P in the soils was extracted as these four forms. It should be noted, however, that part of the fraction extracted as AlP by this procedure could be derived from some of the more soluble calcium phosphates that might be expected to occur in these calcareous soils (Glenn *et al.*,1959; Smith *et al.*, 1957).

When 500 ppm P was added, the increase in P extracted during the fractionation procedure followed the same trends as those present before P was added (Table 7). When the total P in the soil was assumed to be that present originally plus that added for the purposes of this study, the P removed by the fractionation procedure was about 60 percent of the total P for all three soils, indicating that a larger proportion of the applied P was extracted by the fractionation procedure than that of native soil P. Considerably more of the extracted P was present as bound P after P had been applied than before P applications. Note, however, that in the La Molina soil, the amount of CaP was about the same after P was added as before, and that applied P appeared to be present primarily in the bound P and AlP fractions. This was the only coastal soil that did not contain free $CaCO_3$, and it is probable that most of the applied P was present as exchangeable P and as calcium phosphates that are soluble in NH_4F in this soil.

Table 6. Total P and inorganic P fractions in nine Peruvian soils to which no P was applied and after wetting and drying 20 times.

Location	pH	Total P	Inorganic P fractions					Fraction of total P	Inorganic P fractions**			
			BP*	AlP	FeP	CaP	Sum		BP*	AlP	FeP	CaP
		ppm						%	%			
Lambayeque	8.1	1245	7.5	139.0	6.2	540.0	692.7	55.6	1.0	20.0	0.9	78.0
Casagrande	8.2	940	12.5	62.5	16.2	375.0	466.2	49.5	2.7	13.4	3.5	80.4
La Molina	8.1	1170	27.5	85.0	26.2	540.0	678.7	58.0	4.0	12.4	3.8	80.0
Casablanca	4.6	1071	5.0	104.0	218.0	32.5	359.5	33.5	1.4	30.0	60.6	8.0
Cajabamba	5.0	630	T	25.0	65.0	20.0	110.0	17.4	-	22.7	59.2	18.1
Huancayo	7.2	680	2.5	50.0	47.6	50.0	150.1	22.0	1.6	33.3	31.7	33.3
San Ramon	4.8	350	2.5	30.0	35.0	5.2	72.7	20.7	3.4	41.3	48.1	7.1
Satipo	6.3	360	T	16.2	26.0	5.0	47.2	13.1	-	34.3	55.1	10.5
Tingo Maria	4.4	515	T	5.2	12.5	25.0	42.7	8.2	-	12.2	29.3	58.5

* BP = Bound phosphorus (Extracted with NH_4Cl 1N)

** Calculated as % of the sum of (BP + AlP + FeP + CaP)

Table 7. Total P and inorganic P fractions in nine Peruvian soils to which 500 ppm was applied, and after wetting and drying 20 times.

Location	pH	Total P	Inorganic P fractions					Fraction of Total P	Inorganic P fractions**			
			BP*	AlP	FeP	CaP	Sum		BP*	AlP	FeP	CaP
		ppm	ppm	ppm	ppm	ppm	ppm	%	%	%	%	%
Lambayeque	8.1	1745	65.0	255.0	5.0	750.0	1075.0	61.6	6.0	23.7	0.4	69.8
Casagrande	8.2	1440	155.0	257.5	25.0	440.0	877.5	60.9	17.7	29.3	2.8	50.1
La Molina	8.1	1670	162.0	237.5	58.7	550.0	1008.5	60.3	16.1	23.5	5.8	54.6
Casablanca	4.6	1571	12.5	330.0	350.0	37.5	730.0	46.4	1.8	45.3	47.8	5.1
Cajabamba	5.0	1130	22.5	283.7	187.5	24.5	518.2	45.8	4.3	54.7	36.2	4.8
Huancayo	7.2	1180	125.0	275.0	112.5	70.0	582.5	49.3	21.4	47.2	19.3	12.1
San Ramon	4.8	850	25.0	380.0	125.0	8.5	538.5	63.3	4.6	70.6	23.2	1.6
Satipo	6.3	860	85.0	225.0	150.0	10.0	470.0	54.6	18.0	48.0	32.0	2.0
Tingo Maria	4.4	1015	10.0	207.0	143.7	27.5	388.2	38.2	2.6	53.3	37.0	7.1

