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By

Robert Jewell Crabtree

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ABSTRACT

EFFECTS OF RATES AND SOURCES OF POTASSIUM ON YIELDS AND MINERAL CONTENT OF POTATOES AND EVALUATION OF POTASSIUM QUANTITY-INTENSITY RELATIONSHIPS OF SELECTED MICHIGAN SOILS

by Robert Jewell Crabtree

Field experiments were conducted on a McBride sandy loam soil to determine the effects of various rates and sources of potassium fertilization of Russet Burbank and Sebago potato varieities on (1) yields and specific gravity of tubers, (2) the uptake and distribution of potassium, calcium, and magnesium in potato tissue, and (3) reducing sugar content of tubers at harvest

Significant yield responses were obtained from application rates of K_2O as KCl up to 180 pounds per acre and from 150 pounds of K_2O as KCl, KNO_3, K_2SO_4, and K_2CO_3, but yield response was independent of potassium source.

Specific gravity decreased significantly with increasing applications of KCl on both Burbank and Sebago varieties, but larger decreases were noted for the Sebago

variety. Potassium nitrate decreased the specific gravity on the Sebago variety when compared to KCl, K_2SO_4, and K_2CO_3. Potassium concentrations in potato tissue increased with increasing applications of K_2O; however, there was a decrease in potassium content as maturation of plants occurred. The magnitude of potassium concentrations in plant tissue was petioles > leaves > whole plants > tubers.

Concentrations of calcium and magnesium in potato tissue decreased with increasing rates of applied potassium, but increased with maturation of the plant. The calcium concentrations in petioles, leaves, and whole plants were sixty to eighty times that found in tubers. There were no significant differences between sources of potassium and calcium uptake. Applications of 240 and 480 pounds of K_2O per acre as KCl resulted in potassium induced decreases in magnesium and calcium content of petioles, leaves, and whole plants, but the decrease in magnesium was much larger in magnitude than that of calcium.

Rates and sources of potassium had no significant effects on the reducing sugar content of tubers at harvest.

Four oat crops were grown in the greenhouse on sixteen Michigan soils selected for variations in potassium content. Potassium-uptake and yields of each oat crop were measured. On each soil, exchangeable potassium was measured and the relation between equilibrium activity ratios of potassium to calcium and magnesium (AR_e^K) and changes in exchangeable K (ΔKe) were determined.

Exchangeable potassium (1 $\underline{N}$ NH_4OAc extractable) was correlated with yields (r = +0.75**), total potassium-uptake (r = +0.98***), and uptake of nonexchangeable potassium (r = +0.82***). Uptake of nonexchangeable potassium amounted to 50 per cent or more of total uptake of potassium on all soils except three.

Estimates of exchangeable potassium derived from equilibrium curves were found to be much more indicative of the total uptake of potassium (r = +0.83***) than were the AR_e^K values.

The potential buffering capacity (PBC^K) as a single value ($-\Delta K/AR_e^K$) gave poor correlations as an index of potassium availability. When PBC^K was multiplied by $-\Delta K$, the product (potassium-potential) was correlated (r = +0.56*) with the potassium-uptake of the first oat crop, but not the subsequent crops.

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INTRODUCTION

In most areas of Michigan potassium (K) fertilizers are needed for maximum production of potatoes. The amount of K fertilizer required at any specific location can best be determined by means of soil tests which have been calibrated with field experiments.

Considerable research has been done to correlate laboratory measurements of soil K with response of potatoes to K fertilizers, but no one method of measuring the level of soil K has been entirely satisfactory. Exchangeable soil K has generally been used as an index of available K; however, analyses of the soil solution have also been used to obtain an index of K availability to plants.

During growth of a single crop more K may be removed from the soil than is present in both the soil solution and in exchangeable form. Exchangeable K plus estimates of nonexchangeable K which may be released during cropping have been widely used as a criteria for measurement of available K in soils. More recently, available soil K has been defined by intensity and capacity factors: the intensity factor is derived from the activity of K in the soil solution, and the capacity factor from soil exchangeable and nonexchangeable K.

The investigations reported herein are composed of two parts, a field experiment and a greenhouse and laboratory experiment. The objectives of the field investigation were to compare the effects of rates and sources of K on (1) yields and specific gravity of tubers, (2) the uptake and distribution of K, calcium (Ca), magnesium (Mg) in potato tissue, and (3) reducing sugar content of tubers at harvest.

The objectives of the greenhouse and laboratory studies were (1) to evaluate various intensity and capacity factors of soil K in 16 Michigan soils and (2) relate these factors to yield and uptake of K by four successive crops of oats grown in the greenhouse.

PART I

EFFECT OF RATES AND SOURCES OF POTASSIUM ON YIELDS, SPECIFIC GRAVITY, MINERAL CONTENT, AND REDUCING SUGAR CONTENT OF POTATOES

LITERATURE REVIEW

Potassium Deficiency Symptoms in Potato Plants

Potassium (K) deficiency in potatoes (as described by Knowles et al., 1940; Cook, 1962; Wallace, 1961) results in retarded growth and shortening of the internodes, which give the plants a compact appearance. Leaves become crinkled, droop, and are reduced in size due to narrow arrangement of the leaflets which form a sharp angle with the stem. Appearance of abnormally dark green foliage is an early indication of K shortage. Later, older leaves become yellowish, and a brown or bronze color develops, starting at the tip and edge and gradually affecting the entire leaf. The lower leaves may dry up at the same time leaving a tuft of green leaves at the top of the plant. If severe K deficiency develops, the entire plant eventually dies.

Effect of Rate and Source of Potassium on Yields and Specific Gravity of Potatoes

Herman and Merkle (1963) studied the effects of rates and sources of K on potato yields and quality. In field trials at seven locations in the major potato growing areas of Pennsylvania, potato yields were not increased when more than 66 pounds of K per acre were applied as either KCl or K_2SO_4 if the exchangeable soil K was higher than 200 pounds per acre. Soil variability, moisture content, and variety differences apparently affected the yield response of the potatoes as much as the source of K. However, specific gravity of tubers was lower when KCl was applied at rates of 133 and 199 pounds K per acre than when equivalent amounts of K were applied as K_2SO_4.

Rowberry et al. (1963) studied rates and sources (KCl and K_2SO_4) of K fertilizers on potatoes grown on mineral soils in Ontario. Although there were some increases in yield from rates of fertilizer higher than 1000 pounds per acre, yields were generally not increased when more than 1500 pounds per acre of 6-12-12 was applied. However, specific gravity decreased with increasing rates of fertilizer, and also increased with increasing replacement of the chloride salt by the sulfate salt.

Murphy and Goven (1965) compared applications of K_2SO_4 and KCl on Russet Burbank potatoes in Maine. Yields and specific gravities were not significantly affected by source of K but surface russeting was better when K_2SO_4 was used as a source of K.

The results of a ten-year investigation (Murphy and Goven, 1966) on Katahdin potatoes in Maine indicated that (1) source of K did not influence yield of potatoes, (2) specific gravity was higher when K_2SO_4 or KNO_3 were used as K fertilizers than when KCl was applied, (3) potatoes fertilized with KCl tended to produce chips of lighter color than did those fertilized with K_2SO_4 or KNO_3 and (4) specific gravity of the tubers was lower and potato chips tended to be lighter in color for all sources as the rate of K fertilization was increased.

Effect of Potassium Upon the Carbohydrate Composition of Potatoes

The relation of K to the carbohydrate metabolism of potatoes has not been clearly established. Terman (1949, 1950) reported that the starch content of potato tubers is usually decreased as the rate of K fertilization is increased on very fertile soil. Ward (1959) observed a decrease in total starch content at high rates of K fertilization due to a stimulation of the decomposition of carbohydrate reserves. Smith and Nash (1942) reported that carbohydrate production and ultimate starch accumulation were lower in tubers grown in soils to which high rates of chlorides (Cl) had been applied.

Houghland and Shricker (1933) and Ware and Kimbrough (1933) reported that the total starch content of potato tubers was not affected by sources of K fertilizers when KCl and K_2SO_4 were applied. Lucas et al. (1954) reported that tubers fertilized with KCl contained 1.3% less starch and were 6% lighter in weight than those fertilized with K_2SO_4.

There is some evidence that the various anions associated with K fertilizers may differentially influence the enzyme content or the functions of enzymes in potatoes, and thus indirectly affect the starch and dry matter content. James (1930) states that "application of K increases catalytic activity and, therefore, may increase the efficiency of starch formation." Latzko (1955) found that the hydrolytic activity of carbohydrases, such as invertase, amylase, and β-glucosidase, is inhibited by Cl^- ions, and increased by sulfate ($SO_4^=$) ions.

Mulder (1956) noted that K affected the rate of potato tuber respiration more than N, P, Mg, or Ca. Potassium deficient tubers had higher respiration rates than tubers grown with an optimum K supply. The increased rate of respiration was attributed to easier bruising of K-deficient tubers. The increased respiration rate of bruised tuber tissue was related to a stimulation of respiration of healthy cells by substances derived from the damaged cells and diffusing to the intact cells.

Effects of Levels and Sources of Potassium On Absorption of Calcium, Magnesium, and Phosphorus by Potato Plants

High rates of K applied to soils can induce magnesium (Mg) deficiency in crops (Adams and Henderson, 1962; Hovland and Caldwell, 1960; Lucas and Scarseth, 1947). Tissue of Mg-deficient plants frequently contains low levels of Mg and high levels of K. It is difficult to establish any meaningful ratios between these ions to define deficiency or sufficiency levels in various plants. However, Hossner et al. (1968) reported that when soil K:Mg ratio exceeded 5:1, K-induced Mg deficiency occurred on potatoes grown on an acid sandy podzol in northern Michigan.

Scharrer and Mengel (1958) reported that a physiological antagonism exists between K and Mg which is independent of the colloidal effects of the soil and of the anion of the K salt applied. They suggest that this antagonism is restricted to the green tissue and showed that it is most prevalent in the leaves.

Wilcox (1961) grew potatoes on a Genessee sandy loam soil with broadcast applications of 0, 75, 150, and 225 pounds per acre of K_2O applied either as KCl or K_2SO_4. To intensify the anion effect, N was applied as $(NH_4)_2SO_4$ with K_2SO_4 treatments and as NH_4Cl with KCl treatments. Sixty-six pounds per acre of N were applied with the basic treatment. The N and K fertilizer were broadcast and disked into the soil just before planting. In 1959, a 32-128-0 fertilizer treatment was applied in a band and in 1960 a 44-192-0 fertilizer treatment was applied in a band at planting time. Tissue samples at the prebloom stage showed no difference in P composition due to treatment in 1959 and 1960. However, samples collected at time of tuber development in 1960 showed a reduction of P concentration as K fertilizer rate increased. The percentage K in the tissue was increased and that of Ca and Mg decreased as rates of K fertilizer were increased. Percentages of Ca and Mg in the tissue was higher when Cl salts were applied than when SO_4 salts were applied.

Banded Versus Broadcast Application of Potassium Fertilizers on Potatoes

Cooperative field investigations on fertilizer placement for potatoes conducted from 1931 to 1937 in Maine, Michigan, New Jersey, New York, and Ohio were summarized by Cummings and Houghland (1939). The chief comparisons were as follows: (1) fertilizer in two bands, one on each side of and level with the seed piece at distances of 1, 2, and 4 inches from the seed piece; (2) in bands on each side and 2 inches below the seed piece; (3) a single band above the seed piece; (4) in a single band underneath seed piece, with 1 to 2 inches of fertilizer-free soil interposed;

(5) in furrow, lightly mixed with soil, and (6) in furrow well-mixed with soil.

Placement of the fertilizer in a band immediately under or above or mixed with the soil around the seed piece usually resulted in delayed emergence of the sprout and reduction in yield. Fertilizer placed in a band at each side of the row resulted in more rapid emergence of sprouts, more vigorous plant growth, and higher yields than the other methods of application.

Cooke (1953) summarized the results of 29 experiments conducted in England from 1945 to 1947, and recommended that fertilizer be placed in two bands, one on each side of the row, for most efficient utilization of fertilizer applied at rates normally required to give maximum yields. In wet or normal rainfall years, no harmful effects were noted when the fertilizer was placed in contact with the seed. In an abnormally dry year (1947), however, growth was severely retarded at several locations when heavy fertilizer applications were placed in contact with the seed, and yields were decreased as compared to those obtained when fertilizer was placed in side bands.

The effectiveness of fertilizer which was broadcast and plowed down was compared to that when fertilizer was placed in bands on each side of the seed piece on a Caribou loam soil at Aroostook Farm, Presque Isle, Maine, in 1943 and 1944 (Chucka et al., 1944; Hawkins et al., 1947; and Chucka et al., 1945). In these tests, the total amount of nutrients applied per acre in each case was equivalent to 2,000 pounds per acre of 6-6-12 fertilizer. The types of application included (1) broadcasting all the fertilizer before plowing, (2) plowsole placements, (3) broadcasting all the fertilizer after plowing, (4) combining plow-down and row applications, and (5) placing all fertilizer in side bands.

Although some of the other methods of application resulted in yields as good or slightly better than when all the fertilizer was placed in side bands, none of them were consistently superior to side banding in either a wet year (1943) or a dry (1944) season. It was concluded that under the conditions of the experiments, there was no advantage in varying the placement from applying all fertilizer in side bands.

Berger et al. (1961) conducted field trials in Wisconsin using three different soil types and three potato varieties to compare band and broadcast applications of K salts containing chlorides and sulfates. They concluded that chlorides, banded in the row with P and N fertilizers, will inhibit P uptake and reduce yield and dry matter content of potatoes as compared to sulfates. Separating the KCl from the P fertilizer, by broadcasting the KCl and banding the P, increased P uptake and yields in most cases. Potassium sulfate was considered a better source of K than KCl when applied banded in the row with the P and N fertilizer. In general, sulfate of potash-magnesia appeared to be the best source of K for both increasing potato yields and improving quality.

Hawkins (1965) reported that experiments conducted in Connecticut where one half of the K either as KCl or K_2SO_4 was plowed down resulted in as good or slightly better potato yields than applying all the fertilizer in the row using side bands at planting. Under the dry spring conditions of 1963 at locations where irrigation was not used, potatoes which received 75% of the K as a sidedressing (when the plants were at the 3-5 inch stage) were more vigorous and produced slightly larger yields than those which received all the K in side bands at planting. This was true whether chloride, sulfate, or nitrate of K was used. However, the best growth, yield, and dry matter content were obtained with KNO_3. In 1964, on a soil limed to pH 5.4 and testing medium in available K, applications of KCl, either plow-down or broadcast after plowing, were compared with all the K applied in side bands at planting. The plow-down or broadcast treatments resulted in improved early growth under the dry soil conditions in the spring and in equal or slightly higher yields as compared to K applied in side bands.

METHODS AND MATERIALS

In May, 1967, experiments to determine the effects of various rates and sources of K fertilizers on potato yields were initiated on a McBride sandy loam soil at the Montcalm Experimental Farm in Montcalm County, Michigan. Experiments were laid out in a randomized complete block design with 4 replications with each experimental plot being 50 feet long and 16 feet wide and potatoes were planted in 32 inch rows. Of the six potato rows in each plot, three were planted to the Russet Burbank variety, and the other three to the Sebago variety. On all plots, an equivalent of 60 pounds N per acre as NH_4NO_3 was plowed down and another 60 pounds N was banded at planting along with 100 pounds per acre of P_2O_5 as 0-46-0. When banding procedure was used, the fertilizer was placed in 2 bands, 2 inches on either side and level with the seed piece. Potatoes were planted on May 13, 1967.

A. Field Procedure

1. Rate of Potassium Study

Prior to fertilizer application on the experimental area where rates of K were compared, the soil tested pH 6.6, available P was 154 pounds per acre, and extractable K, Ca, and Mg were 210, 1426, and 141 pounds per acre respectively. Soil pH was determined in a 1:1 soil:water suspension using a glass electrode potentiometer. Available phosphorus was extracted for 1 minute with Bray P-1 reagent (0.025 N HCl and 0.03 N NH_4F), using a 1:8 soil:extractant ratio. Cations were extracted for 1 minute with 1.0 N NH_4OAc(pH 7.0) using a 1:8 soil:extractant ratio.

Six levels of K were established by applying the equivalent of 0, 60, 120, 180, 240, or 480 pounds of K_2O per acre as KCl. All K was banded at planting except when 480 pounds K_2O was applied; in this treatment, 360 pounds per acre of K_2O was broadcast and plowed down, and 120 pounds per acre of K_2O was applied in bands at planting.

2. Source of Potassium Study

On the area where sources of K were compared, the soil test values were as follows: pH 6.7, 150 pounds P per acre, and 270, 1336, and 140 pounds per acre of exchangeable K, Ca, and Mg respectively.