* BP = Bound phosphorus (Extracted with NH_4Cl 1N)

** Calculated as % of the sum of (BP + AlP + FeP + CaP)

The relatively high levels of P in the coastal soils are likely a reflection of the high rates of guano de Islas that have been commonly applied annually to these soils for centuries. The recovery of approximately 60 percent of the total P by the fractionation procedure is in agreement with data reported from calcareous soils (Hawkins and Kunze, 1965).

Mountain Soils

In the acid Casablanca and Cajabamba soils, FeP was the dominant mineral P fraction, and a considerable amount of AlP was present in the Casablanca soil (Table 6). The amounts of AlP and CaP were about the same in the Cajabamba soil. In the neutral Huancayo soil, the amounts of AlP, FeP, and CaP were about equal. No appreciable amounts of bound P were noted in any of the mountain soils. The total P in these mountain soils is relatively high and could be a reflection of the high native fertility of these soils and the relatively higher content of organic matter as compared to the coastal and jungle soils. The recovery of from 17 to 33 percent of the total P by the fractionation procedure is less than that noted for the coastal soils, and is indicative of a more advanced stage of weathering (Chang and Jackson, 1958).

When 500 ppm P was applied to these soils, data indicate that most of the applied P was recovered by the fractionation procedure on all three soils (Table 7). Most of the applied P appeared to be removed as AlP, although an appreciable amount was present as bound P in the Huancayo soil. No appreciable change in CaP was noted on any of the soils.

The forms of P in the Huancayo soil were definitely different than those in the more acid mountain soils, and the distribution is also different from that in the more calcareous coastal soils. This may in part be due to more severe weathering in the mountains than in the coast. It is interesting to note that the distribution of P in this soil does not appear to follow the sequence of formation and transformations of the various phosphate species in accordance to the chemical principles of solubility products as used in the preceding sections of this study. It should be emphasized here, however, that the fractionation procedure used accounted for only about half of the total P in this soil after 500 ppm P had been applied.

Jungle Soils

In the San Ramon and Satipo soils, AlP and FeP appeared to be the dominant forms of P removed by the extraction procedure, while most of the P extracted from the Tingo Maria soil was CaP (Table 6). However, it should be noted that the recovery of total P from these soils was very low, ranging from about 8 to 20 percent. This is indicative of the more severe weathering in the jungle soils than in the mountain or coastal soils.

When 500 ppm P was applied, most of the applied P was recovered in the fractionation procedure (Table 7). The lowest recovery was from the Tingo Maria soil, as would be expected from the adsorption data showing the low solubility and the strong bonding energy for P in this soil. Most of the applied P in all three soils was removed as AlP, although appreciable amounts of FeP were noted in all three soils, and a considerable amount of bound P was extracted from the Satipo soil.

The data obtained from the P fractionation of the jungle soils to which no P was applied give very little information relative to the forms of P since the fractionation procedure extracted very little of the total P in these soils. The non-extractable P is of paramount importance for a more complete understanding of the P reactions in the jungle soils. Probably, the greater part of the native P in these soils exists as Fe and Al compounds, possibly in occluded or reductant-soluble form, which have a very low solubility (Syers _et_ _al_., 1969). The high recovery of added P on these soils would indicate that the formation of these compounds probably takes place very slowly, and is a result of the severe weathering conditions under which these soils were developed. Similar results have been reported by Yuan _et_ _al_. (1960) on severely weathered acid soils.

SUMMARY AND CONCLUSIONS

PHOSPHORUS FORMS AND EQUILIBRIA IN SELECTED PERUVIAN SOILS

Phosphorus in the coastal soils was primarily CaP, and the adsorption maxima on these soils was directly related to the amount of free $CaCO_3$ present. Studies of the Ca potential indicated that the solubility of P in these soils is governed mainly by octocalcium phosphate; when 200 or 500 ppm P was applied, P solubility was dependent upon dicalcium phosphate. Not only was the P adsorbing capacity higher on soils with free $CaCO_3$ (Lambayeque and Casagrande) than on that which did not contain free $CaCO_3$ (La Molina), but the P was held more tightly when free $CaCO_3$ was present.

In the mountain soils, the lowest P adsorption maximum was on the neutral Huancayo soil, in which CaP predominated, but which contained no free $CaCO_3$. The P solubility in this soil appeared to be governed by hydroxyapatite, even at the highest rates of applied P. The P adsorption data also indicated that the energy of P adsorption was about twice as high on the Huancayo soil as on the coastal soils. It seems apparent, then, that the CaP in the Huancayo soil is present as a more difficultly-soluble form than that in the coastal soils.

In the acid Casablanca and Cajabamba soils of the mountains, FeP predominated, accompanied by relatively large proportions of AlP; a considerable amount of CaP was extracted from the Cajabamba soil. These soils were undersaturated with respect to strengite except when 500 ppm P was applied, when P solubility appeared to be controlled by varascite and/or strengite. Adsorption maxima on these two soils were higher than those of any of the other soils except for the Lambayeque soil from the coast and the Tingo Maria soil from the jungle, and P was adsorbed more tightly than on any of the other soils except the Tingo Maria soil.

The fractionation of P from the jungle soils indicated that P in the strongly acid San Ramon soil and the slightly acid Satipo soil was mostly AlP and FeP, while that of the strongly acid Tingo Maria soil was mostly CaP. However, only from 8 to 20 percent of the total P in these soils was removed by the fractionation procedure; so these data are not adequate to completely characterize the soil P. The slightly acid Satipo soil was undersaturated with respect to hydroxyapatite except when 200 and 500 ppm P were applied. The San Ramon and Tingo Maria soils were undersaturated with respect to strengite except when 500 ppm P was applied, when variscite seemed to be controlling P solubility. Highest absorbing capacity and highest bonding energy for P were noted for the strongly acid Tingo Maria soil.

Extraction of soil P by the fractionation procedure indicated that the jungle soils are the most severely weathered and the coastal soils the least weathered of the nine soils studied. In general, P was absorbed more strongly on the acid soils than on the calcareous soils.

The forms of P extracted from the soils was related more closely to pH than to any other soil factor measured. Forms of P extracted after P was "fixed" generally were in the same proportions as that extracted prior to P applications.

BIBLIOGRAPHY

PART II

Alban, L. A., Vacharotayan, S., and Jackson, T. L. 1964. Phosphorus availability in reddish brown lateritic soils. I. Laboratory studies. Agron. J. 56:555-558.

Aslyng, H. C. 1954. The lime and phosphate potentials of soils; the solubility and availability of phosphates. Roy. Vet. and Agric. Coll. Copenhagen. Den. Yearbook reprint, pp. 1-50.

Black, C. A. 1942. The penetration of phosphate into the kaolinite crystal. Soil Sci. Soc. Amer. Proc. 6: 157-161.

Bradfield, R., Scarseth, G., and Steele, J. G. 1935. Factors affecting the retention of phosphates by clays. Third Int. Congress of Soil Science, Vol. I:74.

Bray, R. H., and Kurtz, L. T. 1945. Determination of total organic and available phosphorus in soils. Soil Sci. 59:39-45.

Chai-Moo-Cho, and Caldwell, A. C. 1959. Forms of phosphorus and fixation in soils. Soil Sci. Soc. Amer. Proc. 23:458-460.

Chang, S. C., and Chu, W. K. 1961. Fate of soluble phosphate applied to soils. J. Soil Sci. 12:286-293.

Chang, S. C., and Jackson, M. L. 1957. Fractionation of soil phosphorus. Soil Sci. 84:133-144.

Chang, S. C., and Jackson, M. L. 1958. Soil phosphorus fractionation in some representative soils. J. Soil Sci. 9:109-119.

Chang, S. C., and Juo, S. R. 1963. Available phosphorus in relation to forms of phosphorus in soils. Soil Sci. 95:91-96.