Potassium was applied in bands at planting at a rate to supply 150 pounds K_2O per acre as KCl, KNO_3, K_2SO_4, or K_2CO_3. A check treatment was included to which no K was applied.

3. Collection of Plant Tissue Samples

On July 8, when the plants were 12-14 inches high, petiole and leaf samples were obtained from plants where rates of K were compared, and subsequent samples were taken on July 28, and August 18. Each sample consisted of 40 to 50 petioles from the fourth leaf below the growing tip of the plant, which is the youngest fully expanded leaf of the plant. The petiole samples consisted of that portion of the plant between the stem and the base of the first leaflet while the leaf samples consisted of the leaves removed from the end of the petioles.

Whole plant samples (that part of the plant above the soil surface) and the tubers under those plants were obtained on July 28, August 18, and September 21, 1967.

Eight whole plants were chosen at random on one end of the plots at each sampling date.

Where sources of K were compared, petiole and leaf samples were taken as described above on July 14, August 4, and August 25, 1967.

Since length of growing season for potatoes varies widely, even within the same locality, plants and samples were classified according to their physiological age as well as by time from planting. Under certain ideal conditions tubers may be harvested within 90-100 days from planting while under other conditions the crop may be grown for as long as 150 days, as in the case of this study. In this study, plants emerged about two and one half weeks after planting.

The results relating to the mineral concentration in petioles and leaves of the first sampling date will be classified as "early season" which is as soon as plants are large enough (12-14 inches high) to provide adequate petiole samples. The second sampling will be considered "mid-season," which is that time from blossoming to and including tuber set. The third sampling is considered "late season" and is that period when the tubers are one half to three-fourths mature. With respect to the discussion of mineral content of whole plants and tubers, the first sampling date will be considered "early tuber set," the second date "late season" when the tubers are two-thirds to three-fourths mature, and the third samplirg date "mature" when tubers have matured.

4. The Havesting and Specific Gravity Determination of Potatoes

Potatoes from the two inside rows for a length of 30 feet on the rate of K experiment, and of 50 feet on the source of K experiment, were harvested for yields on October 12, 1967.

Specific gravity determinations were made by the hydrometer method as described by Smith (1950). An 8-pound sample of potatoes was placed in a wire basket and the basket suspended from the bulb of the hydrometer. The sample and hydrometer were then immersed in water, and the specific gravity readings were obtained at the water level on the scale in the hydrometer tube.

B. Laboratory Procedure

1. Sample Preparation and Analysis of Plant Tissue

Twelve potato tubers from each treatment and for each sampling date were thoroughly washed in tap water and rinsed under distilled water to remove soil particles and then sliced. All plant samples (the sliced tuber tissue, petioles, leaves, and whole plants) were dried at 65°C and ground to pass a 20 mesh sieve.

All tissue samples were dry ashed according to the procedure of Peech as described by Jackson (1958). One g. of oven-dried tissue was ashed at 400-425°C for 15 hours. After cooling, 25 ml. of 1 N HNO_3 was added to the ash, and evaporated to dryness on a hot plate. The residue was again placed in a muffle furnace at 400°C for 10 minutes, cooled, and then dissolved in 25 ml. of 1 N HCl. The resulting solution was filtered and diluted to 100 ml. for the cation determinations.

Potassium in the filtrate was determined using a Coleman Model 21 flame photometer; Mg and Ca were determined in a diluted filtrate using a Perkin Elmer Model 290 and 303 atomic absorption spectrophotometer respectively; 1500 ppm La was added to the diluted filtrate to eliminate interference from other ions (Doll and Christenson, 1966).

2. Reducing Sugar Determination in Potato Tuber Tissue

Ten tubers from each plot were sampled by forcing a small cork borer through the tuber longitudinally from the stem end to the bud end. Twenty-five g. of tuber tissue were collected in this manner and this then made up to 100 g. with reagent grade methanol.

The 25 g. of tuber tissue and methanol were poured into a blender and ground for 2 minutes at the high blending speed. After blending, the slurry was filtered through Whatman No. 2 filter paper and the filtrate was used for sugar evaluation.

A low-alkalinity copper reagent was made according to the procedure of Somogyi (1950) by dissolving 12 g. of sodium potassium tartrate and 24 g. of anhydrous sodium carbonate in about 250 ml. of H_2O. A solution of 4 g. of cupric sulfate pentahydrate in 50 ml. of H_2O was added while stirring, followed by 16 g. of sodium hydrogen carbonate. A solution of 180 g. of anhydrous sodium sulfate in 500 ml. of H_2O was boiled to expel air, then the two solutions were combined and diluted to 1 liter. After standing one week the clear supernatant solution was used in the procedure given below.

An arsenomolybdate reagent was prepared as described by Nelson (1944). Twenty-one ml. of 96% sulfuric acid was added to 25 g. of ammonium molybdate in 450 ml. of H_2O followed by 3 g. of disodium hydrogen arsenate heptahydrate dissolved in 25 ml. of H_2O. The mixed solution was incubated 24 hours at 37°C and stored in a glass stoppered brown bottle until ready for use.

To 1 ml. of the sugar solution samples, blanks, and standard sugar solutions, an equal volume of the low-alkalinity copper reagent was added, heated 10 minutes in a vigorously boiling water bath, and then cooled. One ml. of arsenomolybdate reagent was added and when all the cuprous oxide was dissolved after mixing, the solution was diluted to 50 ml. and allowed to stand at least 15 minutes but not more than 40 minutes. Absorbances were read at 540 mμ in a Bausch and Lomb colorimeter. Percent transmission was converted to milligrams reducing sugar by reference to a standard curve prepared by using known amounts of reducing sugar. The data were calculated as percent reducing sugar on fresh weight basis.

3. Statistical Analyses

Data were statistically analyzed utilizing a Controlled Data Corporation (CDC) 3600 digital computer. All data from the K rate and source experiments were subjected to analyses of variance using a split block design with K treatments as the whole-plot and potato varieties as the sub-plots. The data concerning the K, Ca, and Mg concentrations in petioles, leaves, whole plants, and tubers were first analyzed for differences between treatments at each time of sampling and then combined and analyzed to determine if a difference existed for the same treatment between sampling dates.

No significant interaction between K rate or source of K and the two varieties were noted with respect to K, Ca, and Mg in potato petioles, leaves, plants, and tubers. All discussion concerning the mineral content will therefore be on the basis of an average of both varieties.

The "honest significant difference" (hsd) as proposed by Tukey (Steel and Torrie, 1960) was calculated from the results of the analyses of variance. Larger differences between means are required for significance using the hsd as compared to the "least significant difference" (lsd) resulting in a more rigorous test for significant differences.

RESULTS AND DISCUSSION

Field experiments on Burbank and Sebago potato varieties were conducted to compare the effects of various rates and sources of K on: (1) yields and specific gravity of tubers, (2) the uptake and distribution of K, Ca, and Mg in potato tissue, and (3) reducing sugar content of tubers at harvest.

A. Rate of Potassium Study

1. Yields and Specific Gravity of Burbank and Sebago Potatoes

Yields of both Burbank and Sebago potatoes were increased when K fertilizer was applied (Tables 1 and 2). An application of 120 or 180 pounds of K_2O per acre resulted in higher yields than when 60 pounds of K_2O was applied, but when 240 or 480 pounds K_2O were applied, yields were lower than those obtained when 120 or 180 pounds were applied (Table 2).

TABLE 1.--Yield and specific gravity of Burbank and Sebago potatoes as related to rate of K fertilization

Pounds K_2O Per Acre	Burbank		Sebago	
	Yield (Cwt/A)	Specific Gravity	Yield (Cwt/A)	Specific Gravity
0	203	1.091	210	1.090
60	212	1.090	226	1.089
120	275	1.090	299	1.089
180	242	1.089	291	1.088
240	214	1.088	208	1.085
480	228	1.088	232	1.085
hsd (.05)	ns	.002	ns	.003

TABLE 2.--Significant differences between Burbank and Sebago potato yields as related to rate of K fertilization

Comparison	Probability Level	
	Burbank	Sebago
No K vs. K_2O	.05	.05
120 vs. 180 lbs. K_2O	ns	ns
60 vs. 120 and 180 lbs. K_2O	.05	.05
240 vs. 480 lbs. K_2O	ns	ns
120 and 180 vs. 240 and 480 lbs. K_2O	.05	.05

Specific gravity decreased with increasing rates of KCl on both Burbank and Sebago potato varieties, and this decrease was most pronounced for Sebagoes (Table 1). The differences in dry matter content were evident throughout the growing season from the time of early tuber set (Table 3), although the percentage of dry matter in the tubers increased as the plants matured. The decrease in dry matter may in part be attributed both to an increase in K uptake by the plants (Tables 4 and 5) and to a probable increase in Cl uptake as has been reported (Terman, 1950; Dunn and Rost, 1948; Nelson and Hawkins, 1947) when rates of KCl are increased. Increased Cl content has the effect of decreasing the starch content of potatoes (Lucas et al., 1954; Smith and Hash, 1942; Terman, 1949; Terman, 1950).

A possible explanation for the decrease in both yields and specific gravity is that large doses of Cl decrease the total amount of carbohydrates in the leaves, apparently caused by reduced chlorophyll content and weakened photosynthetic activity (Baslavskaga, 1936). Corbett and Gausman (1960) suggest the possibility that a high Cl treatment might shunt the carbohydrate metabolism into the

TABLE 3.--Dry matter content (%) of Burbank and Sebago tubers in early tuber set, tubers two-thirds to three-fourths mature, and mature tubers (76, 97, and 131 days after planting, respectively) as related to rate of K fertilization

Pounds K_2O Per Acre	Percent Dry Matter					
	Burbank			Sebago		
	76 days	97 days	131 days	76 days	97 days	131 days
0	23.9	24.2	26.6	23.3	24.8	26.2
60	23.6	24.4	26.4	23.3	23.1	25.5
120	23.9	23.4	24.9	22.2	23.9	26.2
180	21.9	22.6	24.7	21.2	22.7	25.4
240	22.2	22.4	24.0	21.4	22.0	24.3
480	22.2	21.8	24.6	20.9	21.2	24.2
hsd (.05)	1.5	1.2	1.5	.96	.88	.68

TABLE 4.--Potassium content (%) in petioles and leaves in early season, midseason, and late season (56, 76, and 97 days after planting, respectively) as affected by rate of K fertilization

Pounds K_2O Per Acre	Potassium Content (%)							
	Petioles				Leaves			
	56 days	76 days	97 days	Average	56 days	76 days	97 days	Average
0	9.04	6.32	2.69	6.02	4.49	2.00	1.63	2.71
60	11.30	6.43	3.07	6.93	4.63	2.24	1.81	2.89
120	11.55	7.01	4.01	7.52	4.85	2.42	2.07	3.11
180	12.14	8.21	5.19	8.51	5.01	2.80	2.49	3.43
240	12.44	9.38	5.98	9.27	5.40	3.09	2.66	3.72
480	12.78	10.61	7.64	10.34	5.87	3.83	3.24	4.31
hsd (.05)	.52	.30	.23	.10	ns	.84	.57	.73
(.01)	.66	.38	.29	.14	ns	ns	.72	.97

TABLE 5.--Potassium content (%) in plants and tubers in early tuber set, tubers two-thirds to three-fourths mature, and mature tubers (76, 97, and 131 days after planting, respectively) as affected by rate of K fertilization

Pounds K_2O Per Acre	Potassium Content (%)							
	Whole Plants				Tubers			
	76 days	97 days	131 days	Average	76 days	97 days	131 days	Average
0	2.64	1.75	0.45	1.61	1.76	1.57	1.42	1.58
60	3.21	2.10	0.52	1.94	1.86	1.71	1.52	1.69
120	3.67	2.74	0.59	2.33	2.00	1.89	1.61	1.83
180	4.72	3.72	1.10	3.18	2.28	2.05	1.78	2.03
240	5.12	3.91	1.26	3.43	2.38	2.19	1.80	2.12
480	5.61	4.80	1.63	4.01	2.65	2.40	2.09	2.37
hsd (.05)	1.04	.94	.68	.58	.27	.23	.23	.19
(.01)	1.31	1.18	.86	.80	.34	.29	.29	.25

triose phosphate to pyruvate pathway by increasing the inorganic P in the plant. This would result in a high CO_2 output, low energy release, and result in a decrease in dry weight. From the literature reviewed, it appears that the exact function of chloride in potato plant nutrition as related to yields and specific gravity is not yet known.

2. Potassium Concentration in Potato Petioles

No significant interaction between rate of applied K and potato variety was obtained with respect to K content of potato petioles, leaves, plants, or tubers. Data relative to the K content of the plants therefore are presented as an average of the two varieties.

Potassium concentration in the petioles tended to increase with increasing rates of K_2O, although the concentration of K in the tissue decreased with maturation (Table 4). In the early season sampling (56 days after planting), K in the petioles was higher when K fertilizer was applied than when no K was applied, and the petioles from the 240 and 480 pound K_2O treatments contained more K than those from the 60 and 120 pound K_2O treatments (Table 4).

At midseason (76 days after planting), the K concentration in the petioles increased with each additional increment of applied K_2O (Table 4). At the late season (97 days after planting) sampling, the petioles contained less K than the early or midseason samplings; however, the K content in petioles increased with each increment of applied K_2O (Table 4).

When all sampling dates were averaged for each treatment the K concentrations in petioles were higher with increasing increments of K (Table 4).

3. Potassium Concentration in Potato Leaves

As in the petioles, the K concentration in potato leaves tended to increase with increasing rate of K_2O application, but the K content of leaves was only about one half that of the petioles (Table 4). At the early season sampling (56 days after planting) no significant differences in K concentrations of potato leaves were noted between rate of K treatments. At midseason (76 days after planting) the K content in leaves increased (0.05 level) when 480 pounds K_2O was applied as compared to the

0, 60, 120, and 180 pound treatments (Table 4). At the late season sampling (97 days after planting), the leaves from the 180, 240, and 480 pounds of applied K_2O treatments were significantly higher in K content when compared to no K. Leaves on plants to which a treatment of 480 pounds of K_2O was applied had significantly higher K concentration than treatments of 60, 120, 180 pounds of K_2O (Table 4).

When all sampling dates were averaged for each treatment (Table 4), the leaves from the 240 and 480 pound K_2O treatments were higher in K content than those from the 60 pound and no K_2O treatments.

4. Potassium Concentration in Potato Plants

The K concentration in whole plants increased as the rate of applied K_2O increased and concentrations were more similar to those found in leaves than in petioles (Table 5). Concentrations of K in plants at early tuber set (76 days after planting) increased with each increment of applied K_2O (Table 5). When tubers were two-thirds to three-fourths mature (97 days after planting) the K concentration in whole plants decreased as compared to the concentrations at early tuber set. At this physiological stage of growth, the K content in whole plants from treatments of 180, 240, and 480 pounds of applied K_2O were higher than those from the 60 pound K_2O and no K treatments (Table 5). Concentration of K in the whole plants when tubers were fully mature (131 days after planting) were only about one-third of that at the earlier samplings.

When all sampling dates were averaged for each treatment the K concentration was higher in whole plants with an application of 480 pounds of K_2O when compared with the no K, 60, 120, and 180 pound of applied K_2O treatments (Table 5). These data indicate that the magnitude of seasonal fluctuation in K concentrations of whole plants is less than that found in petioles.

5. Potassium Concentration in Potato Tubers

Potassium concentrations in potato tubers, as an average of both varieties, are considerably less when compared to petioles, leaves, and whole plants at the early tuber set stage of physiological development (Tables 4 and 5). At early tuber set (76 days after planting) K content in tubers from treatments which received 180, 240, and 480 pounds of K_2O was higher than those from the no K treatment, and the K content in tubers from the 480 pound K_2O treatment was higher than those from the 60 and 120 pounds K_2O treatments (Table 5). When tubers were two-thirds to three-fourths mature (97 days after planting) K content decreased slightly and the significant differences in K content of tubers between treatments were the same as at early tuber set. When tubers were mature (131 days after planting), the same general differences in K content of tubers between treatments were apparent, but the total K content was less (Table 5). Potato tubers have the least amount of seasonal variation in K content when compared to petioles, leaves, and whole plants (Table 5).

6. Calcium Concentration in Potato Petioles

No significant interaction between rate of applied K and potato variety was obtained with respect to Ca content in potato petioles, leaves, plants, and tubers. Calcium content of the plant tissue is an average of both potato varieties.

Although Ca in petioles tended to decrease as rate of applied K increased and to increase as the plant matured, these differences were not statistically significant in any sampling date or when values for all sampling were averaged (Table 6).

7. Calcium Concentration in Potato Leaves

In general, Ca concentration in potato leaves increased as the plant matured, and decreased as the rate of applied K was increased (Table 6), although these differences were not statistically significant at the early season (56 days after planting) sampling. At midseason (76 days after planting) the concentration of Ca in the potato leaves when 240 and 480 pounds of K_2O were applied was less than that when no K was applied (Table 6). At late season (97 days after planting) the Ca content of potato leaves was less when 240 and 480 pounds of K_2O were applied than when 60 pounds K_2O and no K were applied (Table 6).

When all sampling dates for each treatment were averaged (Table 6) the concentration of Ca in the potato leaves when 240 and 480 pounds of K_2O were applied was less than that when 60 pounds and no K_2O were applied.

TABLE 6.--Calcium content (%) in petioles and leaves in early season, midseason, and late season (56, 76, and 97 days after planting, respectively) as affected by rate of K fertilization

Pounds K_2O Per Acre	Calcium Content (%)							
	Petioles				Leaves			
	56 days	76 days	97 days	Average	56 days	76 days	97 days	Average
0	1.22	1.39	1.59	1.40	1.62	1.98	2.35	1.98
60	0.99	1.35	1.67	1.34	1.30	1.97	2.39	1.88
120	1.09	1.36	1.73	1.39	1.44	1.83	2.19	1.82
180	0.93	1.35	1.71	1.33	1.26	1.76	2.21	1.73
240	1.03	1.25	1.61	1.29	1.33	1.60	1.94	1.62
480	1.05	1.22	1.66	1.30	1.27	1.63	1.94	1.61
hsd (.05)	ns	ns	ns	ns	ns	.23	.37	.20
(.01)	ns	ns	ns	ns	ns	.29	.45	.29

8. Calcium Concentration in Potato Plants

Whole plant concentrations of Ca decreased with increasing rates of applied K_2O (Table 7) and were similar to the trends observed for petioles and leaves (Table 6). At early tuber set (76 days after planting) plants from plots to which 180, 240, and 480 pounds of K_2O had been applied contained less Ca than those from plots to which no K had been applied (Table 7). When tubers were two-thirds to three-fourths mature (97 days after planting), the concentration of Ca in plants was not affected by applications of K. When tubers were mature (131 days after planting) Ca in the whole plants was higher than at previous samplings, and Ca still tended to decrease as rate of K_2O was increased (Table 7). When all sampling dates were averaged for each treatment the Ca concentrations in whole plants were not significantly different (Table 7).

9. Calcium Concentration in Potato Tubers

Calcium concentrations in potato tubers, as an average of both varieties, ranged from 0.02 to 0.03 per

TABLE 7.--Calcium content (%) in plants and tubers in early tuber set, tubers two-thirds to three-fourths mature, and mature tubers (76, 97, and 131 days after planting, respectively) as affected by rate of K fertilization

Pounds K_2O Per Acre	Calcium Content (%)							
	Whole Plants				Tubers			
	76 days	97 days	131 days	Average	76 days	97 days	131 days	Average
0	2.02	1.94	2.18	2.04	0.030	0.031	0.030	0.030
60	1.94	1.90	2.14	1.99	0.027	0.029	0.030	0.029
120	1.92	1.86	1.97	1.91	0.026	0.027	0.029	0.027
180	1.76	1.76	1.99	1.83	0.023	0.026	0.027	0.026
240	1.69	1.77	1.84	1.76	0.021	0.025	0.026	0.024
480	1.67	1.74	1.85	1.75	0.020	0.023	0.024	0.022
hsd (.05)	.19	ns	ns	ns	ns	ns	ns	ns
(.01)	.24	ns	ns	ns	ns	ns	ns	ns

cent and tended to decrease, but not significantly so, with increasing amounts of applied K_2O (Table 7). When all sampling dates were averaged, Ca in tubers was not affected by rates of applied K (Table 7). These data show that the concentration of calcium in potato petioles, leaves, and whole plants is 60 to 80 times that found in tubers, and is in agreement with the results of Laughlin (1966).

10. Magnesium Concentration in Potato Petioles

No significant interaction between rate of applied K and potato variety was obtained with respect to Mg concentrations in potato tissue. Concentrations of Mg in all tissue are an average of both varieties.

Magnesium content of petioles tended to increase as the plants matured. At each sampling date, Mg in the petioles decreased as the rate of K fertilizer was increased (Table 8), although this decrease was not statistically significant at the early season sampling. Application of 240 and 480 pounds of K_2O decreased (0.05 level) the Mg concentration in petioles at the midseason sampling as compared with those from the plots to which no K was applied.

TABLE 8.--Magnesium content (%) in petioles and leaves in early season, midseason, and late season (56, 76, and 97 days after planting, respectively) as affected by rate of K fertilization

Pounds K_2O Per Acre	Magnesium Content (%)							
	Petioles				Leaves			
	56 days	76 days	97 days	Average	56 days	76 days	97 days	Average
0	0.821	1.38	1.69	1.29	1.01	1.15	1.41	1.18
60	0.607	1.39	1.96	1.31	0.822	1.13	1.41	1.12
120	0.656	1.26	1.68	1.19	0.873	1.04	1.21	1.04
180	0.468	1.14	1.53	1.04	0.762	0.96	1.15	0.96
240	0.466	0.87	1.27	0.87	0.793	0.85	0.98	0.87
480	0.491	0.80	1.22	0.87	0.739	0.81	0.92	0.82
hsd (.05)	ns	.27	.55	.28	ns	.14	.25	.15
(.01)	ns	.34	.69	ns	ns	.18	.32	.20

Magnesium content of the petioles at late season (97 days after planting), decreased (0.01 level) when 240 and 480 pounds of K_2O were applied as compared to that when no K was applied (Table 8).

These results are in contrast to those reported by Doll and Hossner (1964). Concentrations of Mg in potato petioles decreased with maturation of potato plants when grown on a Karlin loamy sand soil testing between 30 and 40 pounds of exchangeable Mg per acre. This difference may in part be attributed to the differences in the level of exchangeable Mg and, thus, be merely a comparison of plants grown on a Mg-deficient as compared to a Mg-sufficient soil. The McBride sandy loam soil contains more clay in the B horizon which might release Mg to the plants, while the clay content of the Karlin soil decreases with depth.

When all sampling dates were averaged for each treatment the Mg concentration in petioles decreased significantly when the 240 and 480 pounds of applied K_2O treatments were compared to the 60 pound K_2O and no K treatments (Table 8).

11. Magnesium Concentration in Potato Leaves

Concentration of Mg in potato leaves as affected by rate of applied K_2O followed the same general pattern as in the petioles. At the early season sampling (56 days after planting), Mg content of the leaves tended to decrease with increasing applications of K_2O although this decrease was not statistically significant. For both the midseason (76 days after planting) and the late season (97 days after planting) samplings, Mg concentration in the leaves of plants grown on plots to which 240 and 480 pound K_2O had been applied decreased (0.01 level) when compared to those to which no K had been applied (Table 8). The average leaf Mg content throughout the season was higher when no K, 60 or 120 pounds K_2O had been applied than when 240 or 480 pounds of K_2O were applied (Table 8).

12. Magnesium Concentration in Potato Plants

In general, Mg concentration in whole plants, as in petioles and leaves, also tended to decrease as the rate of K was increased (Table 9). Magnesium content in plants

TABLE 9.--Magnesium content (%) in plants and tubers in early tuber set, tubers, two-thirds to three-fourths mature, and mature tubers (76, 97, and 131 days after planting respectively) as affected by rates of K fertilization

Pounds K_2O Per Acre	Magnesium Content (%)							
	Whole Plants				Tubers			
	76 days	97 days	131 days	Average	76 days	97 days	131 days	Average
0	1.050	1.31	1.41	1.27	0.090	0.090	0.095	0.091
60	0.938	1.19	1.34	1.15	0.090	0.091	0.097	0.092
120	0.911	1.12	1.17	1.06	0.093	0.093	0.103	0.097
180	0.808	1.03	1.15	0.99	0.095	0.098	0.101	0.098
240	0.780	0.90	0.99	0.89	0.095	0.096	0.101	0.097
480	0.746	0.86	0.87	0.82	0.101	0.102	0.106	0.103
hsd (.05)	.127	.21	.24	.19	.009	.011	ns	ns
(.01)	.218	.27	.31	.26	ns	ns	ns	ns

from treatments which received 240 or 480 pound K_2O was significantly lower at all three sampling dates than those when no K, 60, or 120 pounds K_2O were applied (Table 9). The average Mg concentration in whole plants throughout the season was lower when 240, or 480 pound K_2O was applied than when no K or 60 pounds K_2O were applied (Table 9).

13. Magnesium Concentration in Potato Tubers

A somewhat different pattern of Mg concentration in potato tubers as related to rate of applied K_2O was obtained. Although not always statistically significant, as rates of applied K_2O were increased, the Mg concentration in tubers also tended to increase (Table 9). This is in contrast to the results found for the petioles, leaves and whole plants, but is in agreement with the results of Laughlin (1966).

14. Effect of Rates of Potassium on Reducing Sugar Content of Tubers at Harvest

An important consideration involved in the production of high quality potatoes is obtaining a tuber free of degradation products and which will be resistant to non-enzymatic browning. Dehydrated and other forms of processed potatoes should be prepared from raw materials that are relatively low in reducing sugar content if the product is to be free from non-enzymatic discoloration when first produced and is to remain reasonably so in storage (Talburt and Smith, 1959).

No significant difference in reducing sugar content at harvest was found due to rates of applied K on Burbank and Sebago potato varieties (Table 10).

TABLE 10.--Per cent reducing sugar in tubers on a fresh weight basis as related to rate of K fertilization

Lbs. of K_2O per acre	Per cent Reducing Sugar	
	Sebago	Burbank
0	1.32	1.22
60	1.29	1.28
120	1.40	1.32
180	1.34	1.25
240	1.32	1.29
480	1.24	1.23
hsd (.05)	ns	ns

B. Source of Potassium Study

1. Yields and Specific Gravity of Burbank and Sebago Potatoes

Yields of both Burbank and Sebago potatoes were increased by K fertilizers; however, yields were not affected by the source of K for the 1967 growing season (Tables 11 and 12). Similar results have been reported by Terman, 1950; Rowberry et al., 1963; and Murphy and Goven, 1966.

TABLE 11.--Yield and specific gravity of Burbank and Sebago potatoes as affected by source of K fertilization

Lbs. of K_2O/A and source	Burbank		Sebago	
	Yield Cwt/A	Specific Gravity	Yield Cwt/A	Specific Gravity
0	150	1.091	214	1.088
150 KCl	184	1.089	245	1.087
150 KNO_3	184	1.089	262	1.082
150 K_2SO_4	197	1.089	237	1.088
150 K_2CO_3	161	1.089	241	1.088
hsd (.05)	ns	ns	ns	.004

TABLE 12.--Significant differences between Burbank and Sebago potato yields as affected by source of K fertilization

Comparison	Probability Level	
	Burbank	Sebago
No K vs. K sources	.05	.05
KCl vs. KNO_3	ns	ns
K_2SO_4 vs. K_2CO_3	ns	ns
KCl and KNO_3 vs. K_2SO_4 and K_2CO_3	ns	ns

The specific gravity of the Sebago variety was lower when KNO_3 was used as a source of K than when the other K fertilizers was applied (Table 11). The specific gravity of Russet Burbank potatoes was not affected by the source of K fertilizer.

2. Potassium Concentration in Potato Petioles

No significant interaction between K source treatments and potato variety was noted with respect to K concentrations in potato leaves and petioles, so the data presented are on average concentration of K for both varieties.

Concentration of K in petioles tended to be highest at the early season sampling and decreased as the plants matured (Table 13). At the early season (62 days after planting) and midseason sampling (83 days after planting), the concentration of K in the petioles was higher when K was applied, regardless of the source, than when no K was applied: concentrations of K in petioles were higher when KCl and K_2CO_3 were applied than when KNO_3 or K_2SO_4 were applied (Table 13). The K content in petioles was less at midseason and late season when K_2SO_4 was applied. The average K content throughout the season was higher in petioles from plants grown on plots to which K was applied than in those to which no K was applied (Table 13).

3. Potassium Concentration in Potato Leaves

Potassium concentration in potato leaves was higher early in the season and decreased as the plants matured (Table 13). The concentration of K in the leaves at early season (62 days after planting) increased when K was applied, although this increase was not statistically significant (Table 13). The content of K in the leaves at midseason

TABLE 13.--Potassium content (%) in petioles and leaves at early season, midseason, and late season (62, 83, and 104 days after planting, respectively) as affected by source of K fertilization

Treatment	Potassium Content (%)							
Lbs. of K_2O/A and source	Petioles				Leaves			
	62 days	83 days	104 days	Average	62 days	83 days	104 days	Average
0	8.66	5.92	3.40	5.99	4.44	2.16	1.81	2.80
150 KCl	10.63	7.29	5.15	7.69	4.75	2.54	2.29	3.19
150 KNO_3	9.77	7.37	5.19	7.44	4.83	2.70	2.34	3.29
150 K_2SO_4	9.78	6.83	4.71	7.10	4.78	2.62	2.18	3.19
150 K_2CO_3	10.34	7.64	6.71	8.03	4.85	2.89	2.76	3.15
hsd (.05)	.72	.61	.71	.34	ns	.18	.38	.23
(.01)	.93	.79	.93	.49	ns	.24	.50	.27

(83 days after planting) for all K treatments was higher than for the no K treatment. As in the case of the petioles, the concentration of K in the leaves when K_2SO_4 was applied was lower than when K_2CO_3 was applied at mid-season and late season (Table 13). The average K content at all sampling dates increased in leaves on plants grown on plots to which K had been applied as compared to those which did not receive K (Table 13).

The concentration of K in both petioles and leaves on plants grown on plots to which K_2SO_4 was applied was lower throughout the growing season than to those to which K_2CO_3 was applied. This is in agreement with results reported by Younts and Musgrave (1958). Under the conditions of this experiment, it is difficult to explain the reason for a high K uptake from the K_2CO_3 source and lower yield response for the Burbank potato variety (Table 13). It is suggested that more work needs to be done with this source of K before a reasonable conclusion can be drawn.

4. Calcium Concentration in Potato Petioles

No significant interaction between K source treatments and potato variety was obtained with respect to Ca content in potato petioles and leaves, so the data presented are an average of both varieties.

Calcium concentration increased in petioles as the potato plant matured. At the early season sampling (62 days after planting), the Ca content decreased in petioles from plants grown on plots to which K_2CO_3 was applied as compared to those to which no K was applied (Table 14). The concentration of Ca in the petioles was not affected by source of K for the midseason or late season samplings (Table 14), nor were the average Ca concentrations for those samplings.

5. Calcium Concentration in Potato Leaves

For the early season sampling the Ca content of potato leaves was less when K_2CO_3 was applied than when no K was applied (Table 14). The Ca content in potato leaves was not significantly affected by various sources of K at the midseason or late season samplings (Table 14).

TABLE 14.--Calcium content (%) in petioles and leaves at early season, midseason, and late season (62, 83, and 104 days after planting, respectively) as affected by source of K fertilization

Treatments	Calcium Content (%)							
Lbs. of K_2O/A and source	Petioles				Leaves			
	62 days	83 days	104 days	Average	62 days	83 days	104 days	Average
0	1.06	1.23	1.38	1.22	1.39	1.49	2.19	1.69
150 KCl	0.94	1.16	1.40	1.16	1.27	1.36	2.07	1.56
150 KNO_3	0.94	1.11	1.31	1.12	1.20	1.35	1.98	1.51
150 K_2SO_4	0.91	1.22	1.43	1.18	1.25	1.51	2.15	1.63
150 K_2CO_3	0.85	1.14	1.39	1.12	1.16	1.33	1.99	1.49
hsd (.05)	.12	ns	ns	ns	.17	ns	ns	ns
(.01)	.16	ns	ns	ns	.23	ns	ns	ns

6. Magnesium Concentration in Potato Petioles

No significant interactions between K treatments and variety were noted with respect to Mg content in potato tissue and the data presented are an average of both varieties.

The Mg content in potato petioles increased with maturation (Table 15). At the early season sampling (62 days after planting), Mg content in petioles was less when KCl, KNO_3, and K_2SO_4 were applied than when no K was applied. The Mg content of petioles was lower when K_2CO_3 or K_2SO_4 were applied (0.01 and 0.05 level, respectively) than when no K, KCl, or KNO_3 were applied (Table 15).

At midseason (83 days after planting) the Mg in petioles was lower when K_2CO_3, KCl or KNO_3 were applied than when no K was applied. At late season (104 days after planting), the Mg content was lower in petioles from plots to which K_2CO_3 or K_2SO_4 were applied (0.01 and 0.05 level, respectively) than from those to which no K was applied (Table 15). The average Mg content was lower (0.01 level) in petioles of plants grown on plots to which K_2CO_3 was applied than in those from any of the other treatments (Table 15).