Chu, W. K., and Chang, S. C. 1960. Forms of phosphorus in the soils of Taiwan. J. Agric. Assoc., China. 30: 1-12.

Clark, J. S., and Peech, M. 1955. Solubility criteria for the existence of calcium and aluminum phosphates in soils. Soil Sci. Soc. Amer. Proc. 19:171-174.

Cole, C. V., and Jackson, M. L. 1950. Colloidal dihydroxy dehydrogen phosphates of aluminum and iron with crystalline character established by electron and X-ray diffraction. J. Phys. and Colloid Chem. 54: 128-142.

Cole, C. V., Olsen, S. R., and Scott, C. O. 1953. The nature of phosphate sorption by calcium carbonate. Soil Sci. Soc. Amer. Proc. 17:352-356.

Coleman, R. 1945. The mechanism of phosphate fixation by montmorillonitic and kaolinitic clays. Soil Sci. Soc. Amer. Proc. 9:72-78.

Coleman, R., Throup, J. T., and Jackson, W. A. 1960. Phosphate sorption reactions that involve exchangeable aluminum. Soil Sci. 90:1-7.

Dahnke, W. C., and Malcolm, J. L. 1964. Phosphorus fractions in selected soil profiles of El Salvador as related to their development. Soil Sci. 98:33-38.

Davis, L. E. 1935. Sorption of phosphates by non-calcareous Hawaiian soils. Soil Sci. 40:129-148.

Dean, L. A. 1938. An attempted fractionation of soil phosphorus. J. Agric. Sci. 28:234-246.

Dean, L. A. 1949. Fixation of soil phosphorus. Advances in Agronomy. 1:391-411.

Drossdoff, M., Quevedo, F., and Zamora, C. 1960. Soils of Peru. 7th Intern. Congress of Soil Sci., Madison, Wisc.

Ellis, R., and Troug, E. 1955. Phosphate fixation by montmorillonite. Soil Sci. Soc. Amer. Proc. 19:451-454.

Fassbender, H. W. 1966. La adsorcton de fosfatos en suelos fuertemente acidos y su evolucion usando la isoterma de Langmuir. Fitotecnia Latinoamericana. 3(1-2) 203-216.

Fassbender, H. W., Muller, L., and Balerdi, F. 1968. Estudio del fosforo en suelos de Centroamerica. II. Formas y su relacion con la planta. Turrialba 18(4):333-347.

Fife, C. V. 1959a, 1959b, 1962, 1963. An evaluation of ammonium fluoride as a selective extractant for aluminum bound soil phosphate: I-IV. Soil Sci. 87:13-21, 83-88; 93:113-123; 96:112-120.

Fraps, G. S. 1906. Availability of phosphoric acid of the soil. J. Amer. Soc. Agron. 28:823-834.

Fried, M., and Shapiro, R. E. 1960. Soil-Plant relations in phosphorus uptake. Soil Sci. 90:69-76.

Glenn, R. C., Hsu, P. H., Jackson, M. L., and Corey, R. B. 1959. Flow sheet for soil phosphate fractionation. Agr. Abst. pp. 9.

Hanley, K. 1962. Soil phosphorus forms and their availability to plants. Irish J. Agric. Res. 1:192-193.

Hawkins, R. H., and Kunze, G. W. 1965. Phosphate fractions in some Texas grumosols and their relation to soil weathering and available phosphorus. Soil Sci. Soc. Amer. Proc. 29:650-656.

Henwall, J. B. 1957. The fixation of phosphorus by soils. Advances in Agronomy. 9:95-112.

Hsu, P. H., and Jackson, M. L. 1950. Inorganic phosphate transformations by chemical weathering in soils as influenced by pH. Soil Sci. 90:16-24.

Hsu, P. H., and Rennie, D. A. 1962. Reactions of phosphate in aluminum systems: II. Precipitation of phosphate by exchangeable aluminum on a cation exchange resin. Can. J. Soil Sci. 42:210-221.

Huffman, E. O. 1968. The reactions of fertilizer phosphate with soils. Outlook on Agriculture. 5:(5) 202-207.

Jackson, M. L. 1958. Soil Chemical Analysis. Prentice Hall, Inc., New Jersey.

Juo, A. S., and Ellis, B. G. 1968. Particle size distribution of aluminum, iron and calcium phosphates in soil profiles. Soil Sci. 106:374-380.

Juo, A. S. 1966. Chemical and physical factors affecting the relative availability of inorganic phosphorus in soils. Ph.D. Thesis, Michigan State University.

Kelley, J. B., and Midgley, A. R. 1943. Phosphate fixation and exchange of phosphate and hydroxyl ions. Soil Sci. 55:167-176.

Khin, A., and Leeper, G. W. 1960. Modification in Chang and Jackson's procedure for fractionating soil phosphorus. Agrochimica. 4:246-254.

Kittrick, J. A., and Jackson, M. L. 1956. Electron microscope observations of the reaction of phosphate with minerals leading to a unified theory of phosphate fixation in soils. J. Soil Sci. 7:81-89.

Kurtz, L. T. 1953. Inorganic phosphorus in acid and neutral soils. "Soils and Fertilizer Phosphorus," Chap. III.

Kurtz, L. T., DeTurk, E. E., and Bray, R. H. 1946. Phosphate adsorption by Illinois soils. Soil Sci. 61: 111-124.

Langmuir, I. 1918. The adsorption of gases on plane surfaces of glass, mica and platinum. J. Amer. Chem. Soc. 40:1361-1402.

Larsen, S. 1967. Soil phosphorus. Advances in Agronomy. 19:151-206.

Larsen, S., and Court, M. N. 1960. Chemical potentials of phosphate ions in soil solutions. 7th Intern. Cong. Soil Sci., Madison, Wisc.

Larsen, S., and Court, M. N. 1961. Soil phosphate solubility. Nature. 189:164-165.

Lindsay, W. L., Frazier, A. W., and Stephenson, H. F. 1962. Identification of reaction products from phosphate fertilizers in soils. Soil Sci. Soc. Amer. Proc. 26:446-452.

Lindsay, W. L., and Moreno, E. C. 1960. Phosphate phase equilibria in soils. Soil Sci. Soc. Amer. Proc. 24:177-182.

Low, P. F., and Black, C. A. 1950. Reactions of phosphate with kaolinite. Soil Sci. 70:273-290.

Melton, J. R. 1964. Availability of aluminum, iron and calcium phosphate in soils. M.S. Thesis, Michigan State University.

Midgley, A. R. 1940. Phosphate fixation in soils. A critical review. Soil Sci. Soc. Amer. Proc. 5:24-30.

Murphy, H. F. 1939. The role of kaolinite in phosphate fixation. Hilgardia. 12:343-382.

Olsen, S. R. 1953. Inorganic phosphorus in alkaline and calcareous soils. "Soils and Fertilizer Phosphorus" Chap. IV. Agron. Monographs, Vol. IV. Academ. Press.

Olsen, S. R., and Watanabe, F. S. 1957. A method to determine a phosphorus adsorption maximum of soils as measured by the Langmuir isotherm. Soil Sci. Soc. Amer. Proc. 21:144-149.

Ravikovitch, S. 1934. Anion exchange. II. Liberation of the phosphoric acid ion adsorbed by soils. Soil Sci. 38:279-290.

Russell, E. J., Prescott, J. A. 1916. The reaction between dilute acids and the phosphorus compounds of the soil. J. Agric. Sci. 8:65-110.

Sanchez, C. 1965. Evaluation of certain chemical transformations of soluble fertilizer phosphorus applied to three Michigan soils. Ph.D. Thesis, Michigan State University.

Saunders, W. M. H. 1959. Aluminum extracted by neutral citrate-dithionite reagent. Nature. 184:2037.

Scarseth, G. D. 1935. The mechanism of phosphate retention by natural alumino silicate colloids. J. Amer. Soc. Agron. 27:596-616.

Schofield, R. K. 1955. Can a precise meaning be given to "available" soil phosphorus. Soils Fert. 18:373-375.