TABLE 15.--Magnesium content (%) in petioles and leaves at early season, midseason, and late season (62, 83, and 104 days after planting, respectively) as affected by source of K fertilization

Treatments	Magnesium Content (%)							
Lbs. of K_2O/A and source	Petioles				Leaves			
	62 days	83 days	104 days	Average	62 days	83 days	104 days	Average
0	0.842	1.020	1.59	1.15	0.880	0.933	1.16	0.99
150 KCl	0.693	0.876	1.39	0.98	0.790	0.830	1.02	0.87
150 KNO_3	0.716	0.818	1.38	0.97	0.831	0.860	1.02	0.90
150 K_2SO_4	0.663	0.942	1.50	1.03	0.782	0.897	1.06	0.91
150 K_2CO_3	0.535	0.736	1.21	0.82	0.718	0.800	0.91	0.80
hsd (.05)	.114	.132	.266	.12	.097	.092	.13	.08
(.01)	.147	.171	.345	.21	.126	.119	.17	.10

7. Magnesium Concentration in Potato Leaves

Leaf concentration of Mg increased as potato plants matured (Table 15). Early season, midseason, and late season sampling data show that the Mg content was lower in leaves from plots to which K_2CO_3 or K_2SO_4 were applied (0.01 and 0.05 level, respectively) than from those to which no K was applied (Table 15). Magnesium content of potato leaves was not significantly different between KCl, KNO_3, and K_2SO_4. The average Mg content was lower in leaves from plants grown on plots to which K_2CO_3 was applied than in those to which no K, KNO_3 or K_2SO_4 were applied (Table 15).

8. Effects of Sources of Potassium on Reducing Sugar Content of Tubers at Harvest

No significant differences in reducing sugar content at harvest was found due to sources of applied potassium for Burbank and Sebago potato varieties (Table 16). These results, together with these from the rate of K experiment, suggest that the reducing sugar content is more likely to be affected by storage conditions after harvest.

TABLE 16.--Per cent reducing sugar in tubers on a fresh weight basis as related to source of K fertilization

Lbs. of K_2O/A and source	Per cent Reducing Sugar	
	Sebago	Burbank
0	1.39	1.29
150 KCl	1.43	1.31
150 KNO_3	1.53	1.28
150 K_2SO_4	1.58	1.32
150 K_2CO_3	1.42	1.27
hsd (.05)	ns	ns

C. General Discussion of Potassium Rate and Source Experiments

The yield decreases noted when heavy rates of KCl were applied may be due to a K-induced Mg deficiency. Since Mg is a structural constituent of the chlorophyll molecule and is an activator of many enzyme reactions involving phosphate transfer and carbohydrates metabolism, inadequate Mg would result in decreased yields.

The reason for the depression of Mg uptake is difficult to explain. An increased K activity in soil solution possibly resulted in an interaction with the carrier that combines with the Mg ion or in an interaction with the carrier-producing system so that less Mg carrier is produced. Another possibility is that an increase in soil K results in a lowering of the activity or availability of Mg in the soil. A partial collapsing of the plates of expanding lattice clays could result from high applications of K, and Mg could be trapped in inaccessible interlayer positions in the clay minerals.

The lower Mg content of potato tissue grown on plots to which K_2CO_3 was applied as compared to other K sources cannot be explained on the basis of data obtained in the experiments reported herein. The reducing sugar content of tubers at harvest was not affected by rate or source of K.

Applications of more than 120 pounds K_2O per acre probably resulted in some degree of luxury consumption and was uneconomical with respect to both yields and initial cost of fertilizer. However, critical levels for elements shift as cation contents vary and should make one further aware that we are dealing with 16 or more elements in a plant that are simultaneously interacting. This is an important fact, because unless liming and fertilizer programs are carefully evaluated and monitored, nutrient excesses may cause shifts in the requirements for other elements.

PART II

EVALUATION OF POTASSIUM QUANTITY-INTENSITY RELATIONSHIPS OF SELECTED MICHIGAN SOILS

LITERATURE REVIEW

Potassium Release and Fixation

Potassium, like most other plant nutrients in soils, exists in forms which range from the water-soluble to the extremely inaccessible (Volk, 1933). In many partially-weathered soils, the clay and silt fractions cannot merely be regarded as colloidal frameworks on which cation exchange reactions take place (Arnold, 1960). An understanding of the behavior of lattice K is as important as the understanding of the behavior of the readily exchangeable K (Arnold, 1960).

In soils that are not strongly weathered, feldspars and micas ordinarily are the most abundant of the K-bearing minerals (Reitemeier, 1951). The most important of these are orthoclase and microcline feldspar, biotite and muscovite, mica and illite (Marshall, 1964).

Potassium feldspars are silicates consisting of SiO_4 and AlO_4 tetrahedra linked in all directions through the oxygen of the tetrahedra (Rich, 1968). Potassium in the K-feldspars is held in the interstices of the Si, Al-O framework and the negative charge produced by Al^{3+} in tetrahedral coordination is balanced by the positive charge of the cations in the interstices (Rich, 1968).

Extensive experiments on weathering of feldspars were conducted by Correns (1963). Water and weak acids initially released K from K-feldspar at a more rapid rate than other constituents, but in the course of weathering a Si-Al-O residue layer developed about the particles and reduced the rate of K loss to that of the decomposition rate of the Si-Al-O layer. Correns visualized a complex reaction and suggested that Al^{3+} is the ion which counters the negative charge produced by loss of K^+ to the solution phase. Feldspars occur mostly in the sand and silt fractions of soil and are either absent from or occur only in traces in the clay fraction (Reitemeier, 1951). Black (1966) states that the "stability of feldspars is associated with relative large particle diameter, as would be expected from the resistant residual surface layers."

Micas consist of unit layers each composed of two Si, Al-O tetrahedral sheets between which is a M-O, OH octahedral sheet, where M consists of Al^{3+}, Fe^{2+}, Fe^{3+},

Mg^{2+}, and other cations (Rich, 1968). Micas are classified in two major groups, dioctahedral and trioctahedral (Arnold, 1960). In muscovite, a member of the dioctahedral group, two out of three octahedral cation positions are occupied, whereas in biotite a member of trioctahedral mica, all three positions are occupied (Rich, 1968). In octahedral coordination in dioctahedral minerals Al^{3+} is the principal cation, whereas the divalent ions Mg^{2+} and Fe^{2+} are the main cations in the trioctahedral minerals (Rich, 1968). Potassium ions occupy positions between the unit layers in facing ditrigonal holes and are vulnerable to release when weathering occurs (Arnold, 1960).

Illite is considered to be a mixed-layer mica-montmorillonite (or vermiculite). Rich (1968) states that the "mixing may be in the XY plane as well as in the Z direction, however, the latter type of interstratification is usually recognized as the normal structure of mixed layer minerals."

Under conditions of free drainage, biotite weathers more easily than muscovite (Arnold, 1960) and there is clear evidence that the K in biotite is much more accessible to plants than the K in muscovite (Mortland et al., 1956). The studies of Walker (1949) and Denison et al. (1929) established that the weathering of micas depends on the replacement of some interlayer K by H_2O molecules, or, as is now thought, by hydronium ions, to give the mineral hydrobiotite. On weathering, changes within the silicate layers take place such as oxidation of ferrous iron, the preferential loss of some ions and, possibly, conversion of some oxygen ions to OH^- groups, which decrease the net negative charge on the lattice (Rich, 1968).

Some soils can provide enough K for many years, but the rate of release in others is too slow to meet the immediate needs of crops (Reitemeier, 1951). The categories of K in soils (Mortland, 1961) have been described by such names as "native," "nonexchangeable," "fixed," "lattice," "exchangeable," and "soil solution" K. Mortland states that

> most of these categories of soil K are derived empirically, in that each is frequently defined according to the particular procedure used for its analysis and may give little indication of the dynamics of K in a given soil.

A study of the release of native and fixed K in soils was made by Reitemeier et al. (1951). The mineral composition of various fractions of the soil was included, and no obvious relationship was noted between the extent of K release and the content of hydrous mica. They also pointed out that the role of K minerals must depend not only on their total abundance but also on their present K content and stages of weathering or formation. In their study, the two soils that had the highest rate of K release also had the highest montmorillonite content. Since the clay fraction of all the soils except one studied by Reitemeier et al. had more than 60% hydrous mica (Rich, 1968) pointed out that a combination of a good source of K (such as a fine-grained mica) and a mineral with a high cation exchange capacity and a low fixing capacity, might be necessary for the maintenance of an adequate exchangeable K supply. A high exchangeable K level may not be necessary if K released from a nonexchangeable to an exchangeable form is rapid enough (Rich, 1968).

The rate of release of initially nonexchangeable K thus becomes a matter of critical importance (Rich, 1968). The rate of K release from micas and of "fixed" K from vermiculite has been reported to be a diffusion-controlled process (Ellis and Mortland, 1956; Mortland, 1958; and Mortland and Ellis, 1959). If the rate of release of K from an unavailable to an available form is diffusion-controlled, then this process is more dependent upon diffusion processes than upon the law of mass action (Walker, 1959).

Mortland (1961) used the following equation to express the rate of release of "fixed" K from vermiculite and "native" K from biotite:

$$r = B\ (C^1 - C)$$

where r is the rate of K release; C^1 the activity of K in the lattice; C, the activity of K in solution; and B, the diffusion velocity constant, which contains geometry factors of the diffusion zone and the diffusion coefficient. From this equation it can be observed that if C^1 is greater than C, release occurs. If, however, C is greater than C^1, the opposite process, of fixation, will occur and r will represent the rate of fixation. Mortland points out in a soil with a heterogeneous group of 2:1 clay minerals, it is possible for both release and fixation to be taking place at the same time. If a soil is not at equilibrium, K may be released from one micaceous form and fixed by another.

In terms of the equation used by Mortland (1961), the rate at which K is either fixed or released from any specific mineral is determined by the constants B and C^1 and the variable C. The constants B and C^1 may be considered as characteristic properties of a given mineral that determine, to a large degree, the dynamics of its K reactions.

Measurement of Potassium Potential and Buffering Capacity and Their Relation to the Supply of Potassium to Plants

Scheffer and Ulrich (1962) have suggested that the activity ratio $a_K/a_{(Ca + Mg)}^{1/2}$, or AR_e^K, in a solution in equilibrium with a soil provides a satisfactory measure of the availability or the potential of soil K. AR_e^K is a measure of the intensity of labile K (K ions capable of exchange within 30 minutes at 25°C with Ca or Mg ions in dilute solution) in the soil. Different soils exhibiting the same value of AR_e^K may not possess the same capacity for maintaining AR_e^K while K is removed by plant roots (Beckett, 1964a; Schofield, 1947). When describing the K status of a soil it is desirable to specify not only the current potential of K in the labile pool but also the form of the quantity-intensity relation (Q/I relation) or the way in which the potential depends upon the quantity of labile K present (Beckett, 1964a).

Despite the fundamental nature of these concepts, there are certain difficulties in their use, as discussed by Beckett (1964a, b). The total activity (Low, 1951) and electrochemical potential of an ion throughout the soil solution system is not a constant for the soil, but depends on the total concentration of the solution. The chemical potential of the ion on the solid phase may be assumed to be constant, but this quantity cannot be measured, so Beckett (1964a) has suggested the adoption of activity ratios as a measure of the difference between the chemical potentials of two different ion species on the soil.

As the K potential near a root is reduced, K ions diffuse toward it, under many conditions quite slowly, at a rate depending on the local inequality in K potential (Beckett, 1964b). Potassium at a high activity in an undepleted soil is carried by the flow of water to the root and reducing the potential of the labile K causes the release of K from "fixed" forms, often slowly, but at a rate proportional to the difference between the reduced potential and the normal equilibrium potential for the soil (Mathews and Beckett, 1962). Mortland et al. (1956) have also shown root exudates accelerate the decomposition of unweathered K-bearing minerals.

Tinker (1964) states "there is no fully satisfactory reason for assuming the availability of K to plants depends on the chemical potential." Nevertheless, the chemical potential of an ion on the soil must control the potential of the ion on the plant root exchange sites, and it seems likely that the chemical potential is a major factor in root uptake. Alternatively, the important quality may be the activity of the ion in the soil solution, for some recent work further substantiates the concept that ion uptake by plant roots is from the soil solution and not directly from the solid phase of the soil (Lagerwerff, 1960). The variability of this quantity with solution concentration is then overcome by relating it to the equivalent value for another ion (Tinker, 1964).

Beckett (1964b) has shown that (Ca + Mg) can conveniently be employed as the denominator in measuring the ratio in a single soil. Woodruff (1955a, b, c) has suggested that the function controlling K uptake is the exchange energy, given by $\Delta G° = -RT \ln (K)/(Ca + Mg)^{1/2}$. For corn and soybeans, Woodruff (1955c) set the energy of replacement of K at which deficiencies appeared at -4,000 calories per chemical equivalent, and suggested an upper limit of -3,000 calories per chemical equivalent for normal performance. Arnold (1962) has applied Woodruff's methods to a variety of British soils, and obtained good correlations between exchange energies and uptake of K by ryegrass in pots during short-term cropping.

The activity ratio $a_K/a_{(Ca + Mg)}^{1/2}$, or AR_e^K, of a solution in equilibrium with a soil is taken to be a measure of the K intensity (I_K). It measures the chemical potential of the labile K present, relative to the chemical potential of labile (Ca + Mg) in the same soil (Beckett, 1964a). The quantity of exchangeable K(Q_K) is difficult to define or measure relative to a state of the soil with no labile K present, because of the K held at "specific sites" (Beckett and Nafady, 1967), which gives the Q/I relation its asymptotic form at low values of AR. The form of the Q/I relation has a linear upper part and a curved lower part. Beckett (1964a) has shown that the curvature at low values of AR^K is not an artefact due to the experimental technique, nor was it due to the release of fixed K during the experiment. The asymptotic convergence of the Q/I relation to the Q-axis is one reason why determinations of exchangeable K(Q_K or ΔK) are sometimes not precise.

A graph of ΔK against AR has the same form as a graph of Q_K against AR and avoids the difficulties of measuring Q_K (Beckett and Nafady, 1967). The ΔK must be estimated as the difference between the K concentrations of a solution before and after the addition of soil (Beckett, 1964a).

METHODS AND MATERIALS

A. Greenhouse Procedures

Sixteen soils, from 13 soil series which had a considerable range in K content were selected from different locations in Michigan. Extractable nutrient content and pH (Table 17) were determined as in Part I of this Thesis.

A greenhouse experiment was laid out in a randomized complete block design with four replications. One-gallon galvanized cans lined with plastic bags were used as containers. Soil samples were air-dried and passed through an 8-mesh sieve. Three thousand grams of well-mixed soil was placed in each container. Prior to seeding, 150 ppm phosphorus (P) as $Ca(H_2PO_4)_2$, 6 ppm of manganese (Mn) as $MnSO_4$, 4 ppm zinc (Zn) as $ZnSO_4$, and 150 ppm nitrogen (N) as $Ca(NO_3)_2$ were mixed thoroughly with the soil in each pot.

Thirty oat seeds were planted in each pot at a depth of 1/2 inch and thinned to a uniform number of

TABLE 17.--Extractable cations and pH prior to cropping for 16 Michigan soils used in greenhouse and laboratory evaluations

Soil Type	Extractable[1] cations (meg/100 g.)			pH
	K	Ca	Mg	
1. Charity clay loam I	0.439	20.33	1.56	7.7
2. Charity clay loam II	0.479	22.12	1.69	7.5
3. Lenawee clay loam	0.203	14.04	3.15	6.9
4. Sims clay loam I	0.908	16.50	4.22	6.5
5. Sims clay loam II	0.271	15.84	3.96	7.3
6. Sims clay loam III	0.156	9.77	1.56	7.6
7. Colwood loam	0.330	15.84	4.23	7.5
8. Conover loam	0.241	11.91	2.05	7.1
9. Miami loam	0.203	11.22	1.25	7.2
10. Hettinger silty clay loam	0.290	16.55	4.02	7.3
11. Brimley silt loam	0.156	10.14	1.80	7.5
12. Breckenridge sandy loam	0.165	13.68	2.68	7.4
13. Hillsdale sandy loam	0.156	9.77	1.56	7.6
14. Hodunk sandy loam	0.232	3.64	1.04	6.3
15. McBride sandy loam	0.271	2.67	0.77	6.5
16. Metamora sandy loam	0.339	4.01	0.42	6.2

[1]Extracted with 1 N NH_4OAc for 10 minutes.

plants per pot 10-12 days after emergence. The oat plants were harvested when the inflorescence was beginning to emerge from the sheath. The harvested tissue was dried at 65°C, weighed, ground to pass a 20-mesh sieve, and saved for chemical analysis. Oat tissue was ashed and analyzed for K content as outlined in Part I of this Thesis.