Sen Gupta, M. B., and Cornfield, A. H. 1962. Phosphorus in calcareous soils. IV. The inorganic phosphate fractions and their relation to the amount of calcium carbonate present. J. Sci. Food Agric. 13:652-655.

Sen Gupta, M. B., and Cornfield, A. H. 1963. Phosphorus in calcareous soil. IV. Nature of and factors influencing the fixation of added phosphate. J. Sci. Food Agric. 14:873-877.

Smith, A. N. 1965. Distinction between iron and aluminum phosphate in Chang and Jackson's procedure for fractionating inorganic soil phosphorus. Agrochimica. 9:162-168.

Smith, A. N. 1965. The supply of soluble phosphorus to the wheat plant from inorganic soil phosphorus. Plant and Soil. 22:314-316.

Smith, F. W., Ellis, B. G., and Grava, J. 1957. Use of acid-fluoride solutions for the extraction of available phosphorus in calcareous soils and in soil to which rock phosphate has been added. Soil Sci. Soc. Am. Proc. 21:400-404.

Stout, P. R. 1939. Alteration in the crystal structure of clay minerals as result of phosphate fixation. Soil Sci. Soc. Amer. Proc. 4:177-182.

Susuki, A., Lawton, K., and Doll, E. C. 1963. Phosphorus uptake and soil tests as related to forms of phosphorus in some Michigan soils. Soil Sci. Soc. Amer. Proc. 27:401-403.

Syers, J. K., Williams, J. D. H., Tyner, E. H., and Walker, T. W. 1969. Primary and secondary origin of the "non extractable" soil inorganic phosphorus. Soil Sci. Soc. Amer. Proc. 33:635-637.

Tosi, J. A. 1960. Natural Climatic Life-Zones of Peru. Technical bulletin 5. Inst. Interam. de Ciencias Agricolas O.E.A.

Turner, R. C., and Rice, H. M. 1954. Role of fluoride ion in release of phosphate adsorbed by Al and Fe hydroxide. Soil Sci. 74:141-148.

Weir, C. C., and Soper, R. J. 1963. Solubility studies of phosphorus in some calcareous Manitoba soils. J. Soil Sci. 14:256-261.

Wild, A. 1953. The effects of exchangeable cations on the retention of phosphate by clay. J. Soil Sci. 4:72-85.

Williams, C. H. 1950. Studies in soil phosphorus: I. A method for the partial fractionation of soil phosphorus. J. Agric. Sci. 40:233-242.

Withee, L. V. and Ellis, R., Jr. 1965. Change of phosphate potentials of calcareous soils on adding phosphorus. Soil Sci. Soc. Amer. Proc. 29:511-514.

Woodruff, J. R., Kamprath, E. J. 1965. Phosphorus adsorption maximum as measured by the Langmuir isotherm and its relationship to phosphorus availability. Soil Sci. Soc. Amer. Proc. 29:148-150.

Yuan, T. L., Robertson, W. K., and Neller, J. R. 1960. Forms of newly fixed phosphorus in three acid sandy soils. Soil Sci. Soc. Amer. Proc. 24:447-450.

APPENDIX

APPENDIX I

1. Location and crop history of the Hodunk sandy loam soil.

The M.S.U. Experimental Farm is located in East Lansing on the SW $\frac{1}{4}$ of NE $\frac{1}{4}$ of SE $\frac{1}{4}$, Section 19, T4N, R1W Meridian Township, Ingham County.

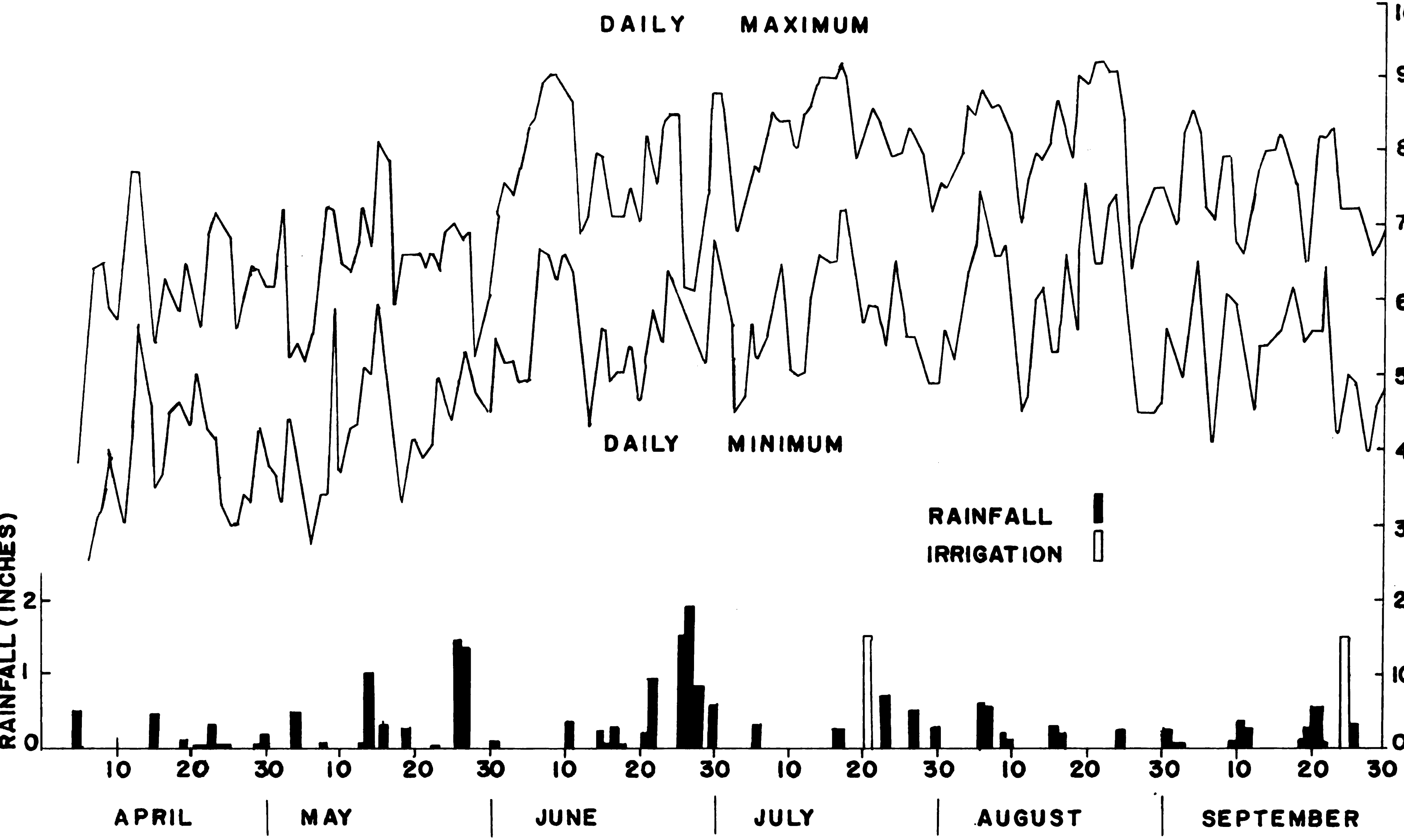
The experimental area used in 1967 was in fallow in the crop year of 1965 and 1966. An experiment on irrigation was set up, using soybeans as a crop. Fertilizers were applied at the rate of 200 pounds per acre of a 6-24-24 fertilizer grade.

The experimental area used in 1968 was cropped with potatoes in the 1966 growing season. The area was fertilized with 166 pounds N per acre, 100 pounds P_2O_5 per acre, and 180 pounds K_2O per acre. In the year 1967, an experiment in corn was carried out where 100 pounds per acre of a fertilizer mixture of 6-24-24 grade was applied, plus additional applications of nitrogen to get a total of 150 pounds N per acre.