Four crops of oats were grown, and prior to each seeding, 100 g. of soil was removed after the soil in the pots had been removed, screened, and well-mixed. The 100 g. soil samples were allowed to air day prior to determining the exchangeable K. The soil in the pots was kept moist between seedings. Planting dates for each crop were February 6, March 28, April 29, and June 12, 1968.

B. Soil Potassium Evaluations

Equilibrium solution concentrations of K, Ca, and Mg were determined as given by Beckett (1964a and 1964b). For each soil, duplicate 5 g. samples were equilibrated with 50 ml 0.00159<u>M</u> $CaCl_2$ containing different amounts of KCl. The amounts of KCl used in the equilibrating solutions were 0, 0.00023, 0.00071, 0.00143, and 0.00181 M/L. Samples were kept at constant temperature (25 ± 1°C) for 24 hours and in this period received 8 hours of shaking. After settling, 25 ml of the supernatant solution were removed. Potassium was determined on a Coleman Model 21 flame photometer; Mg and Ca on a Perkin Elmer Model 290 and 303 atomic absorption spectrophotometer respectively using 1500 ppm La to supress interfering ions (Doll and Christenson, 1966).

Activity ratios were calculated from the composition of supernatant solutions and activity coefficients determined according to the Davies modifications of the Debye-Huckel equation (Butler, 1964). For an ion of charge Z, either positive or negative, the activity coefficient (γ) of the ion is given by

$$- \log_{10} \gamma = 0.5091 \, Z^2 \left(\frac{\sqrt{I}}{1 + \sqrt{I}} - 0.2 \, I \right).$$

The constants apply to solutions at 25°C. The ionic strength (I) of the solution is given by

$$I = 1/2 \, \Sigma \, Ci \, Z^2 i$$

where Ci is the concentration of the ith ion, Zi is its charge and the summation extends over the ions in the solutions.

The gain or loss of K (ΔKe) by the soils was obtained by subtracting the K concentrations of the solution before and after equilibration. The quantity-intensity (Q/I) relation for each soil was determined by plotting ΔKe against the corresponding AR^K value. The activity ratio at equilibrium (AR_e^K) was obtained from the intersection of the Q/I curve with the $\Delta K = 0$ axis. The (AR_e^K) represents the ratio $^{a}K/^{a}(Ca + Mg)^{1/2}$ in a solution that upon admixture with soil maintains its numerical value with respect to the activity of K, Ca, and Mg.

The exchangeable K ($-\Delta K$), values were determined by extending the linear part of the curve to the $AR^K = 0$ line. Potential buffering capacity (PBC^K) was calculated as the slope of the Q/I curve or $-\Delta K/AR_e^K$.

RESULTS AND DISCUSSION

The capacity of soils to supply K to plants depends not only on the quantities of the different forms present, but also on the rate at which nonexchangeable K is released to an available form. In soils, an equilibrium exists between exchangeable and nonexchangeable K, so that nonexchangeable K is released at a low level of exchangeable K, while at high levels, exchangeable K is "fixed" in a nonexchangeable form.

1. Yields and Potassium Uptake by Oats

Yields of the first oat crop were quite similar on all the various soils (Table 18) except Hodunk. The low yields and low K-uptake from the Hodunk soil are due to a residual herbicidal effect. However, large differences in K-uptake (Table 19) were obtained between the other soils for the first crop; for example, oats grown on some soils contained at least twice as much K as those grown on other soils (Table 19).

About two weeks after planting the second crop, oats grown on Sims II, Miami, Brimley, Breckenridge, and

TABLE 18.--Yields of four oat crops grown in greenhouse on sixteen Michigan soils without added potassium

Soil Type	Grams Dry Weight Per Pot				
	Crop 1	Crop 2	Crop 3	Crop 4	Total
1. Charity clay loam I	6.29	7.33	7.40	4.69	25.71
2. Charity clay loam II	6.84	7.92	8.75	4.50	28.01
3. Lenawee clay loam	7.06	7.04	7.90	4.57	26.57
4. Sims clay loam I	7.81	10.19	9.95	7.35	35.30
5. Sims clay loam II	7.26	8.12	8.34	3.10	26.82
6. Sims clay loam III	6.82	6.23	5.53	3.20	21.78
7. Colwood loam	7.56	8.88	9.09	5.10	30.63
8. Conover loam	6.12	8.17	6.62	3.61	24.07
9. Miami loam	6.50	6.42	6.80	3.42	23.14
10. Hettinger silty clay loam	7.86	8.98	8.70	4.49	30.03
11. Brimley silt loam	7.64	7.04	5.07	2.72	22.47
12. Breckenridge sandy loam	7.45	6.89	5.94	3.36	23.64
13. Hillsdale sandy loam	7.27	5.48	3.67	1.70	18.12
14. Hodunk sandy loam	1.84	5.93	6.71	3.58	18.06
15. McBride sandy loam	7.12	6.61	4.83	2.08	20.64
16. Metamora sandy loam	7.35	7.96	5.91	2.17	23.39

TABLE 19.--Potassium uptake by each of four crops and the total uptake by oats grown in greenhouse on sixteen Michigan soils without added potassium

Soil Type	Potassium Removed meq/100 g. soil				
	Crop 1	Crop 2	Crop 3	Crop 4	Total
1. Charity clay loam I	0.246	0.144	0.094	0.061	0.545
2. Charity clay loam II	0.278	0.195	0.116	0.082	0.671
3. Lenawee clay loam	0.129	0.087	0.086	0.047	0.349
4. Sims clay loam I	0.369	0.395	0.201	0.224	1.189
5. Sims clay loam II	0.184	0.113	0.073	0.025	0.395
6. Sims clay loam III	0.108	0.040	0.032	0.020	0.200
7. Colwood loam	0.198	0.160	0.108	0.062	0.528
8. Conover loam	0.126	0.100	0.044	0.032	0.302
9. Miami loam	0.108	0.073	0.046	0.029	0.256
10. Hettinger silty clay loam	0.231	0.103	0.088	0.044	0.466
11. Brimley silt loam	0.084	0.051	0.034	0.017	0.186
12. Breckenridge sandy loam	0.118	0.050	0.045	0.027	0.240
13. Hillsdale sandy loam	0.075	0.040	0.027	0.016	0.158
14. Hodunk sandy loam	0.062	0.126	0.062	0.029	0.279
15. McBride sandy loam	0.164	0.086	0.036	0.015	0.301
16. Metamora sandy loam	0.187	0.111	0.060	0.022	0.380

Hillsdale soils showed moderate K deficiency symptoms; both yields and uptake of K were decreased when compared to the other soils (Tables 18 and 19). Yields of the second oat crop were higher than those of the first crop on the Charity I, Charity II, Sims I, Sims II, Colwood, Conover, and Hettinger soils. The higher yields are probably due to both more total hours of higher light intensity and higher K supplying power (Table 19).

Yields of the third crop generally decreased as compared to the second crop (Table 18), except on Charity I, Charity II, Lenawee, Sims I, Sims II, Colwood, and Hettinger soils. Comparable yields for the second and third crop on these seven soils can be attributed to the high clay content and the capacity of these soils to maintain higher levels of exchangeable K. Severe K deficiency symptoms were observed at early growth stage on oats grown on Sims III, Conover, Miami, Brimley, Breckenridge, Hillsdale, Hodunk, McBride, and Metamora soils, from none of which was more than 0.075 meq K/100 g. soil removed by the oats (Table 19).

Severe K deficiency symptoms were noted in the fourth crop of oats grown on all soils except Sims clay loam I. Yields of the fourth crop were frequently only one half those of the third crop (Table 18). This yield decrease can be attributed to severe stress on the K-supplying capacity of the soils due to intensive cropping (Table 19).

2. Uptake of Exchangeable and Nonexchangeable Potassium by Oats

Exchangeable K, as measured by 1 N NH_4OAc, prior to cropping was significantly correlated (r = +0.98***) with total uptake of K; with uptake of nonexchangeable K (r = +0.82***) by four oat crops and with the K-uptake by each oat crop (Table 20). This correlation was noted despite wide variations in the extent to which initial exchangeable K in the soils represented a source of K for the oats (Table 21). For example, exchangeable K (measured as the difference between exchangeable K prior to cropping and that after the fourth crop) comprised 77 per cent of the total K-uptake on the McBride soil, but only 26 per cent in Sims IIand Hettinger soils (Table 21), with the remaining K taken up by the plants being derived from nonexchangeable forms. The amount of exchangeable K in the

TABLE 20.--Correlation between exchangeable potassium prior to cropping; uptake of potassium and yields of four crops of oats grown in greenhouse on 16 Michigan soils

Measurement	DF	r
Total K-uptake by oats	14	0.98***
K-uptake by crop 1	14	0.97***
K-uptake by crop 2	14	0.96***
K-uptake by crop 3	14	0.92***
K-uptake by crop 4	14	0.94***
Nonexchangeable K-uptake by oats	14	0.82***
Total yield of oats	14	0.74**

**Significant at 0.01 level.
***Significant at 0.001 level.

McBride soil represented the major portion of plant-available K, whereas in the Sims and Hettinger soils a considerable portion of the plant-available K was present in a nonexchangeable form.

Potassium released from nonexchangeable form during cropping (Table 21) accounted for over 50 per cent of the K taken up by oats on all soils except Hodunk, McBride, and Metamora. At least 0.10 meq K/100 g. soil (equivalent to 78 pounds/acre) was released to the first oat crop (Table 22) from Charity I, Charity II, Sims I, Sims II, Colwood, and Hettinger soils. This is in part reflected by the high levels of exchangeable K in these soils prior to the second cropping (Table 23).

TABLE 21.--Uptake of exchangeable and nonexchangeable potassium by four crops of oats grown in greenhouse on 16 Michigan soils

Soil Type	Uptake of Potassium in Soil (meq/100 g.)				
	Exchangeable	% of Total K Uptake	Nonexchangeable	% of Total K Uptake	Total
1. Charity clay loam I	0.265	49	0.265	51	0.545
2. Charity clay loam II	0.274	41	0.397	59	0.671
3. Lenawee clay loam	0.091	26	0.258	74	0.349
4. Sims clay loam I	0.560	47	0.629	53	1.189
5. Sims clay loam II	0.102	26	0.293	74	0.395
6. Sims clay loam III	0.074	37	0.126	63	0.200
7. Colwood loam	0.228	43	0.300	57	0.528
8. Conover loam	0.139	46	0.163	54	0.303
9. Miami loam	0.111	43	0.145	57	0.256
10. Hettinger silty clay loam	0.122	26	0.344	74	0.466
11. Brimley silt loam	0.077	41	0.109	59	0.186
12. Breckenridge sandy loam	0.093	38	0.147	62	0.240
13. Hillsdale sandy loam	0.067	42	0.081	58	0.158
14. Hodunk sandy loam	0.180	64	0.099	36	0.279
15. McBride sandy loam	0.232	77	0.069	23	0.301
16. Metamora sandy loam	0.288	76	0.092	24	0.380

[1]Extracted with 1 N NH_4OAc for 10 minutes.

[2]Extimated uptake of nonexchangeable K = uptake of K by oats—(exchangeable K prior to cropping—exchangeable K after cropping).

TABLE 22.--Nonexchangeable potassium taken up by each oat crop and total uptake of nonexchangeable potassium

Soil Type	Nonexchangeable[1] K-Uptake meq/100 g. soil				
	Crop 1	Crop 2	Crop 3	Crop 4	Total
1. Charity clay loam I	0.116	0.076	0.051	0.032	0.265
2. Charity clay loam II	0.137	0.118	0.077	0.065	0.397
3. Lenawee clay loam	0.082	0.068	0.067	0.041	0.258
4. Sims clay loam I	0.130	0.175	0.111	0.213	0.629
5. Sims clay loam II	0.174	0.084	0.016	0.019	0.293
6. Sims clay loam III	0.059	0.024	0.024	0.019	0.126
7. Colwood loam	0.120	0.102	0.070	0.008	0.300
8. Conover loam	0.058	0.045	0.035	0.025	0.163
9. Miami loam	0.043	0.046	0.036	0.021	0.145
10. Hettinger silty clay loam	0.170	0.065	0.076	0.034	0.344
11. Brimley silt loam	0.037	0.033	0.025	0.014	0.109
12. Breckenridge sandy loam	0.099	0.013	0.016	0.019	0.147
13. Hillsdale sandy loam	0.020	0.031	0.018	0.012	0.081
14. Hodunk sandy loam	0.005	0.013	0.053	0.028	0.099
15. McBride sandy loam	0.011	0.018	0.032	0.008	0.069
16. Metamora sandy loam	0.002	0.037	0.031	0.019	0.092

[1]Estimated uptake of nonexchangeable K = uptake of K by oats - (exchangeable K prior to cropping - exchangeable K after cropping).

TABLE 23.--Exchangeable potassium in 16 Michigan soils before and after four oat crops were grown in the greenhouse

Soil Type	Exchangeable[1] K(meq/100 g. soil)				
	Prior to Crop 1	Prior to Crop 2	Prior to Crop 3	Prior to Crop 4	After Crop 4
1. Charity clay loam I	0.439	0.309	0.241	0.203	0.174
2. Charity clay loam II	0.479	0.338	0.261	0.222	0.205
3. Lenawee clay loam	0.203	0.156	0.137	0.118	0.112
4. Sims clay loam I	0.908	0.669	0.449	0.359	0.348
5. Sims clay loam II	0.271	0.261	0.232	0.175	0.169
6. Sims clay loam III	0.156	0.109	0.091	0.082	0.080
7. Colwood loam	0.330	0.252	0.194	0.156	0.102
8. Conover loam	0.241	0.175	0.118	0.109	0.102
9. Miami loam	0.203	0.137	0.110	0.100	0.092
10. Hettinger silty clay loam	0.290	0.232	0.194	0.168	0.156
11. Brimley silt loam	0.156	0.109	0.091	0.082	0.079
12. Breckenridge sandy loam	0.165	0.146	0.109	0.100	0.072
13. Hillsdale sandy loam	0.118	0.063	0.054	0.045	0.041
14. Hodunk sandy loam	0.232	0.175	0.063	0.062	0.052
15. McBride sandy loam	0.271	0.118	0.054	0.050	0.041
16. Metamora sandy loam	0.339	0.137	0.063	0.054	0.051

[1]Extracted with 1 N NH_4OAc for 10 minutes.

The Charity II, Sims I, and Colwood soils were the only soils from which 0.1 meq K/100 g. soil or more was released during the second cropping (Table 22).

The contribution of nonexchangeable K to the third crop from the Charity I, Charity II, Lenawee, Sims I, Colwood, and Hettinger soils was considerably more than from the other ten soils, but the release of nonexchangeable K from Sims clay loam I was much larger (Table 22) than from the Charity I, Charity II, Lenawee, Colwood, and Hettinger soils.

Nonexchangeable K released from the soils during the fourth cropping period was quite small, except, that K released from the Sims clay loam I. The relative high quantity of exchangeable K prior to and after the fourth crop is indicative of the K supplying capacity of this soil (Table 23).

The correlation relating total yield to exchangeable K ($r = +0.74^{**}$) was significant, but it is difficult to provide a meaningful interpretation due to possible luxury consumption of K by the first oat crop.

3. Labile Potassium in Soils

Ionic equilibria play a fundamental role in fertility relationships because they govern the ability of the soil to supply a particular nutrient. Of the essential cations in the soil, K is used in largest amounts by plants, whereas Ca and Mg are normally the dominant cations in arable soils. For a better understanding of the K status of soils, the activity of $K/(Ca + Mg)^{1/2}$ equilibria in relation to adsorption characteristics of the soil material are important.

The capacity of a given soil to supply any particular nutrient is characterized by both the total amount of nutrient present and the energy level or intensity at which it is supplied. The relationship between these two parameters may be determined by the Quantity-Intensity (Q/I) method given by Beckett (1964a). This technique is based on thermodynamic principles, and holds promise of being applicable to all soils.

Quantity-Intensity (Q/I) curves (Figures 1-16, Appendix) illustrates how the AR^K in the soil solution depends on the exchangeable K content of the soil represented by ΔK, which is the change in exchangeable K relative to the value for exchangeable K at AR_e^K, the equilibrium ratio, where the soil neither gains or loses K. Since nearly all the labile K in field soils is exchangeable (Figures 1-16, Appendix) gives a close approximation to the relationship between the amount of labile K (Quantity factor Q) and AR^K (intensity factor I). The slope of the linear portion of the Q/I relation, $\Delta Q/\Delta I$, gives the amount of labile K that can be removed before AR_e^K changes by a given amount. This represents the Potential Buffering Capacity (PBC^K) of the soil for K, as defined by Beckett (1964a).

4. Equilibrium Activity Ratio and Potential Buffering Capacity of the Soils

The part of the equilibrium curves (Figures 1-16, Appendix), showing the relationship between release or adsorption of K by the soils and the activity ratio, were linear and allowed for estimates of AR_e^K and $-\Delta K$ values which are given in Table 24.