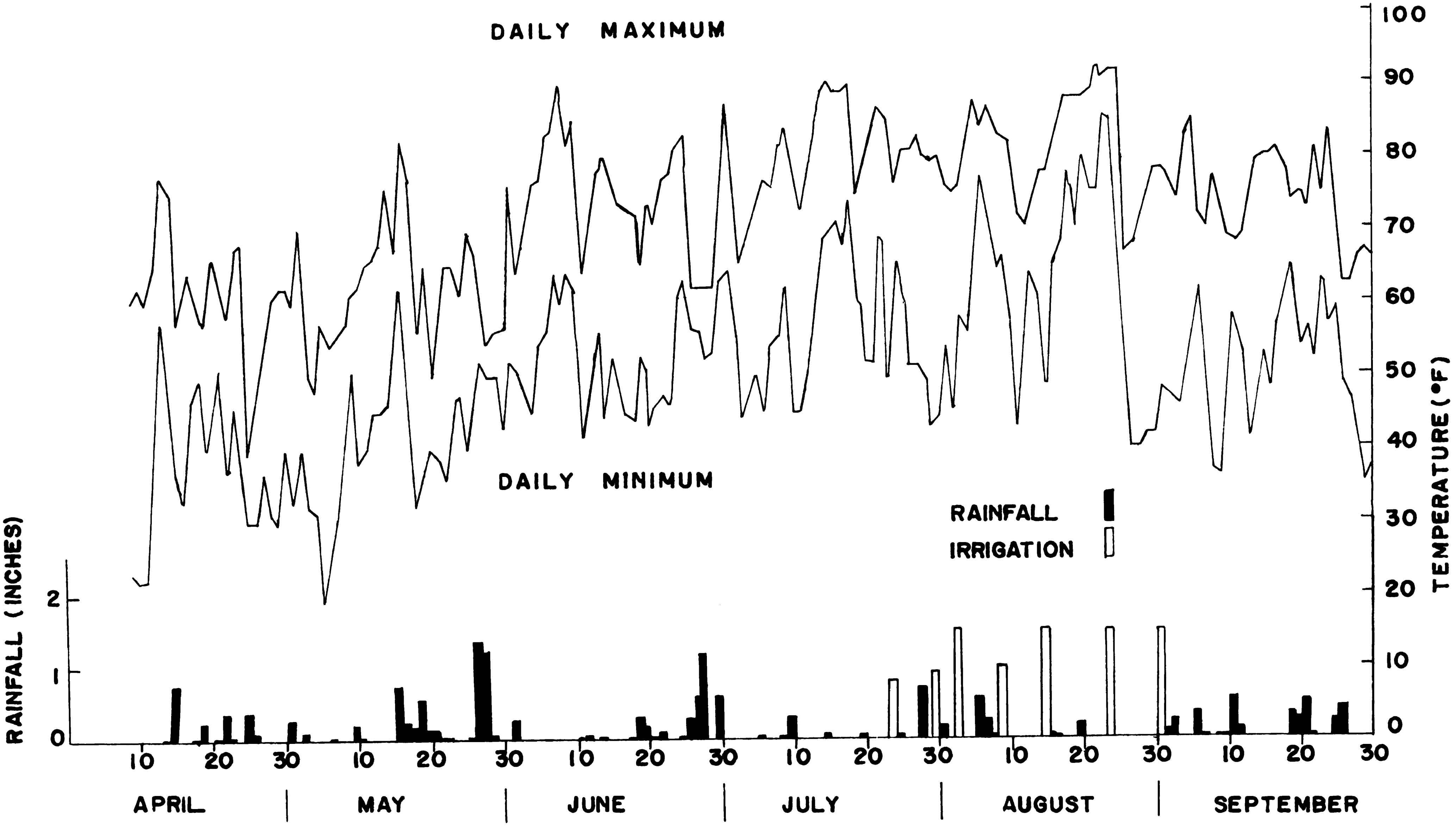
2. Location and crop history of the Mc Bride sandy loam soil.

The Montcalm Experimental Farm is located on the SW $\frac{1}{4}$ of SW $\frac{1}{4}$ of Section 8, T11N, R7W Douglas Township, Montcalm County.

The experimental area used in 1968 was in fallow in 1967, and in 1968 was cropped with kidney beans.



Air temperatures, rainfall and irrigation at East Lansing, 1968.



Air temperatures, rainfall and irrigation at Montcalm, 1968.