Soils varied from 0.0009 to 0.0146 $(moles/liter)^{1/2}$ in their AR_e^K values and are similar to those reported by Beckett (1964b) and Zandstra and MacKinzie (1968). All the

TABLE 24.--Summary of soil potassium properties derived from equilibrium experiments before and after cropping

	Soil Type	Sample Relative to Cropping	pK - 1/2p (Ca + Mg)	AR_e^K $(M/1)^{1/2}$	Exchangeable K (-ΔK) Meq/100 g.	PBC^K $(-\Delta K/AR_e^K)$
1.	Charity clay loam I	before	2.77	0.0024	0.280	117.0
		after	3.44	0.0007	0.084	120.0
2.	Charity clay loam II	before	2.52	0.0050	0.256	51.2
		after	3.30	0.0007	0.037	52.9
3.	Lenawee clay loam	before	3.19	0.0009	0.049	54.5
		after	3.66	0.0004	0.022	55.0
4.	Sims clay loam I	before	2.46	0.0092	0.294	31.9
		after	2.85	0.0025	0.175	70.1
5.	Sims clay loam II	before	3.02	0.0015	0.091	66.5
		after	3.81	0.0004	0.028	70.0
6.	Sims clay loam III	before	3.14	0.0012	0.098	81.6
		after	3.82	0.0005	0.042	84.0
7.	Colwood loam	before	2.88	0.0015	0.189	12.6
		after	3.68	0.0003	0.038	12.7
8.	Conover loam	before	2.86	0.0020	0.112	56.0
		after	3.59	0.0006	0.038	63.4
9.	Miami loam	before	2.95	0.0016	0.100	62.5
		after	3.67	0.0008	0.050	62.5
10.	Hettinger silty clay loam	before	2.93	0.0013	0.168	129.0
		after	3.44	0.0005	0.070	140.0
11.	Brimby silt loam	before	3.22	0.0011	0.040	38.2
		after	3.68	0.0003	0.014	46.7
12.	Breckenridge sandy loam	before	3.12	0.0015	0.070	46.0
		after	3.57	0.0006	0.035	58.4
13.	Hillsdale sandy loam	before	2.98	0.0033	0.062	18.8
		after	3.69	0.0016	0.038	23.8
14.	Hodunk sandy loam	before	2.62	0.0065	0.161	24.8
		after	3.60	0.0014	0.035	25.0
15.	McBride sandy loam	before	2.68	0.0122	0.133	10.9
		after	3.81	0.0024	0.028	11.7
16.	Metamora sandy loam	before	2.50	0.0146	0.128	8.8
		after	3.58	0.0024	0.028	11.7

AR_e^K values decreased with cropping, and the amount of the decrease tended to become greater with higher degrees of K saturation in the uncropped samples (Table 24). All $-\Delta K$ (meq/100 g. soil) values also decreased with cropping, but the amount of decrease was generally less for those soils having a low initial AR_e^K value (Table 24).

Higher PBC^K tended to be associated with higher amounts of clay, which represented a major source of K released from nonexchangeable form during the cropping period (Table 24). The amounts of exchangeable K showed a poor correlation to PBC^K ($r = -0.34$). Exchangeable K determinations therefore did not provide information about the amount of K released from a soil per unit reduction in the AR^K value. This can be explained on the basis that the kinetics of K release of nonexchangeable form from soil minerals during the cropping period was in no way measured. These data suggest that the immediate Q/I relation will regulate the uptake of K over a short period, but would not be expected to show a simple relation to the K status of the soil where the oats benefited from initially non-labile K released during the cropping period.

The $-\Delta K$ values, indicative of release of K when $AR^K = 0$, were found to be correlated with exchangeable K prior to cropping when the exchangeable K was obtained by extration with 1 N NH_4OAc. The correlation coefficients relating $-\Delta K$ to total K-uptake (r = +0.83***) and to exchangeable K (r = +0.84***) were in good agreement; also the correlation coefficients relating $-\Delta K$ with K-uptake of each crop, and with uptake of nonexchangeable K (r = +0.70**) were significant (Table 25).

The AR_e^K values for Ke = 0, which were derived from the curves by interpolation, were correlated with corresponding values obtained from equilibration of a single sample and expressed in logarithmic form. When confined to the samples before cropping the correlation coefficient (r = -0.77**) was significant. A significant correlation was obtained (r = +0.62**), relating the AR_e^K values to that portion of K-uptake derived from exchangeable K, that is, the reduction in exchangeable K during cropping, but correlations relating AR_e^K and yields for each crop, total yields, K-uptake by each crop, and total K-uptake were poor. The AR_e^K did not provide a measure of the amount of K available to the oat plants.

TABLE 25.--Correlation between $-\Delta K$ prior to cropping; potassium uptake, and yields of oats grown in greenhouse on 16 Michigan soils

Measurement	DF	r
Total K-uptake by oats	14	0.83***
K-uptake by crop 1	14	0.83***
K-uptake by crop 2	14	0.81***
K-uptake by crop 3	14	0.78***
K-uptake by crop 4	14	0.72**
Total yield of oats	14	0.59*
Exchangeable K prior to cropping	14	0.84***
Nonexchangeable K-uptake by oats	14	0.70**

*Significant at 0.05 level.
**Significant at 0.01 level.
***Significant at 0.001 level.

This can be explained on the basis that K-uptake from soils represents uptake from a dynamic system that is not at equilibrium; therefore, rate processes involved with ion movement may become the limiting factor in determining absorption rates by plant roots.

While the soil may have a more or less uniform distribution of ions, initially the root alters this uniformity. The influence of the plant root on the ionic conditions of the soil begins when the root starts to force its way through the soil. Since the diameter of the root is frequently larger than the diameter of the majority of soil pores, the root moves soil particles aside and in so doing increases the density of soil in the immediate vicinity of the root so that it has greater than average density. This will also increase the concentration of exchangeable K per unit volume of soil. In addition to pushing the soil aside, the root will intercept K ions in its path and absorbtion will occur. The root absorbs water and causes a flow of water through the soil toward the root. Since this water contains K ions, these ions are transported to the root. The amount reaching the root will probably depend on the water used and the K concentration in the soil water.

5. Potassium Potential of Soils

The AR_e^K indicates the status of the immediately exchangeable K and, therefore, should regulate exchange of K ions from the complex; the $-\Delta K$ denotes the amount of exchangeable K and supposedly rate at which the activity of K on the exchange complex decreases as K is removed from the complex as indicated by the PBC^K. As the activity ratio of K is reduced, the diffusion gradient away from the complex is also reduced, and K supply to the plant root may be insufficient. Thus for plant nutrition purposes, a correction in the $-\Delta K$ should be made which takes into account differences in buffering capacities between different soils (Zandstra and MacKenzie, 1968). By multiplying the $-\Delta K$ by the PBC^K measurements, the Q/I relation could be defined in a single parameter in which the $-\Delta K$ value of the soil is related to a standard PBC^K (Zandstra and MacKenzie, 1968). This product, the K-potential, is supposedly the amount of exchangeable K ($-\Delta K$) multiplied by the ease of release of the K.

A significant correlation coefficient (r = +0.56*) relating K-potential and K-uptake by the first oat crop was obtained; however, the correlation coefficients for the second (r = +0.40), third (r = +0.32), fourth (r = +0.30) crops, and total K-uptake (r = +0.42) were not significant. These results can be attributed to the decrease in the original labile pool of K by the first oat crop, such that when nonexchangeable K was released from the soils the PBC^K (obtained prior to cropping) is no longer valid with respect to the amount of K released from the soil complex (labile K) per unit reduction in the AR^K. The correlation coefficients relating K potential to yields of each crop and to total yields were nonsignificant.

6. The evaluation of exchangeable K, $-\Delta K$, AR_e^K, PBC^K, and K-potential as indexes of plant available K

Exchangeable K as determined by 1 N NH_4OAc was more highly correlated with total K-uptake, total yields of four oat crops, and nonexchangeable K-uptake than $-\Delta K$ (Table 26). This may be explained on the basis that the NH_4^+ replaced most of the exchangeable K and possibly some fixed K along the "edge" sites of the clay minerals. Another possible explanation is that the extrapolation of the equilibrium curves should have included that K represented by the asymptotic convergence of the Q/I relation to the Q-axis. This method of extrapolation would have resulted in larger $-\Delta K$ values and improved the correlation coefficient relating $-\Delta K$ to total K-uptake.

The activity ratio (AR_e^K) is not a suitable index of plant available K and is in no way a measure of the rate of release of nonexchangeable K from the soil.

The PBC^K as a single value (slope of $-\Delta K/AR_e^K$) gave poor correlations as an index of K availability. When PBC^K was multiplied by $-\Delta K$, the product (K-potential) was correlated ($r = + 0.56^*$) with the K-uptake of the first oat crop (Table 26). The data presented in Table 26 clearly shows

TABLE 26.--Correlation coefficients relating exchangeable K, $-\Delta K$, AR_e^K, PBC^K, and K-potential with potassium uptake and yields of four oat crops grown in greenhouse on 16 Michigan soils

Measurement	Exchangeable[1] K	$-\Delta K$	AR_e^K	PBC^K	K-potential
total K-uptake by oats	0.98***	0.83***	0.29	0.09	0.42
K-uptake by crop 1	0.91***	0.83***	0.30	0.24	0.56*
K-uptake by crop 2	0.97***	0.81***	0.35	0.15	0.40
K-uptake by crop 3	0.92***	0.78***	0.21	0.11	0.32
K-uptake by crop 4	0.94***	0.72**	0.17	0.06	0.30
total yield of four oat crops	0.74**	0.59*	-0.08	0.29	0.41
yield of crop 1	0.16	0.10	-0.08	0.10	0.11
yield of crop 2	0.74**	0.57*	-0.10	0.16	0.32
yield of crop 3	0.66**	0.66**	-0.12	0.32	0.45
yield of crop 4	0.78***	0.70**	-0.13	0.29	0.46
nonexchangeable K-uptake	0.82***	0.70**	-0.06	0.23	0.43

[1]Extracted with 1 <u>N</u> NH_4OAc for 10 minutes.

*Significant at 0.05 level.

**Significant at 0.01 level.

***Significant at 0.001 level.

that exchangeable K (1 N NH_4OAc extractable) was a better index of total supply of K than equilibrium exchangeable K (-ΔK) under exhaustive cropping; but this does not necessarily mean that exchangeable K extracted with NH_4OAc would be a superior index under field conditions, because K reserves would seldom be as severely depleted as they were in the greenhouse pot trial.

The soils used in this study released large amounts of K from nonexchangeable form and, therefore, provided an extremely complicated medium when trying to assess the K supplying power.

SUMMARY AND CONCLUSIONS

EFFECTS OF RATES AND SOURCES OF POTASSIUM ON YIELDS, SPECIFIC GRAVITY, MINERAL CONTENT AND REDUCING SUGAR CONTENT OF BURBANK AND SEBAGO POTATOES

The objectives of the field investigation were to compare the effects of various rates and sources of K on: (1) yields and specific gravity of tubers, (2) the uptake and distribution of K, Ca, and Mg in potato tissue, and (3) reducing sugar content of potato tubers at harvest. The results from this field investigation are summarized as follows:

1. Significant yields of potatoes for the 1967 growing season were obtained from application rates of K_2O as KCl up to 180 pounds per acre with a 210 pound per acre level of exchangeable K.

2. A significant yield response was obtained from 150 pounds of applied K_2O, but was independent of K source when the level of exchangeable K was 270 pounds per acre.

3. Specific gravity decreased significantly with increasing applications of KCl on both Burbank and Sebago varieties, but larger decreases were found for the Sebago variety. For the source of K study, KNO_3 decreased the specific gravity on the Sebago variety at the (0.05 level) when compared to KCl, K_2SO_4, and K_2CO_3 sources.

4. Potassium concentrations in potato petioles, leaves, whole plants and tubers increased with increased applications of K_2O; however, for all tissue sampled there was a decrease in K as maturation of the plant occurred. The magnitude of K concentrations were petioles > leaves > whole plants > tubers. Potassium concentration in potato plant tissue averaged over three sampling dates shows that the greatest range of K concentrations are found to be petioles > whole plants > leaves > tubers.

5. For the source of K study the concentrations of K in petioles and leaves were high at the early season sampling and decreased in magnitude with increasing maturation of the plant. When all sampling dates

were averaged KCl as a source of K resulted in higher concentrations of K in the petioles (0.01 level) when compared to K_2SO_4. The K_2CO_3 source resulted in higher concentrations of K in the petioles (0.01 level) when compared with K_2SO_4 and KNO_3.

6. Concentrations of Ca in petioles, leaves, and whole plants decreased with increasing rates of applied K, but increased with maturation of the plant. These results suggest once the suppression of Ca uptake occurs it remains suppressed throughout the growing season and the magnitude of suppression will increase as the rate of applied K increases. Concentrations of Ca found in the petioles, leaves, and whole plants were sixty to eighty times that found in tubers.

   Sources of K resulted in suppression of Ca uptake when compared with the no K treatment. However, there were no significant differences between sources of K and suppression of Ca uptake probably eliminating any external anion effect.

7. Magnesium concentrations in petioles, leaves, and whole plants generally decreased with increasing rates of K and increased as the plants matured. Applications of 240 and 480 pounds of K_2O per acre decreased the concentration of Mg in the petioles, leaves (Table 8), and whole plants (Table 9) resulting in a K induced decrease in Mg much larger in magnitude than a K induced decrease in Ca. This may be a partial explanation for the decrease in yields obtained from the higher rates of applied K_2O (Table 1). Concentrations of Mg were 8-12 times higher in magnitude in petioles, leaves, and whole plants than in tubers.

   Potassium carbonate as a source of K decreased Mg content in petioles (0.05 level) when compared to the K_2SO_4 source. When compared to the no K treatment, K_2CO_3 decreased the Mg concentration significantly at the 0.01 level.

8. Rates and sources of K had no significant effect on the reducing sugar content of tubers at harvest for the Burbank or Sebago varieties.

EVALUATION OF POTASSIUM QUANTITY-INTENSITY RELATIONSHIPS OF SELECTED MICHIGAN SOILS

The equilibrium activity ratio (AR_e^K) and equilibrium exchangeable K ($-\Delta K$) were obtained from curves of activity ratios, $a_K/a_{(Ca + Mg)}^{1/2}$ or AR^K, against changes in exchangeable K (ΔKe) based on equilibration of the soils in 0.00159 M $CaCl_2$ containing different amounts of K. These were compared to exchangeable (1 N NH_4OAc extractable) K measurements and related to total K-uptake and yield responses of four oat crops grown in the greenhouse without added K. The findings may be summarized as follows:

1. Exchangeable K (1 N NH_4OAc extractable) was correlated with yields ($r = +0.75^{**}$), nonexchangeable K-uptake ($r = +0.98^{***}$) by four oat crops. Nonexchangeable K-uptake amounted to 50 percent or more of total K-uptake by oats grown on all soils, except Hodunk, McBride, and Metamora.

2. Equilibration of soils in 0.00159 M $CaCl_2$ containing 0, 0.230, 0.716, 1.43, and 1.81 mmoles of KCl resulted in activity ratios (AR_e^K) which gave a higher correlation (r = +0.63**) with that part of K-uptake derived from the exchangeable form than with the total K-uptake.

3. Estimates of the quantities of K released ($-\Delta K$) as obtained from equilibrium curves were found to be much more indicative of the total K-uptake (r = +0.83***) and to exchangeable K (r = +0.84***) prior to cropping than were the AR_e^K values. The $-\Delta K$ values were correlated (r = +0.70**) with K-uptake of the nonexchangeable form.

4. The PBC^K as a single value (slope of $-\Delta K/AR_e^K$) gave poor correlations as an index of K availability. When PBC^K was multiplied by $-\Delta K$, the product (K-potential) was correlated (r = +0.56*) with the K-uptake of the first oat crop. This supports the principle that the Q/I relationship derived from the equilibrium curves is for the immediate labile pool of K, and in no way measures the kinetics of K release from nonexchangeable form.

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APPENDIX

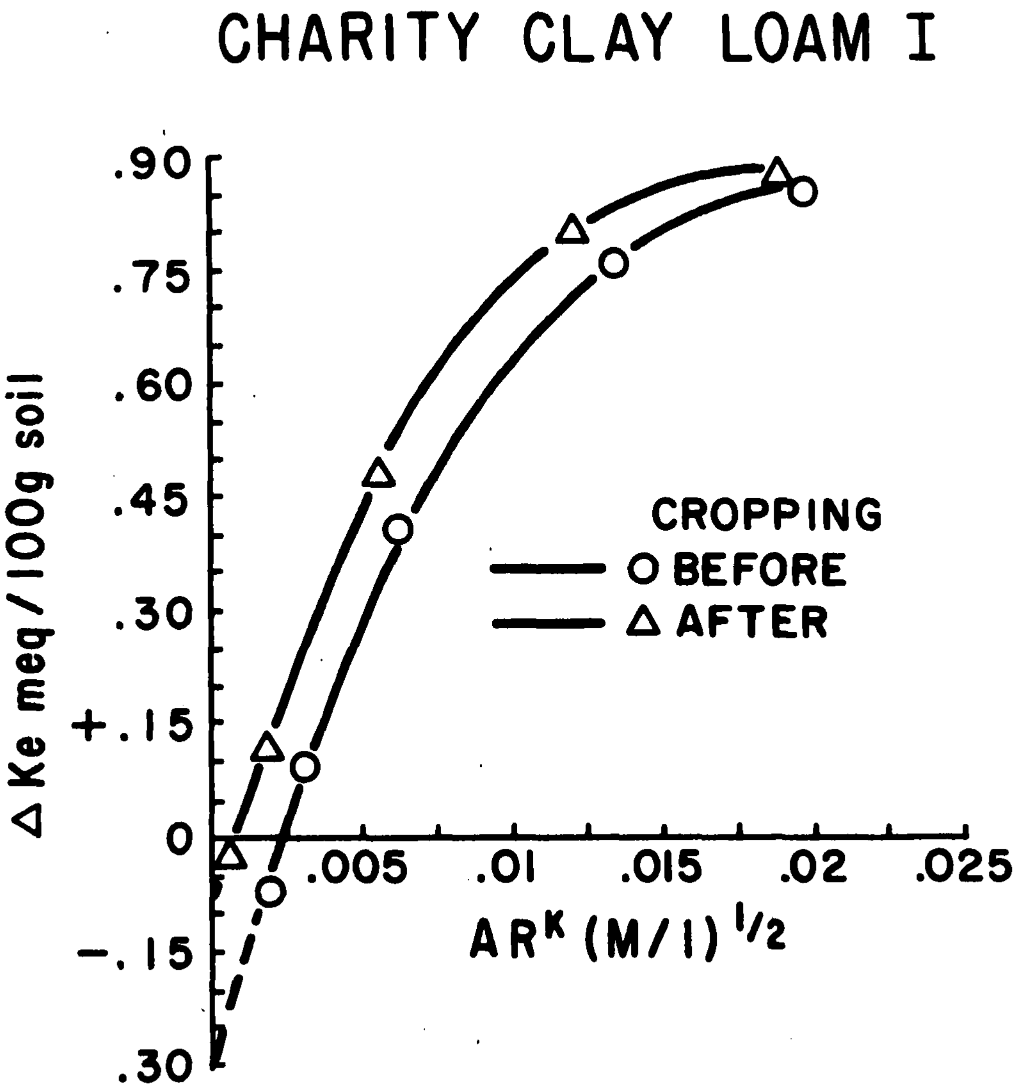

Fig. 1.--Relation of potassium activity ratio (AR_e^K) to $-\Delta K$ before and after cropping on Charity clay loam I.

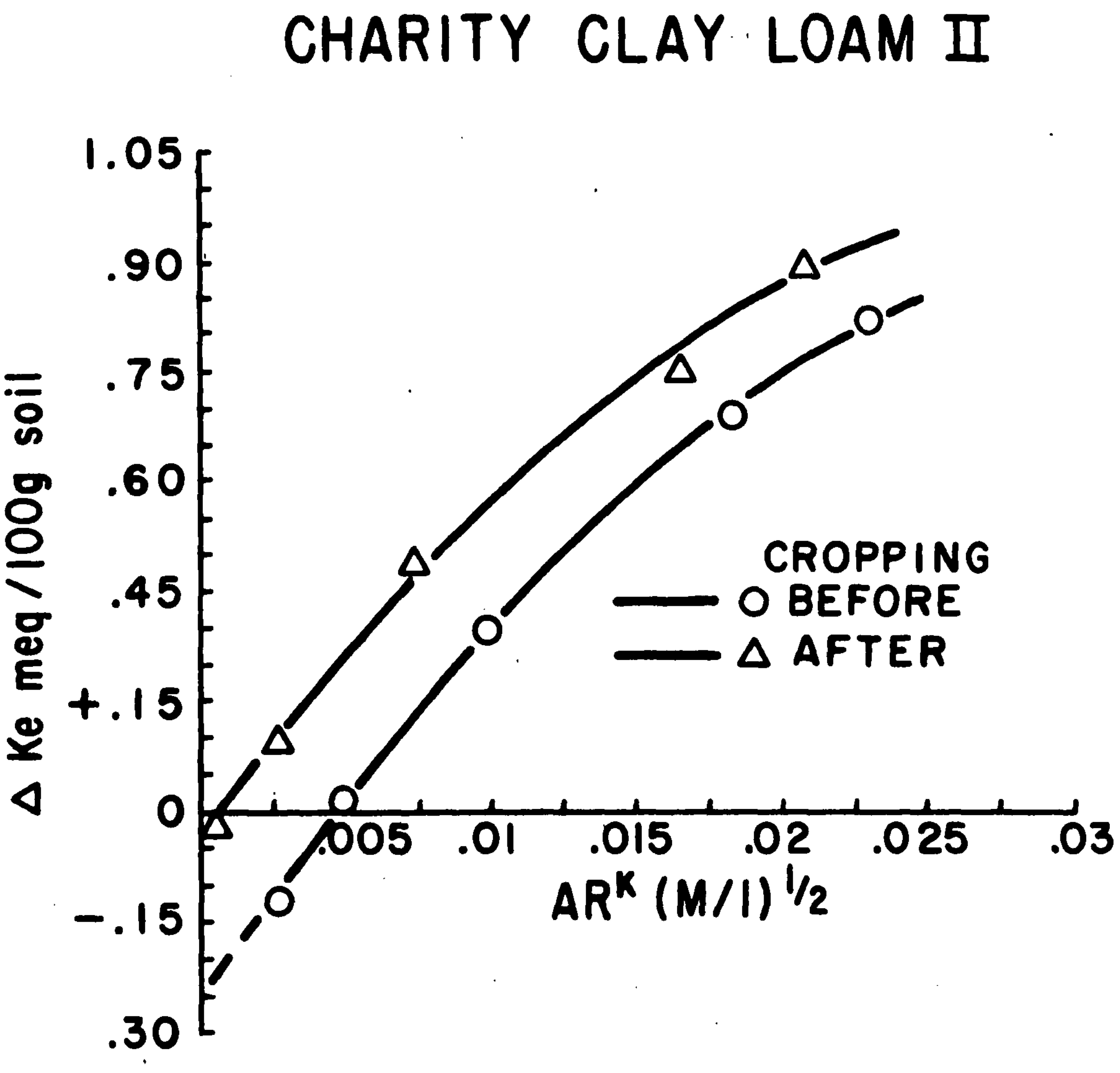

Fig. 2.--Relation of potassium activity ratio (AR_e^K) to -ΔK before and after cropping on Charity clay loam II.

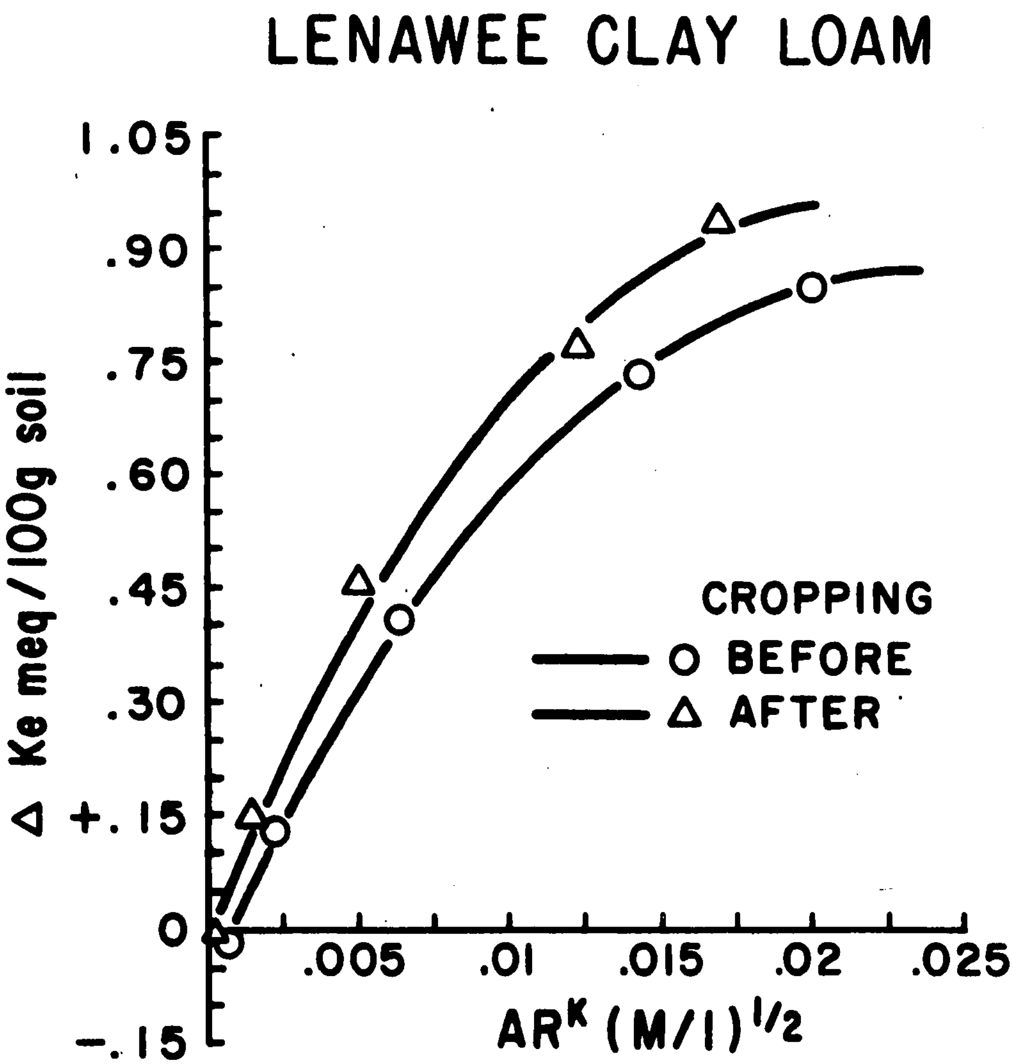

Fig. 3.--Relation of potassium activity ratio (AR_e^K) to $-\Delta K$ before and after cropping on Lenawee clay loam.

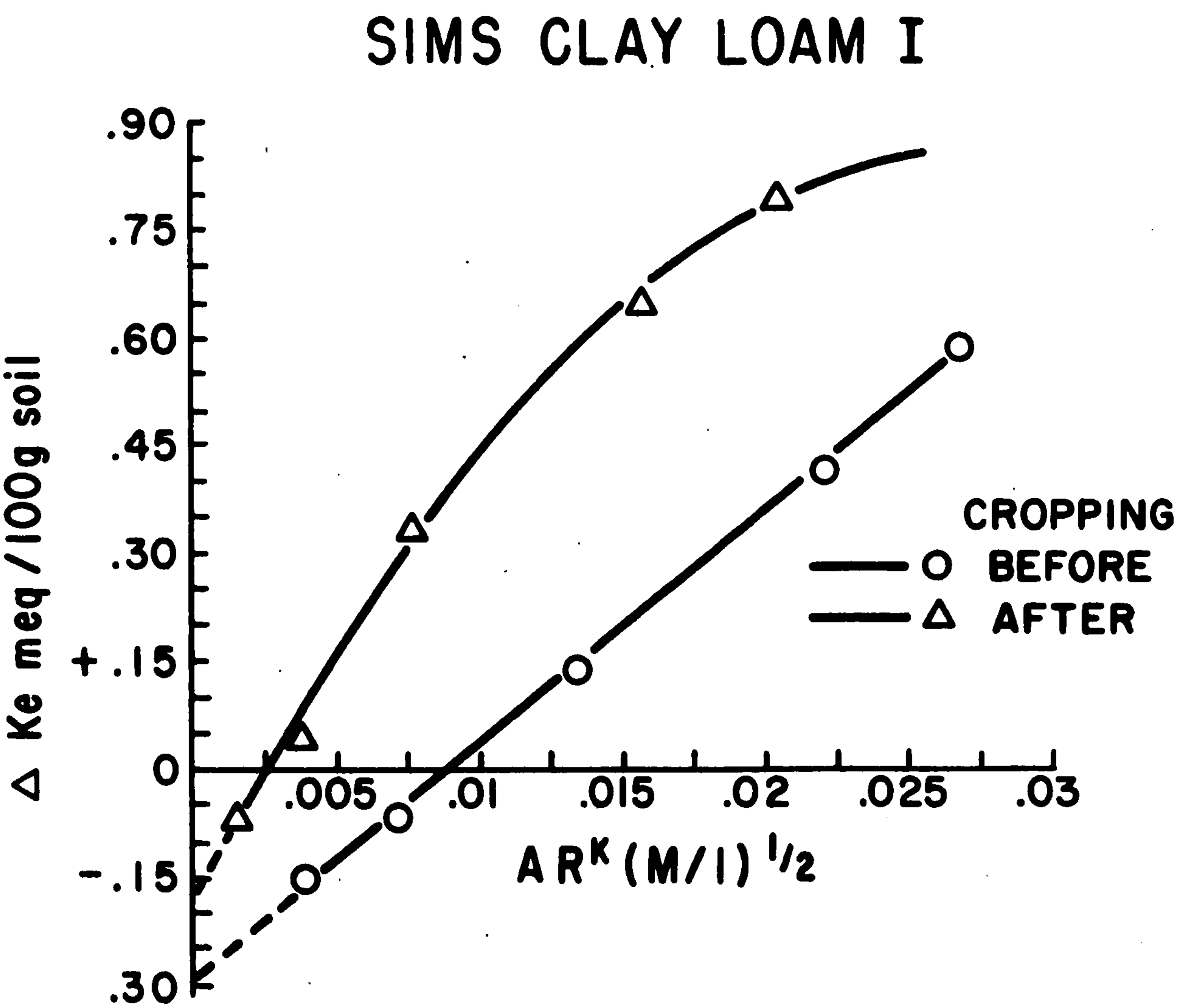

Fig. 4.--Relation of potassium activity ratio (AR_e^K) to $-\Delta K$ before and after cropping on Sims clay loam I.

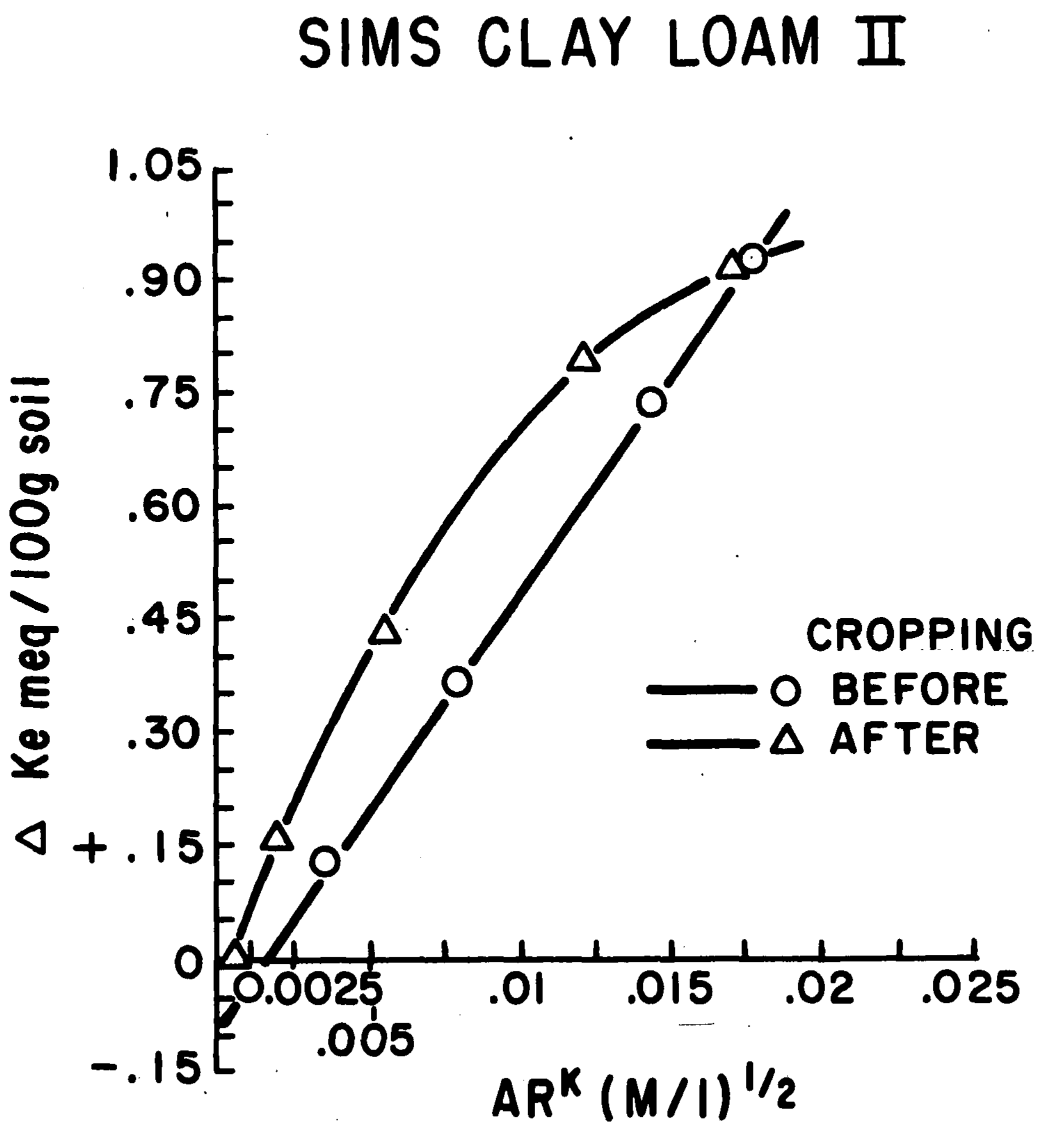

Fig. 5.--Relation of potassium activity ratio (AR_e^K) to $-\Delta K$ before and after cropping on Sims clay loam II.

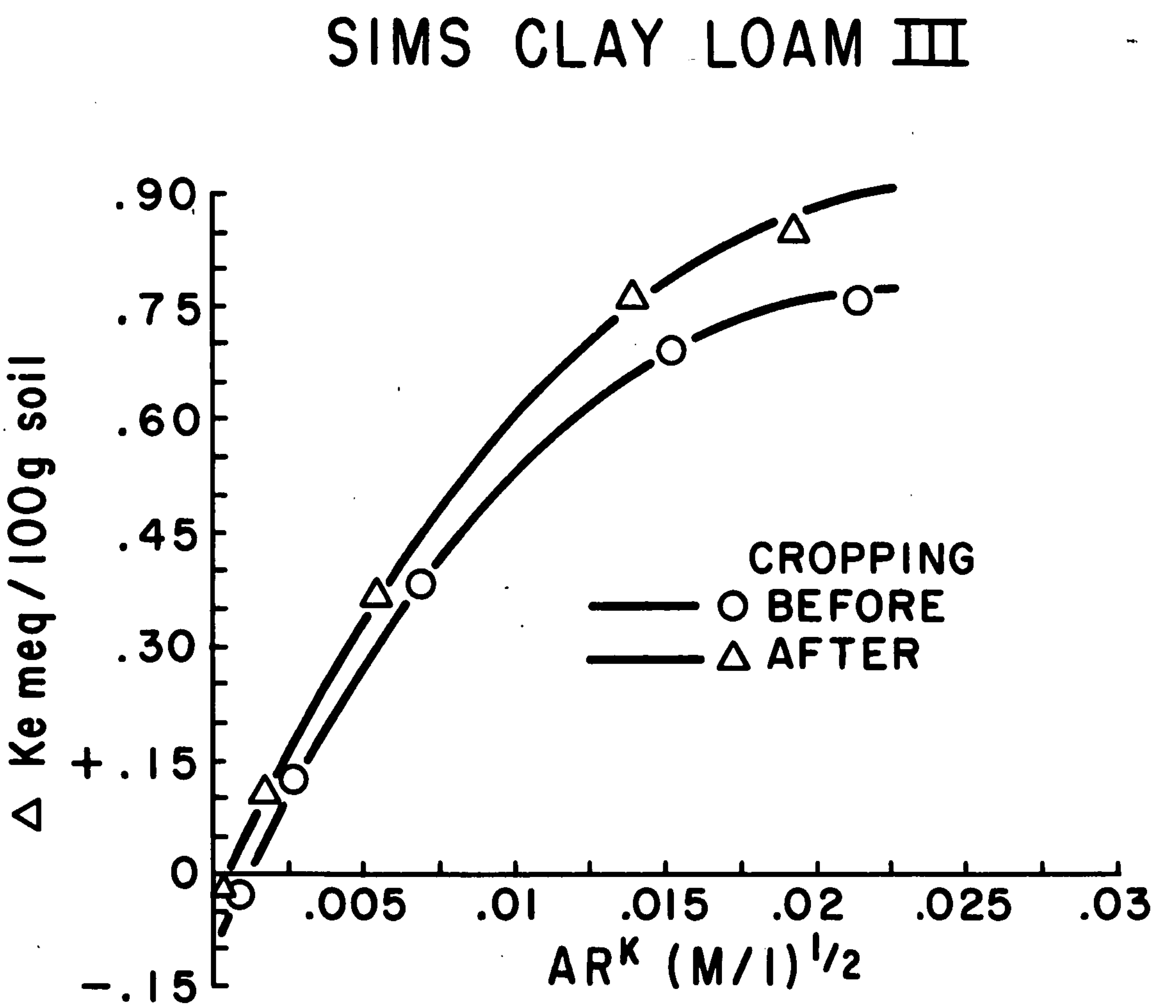

Fig. 6.--Relation of potassium activity ratio (AR_e^K) to $-\Delta K$ before and after cropping on Sims clay loam III.

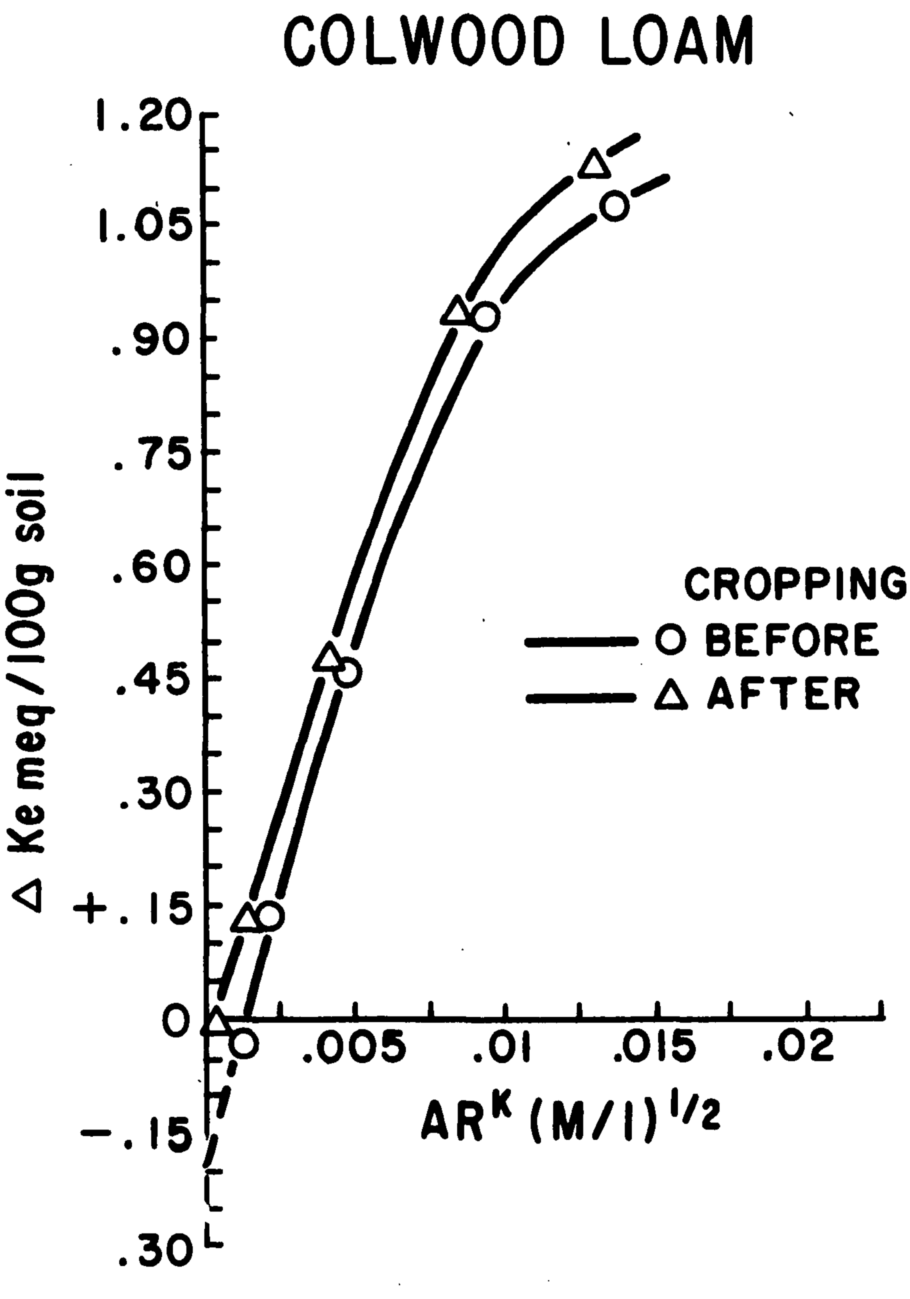

Fig. 7.--Relation of potassium activity ratio (AR_e^K) to -ΔK before and after cropping on Colwood loam.

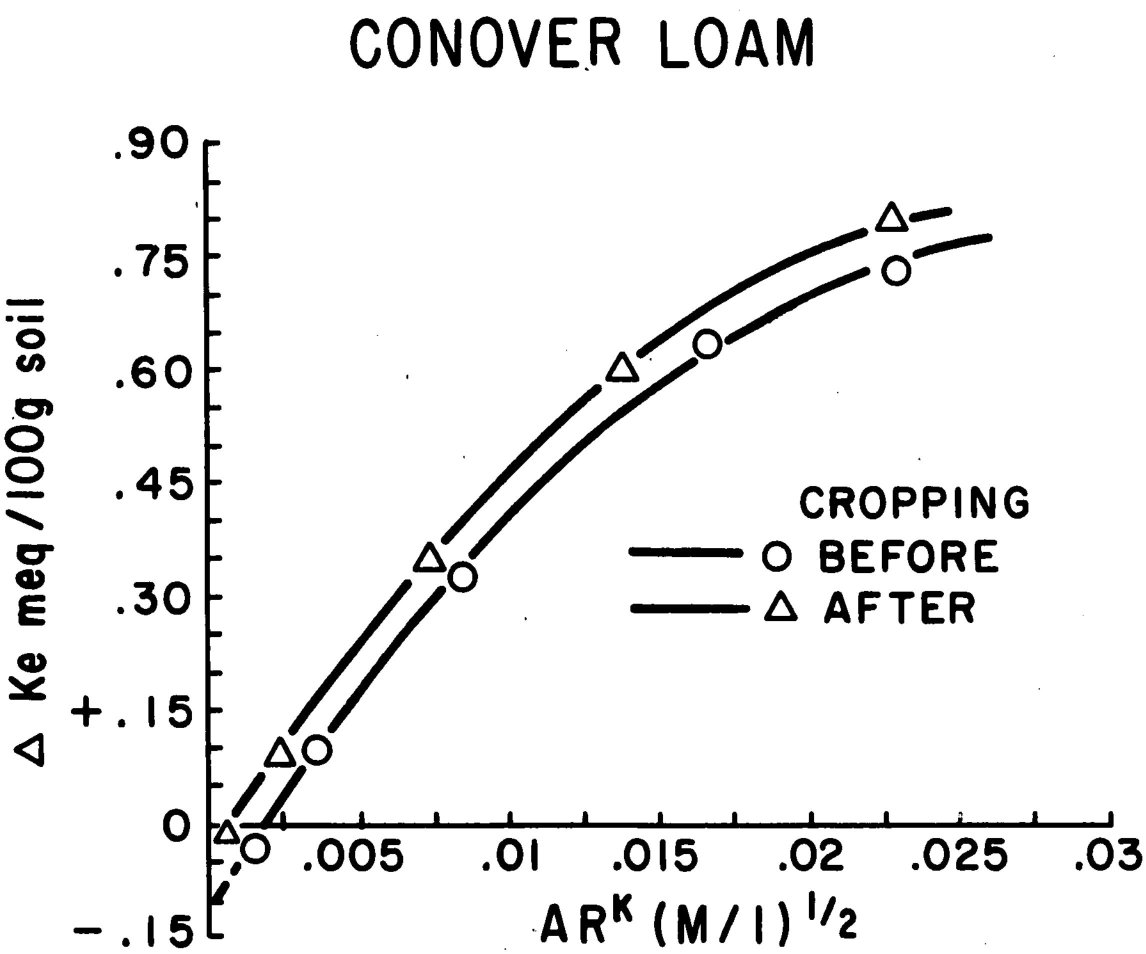

Fig. 8.--Relation of potassium activity ratio (AR_e^K) to $-\Delta K$ before and after cropping on Conover loam.

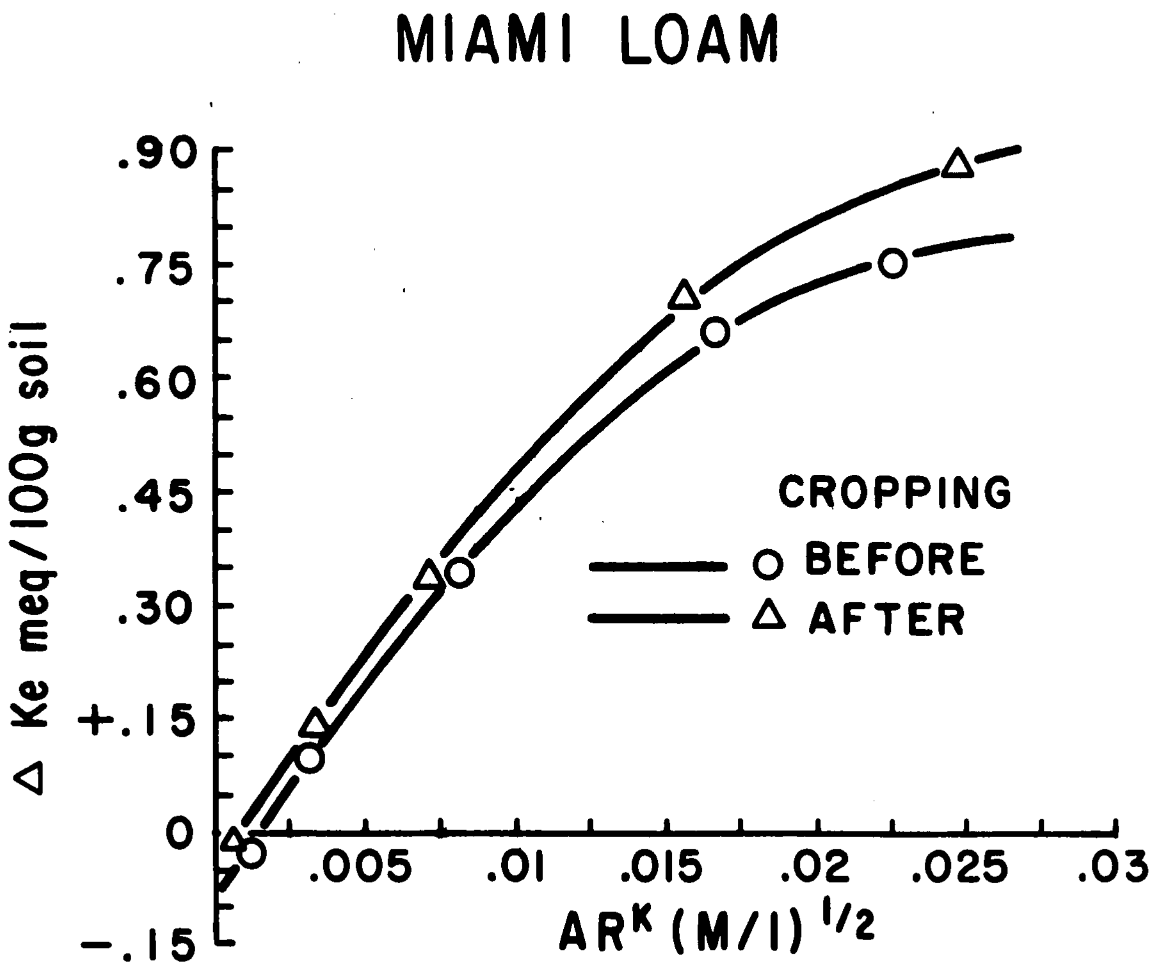

Fig. 9.--Relation of potassium activity ratio (AR_e^K) to $-\Delta K$ before and after cropping on Miami loam.

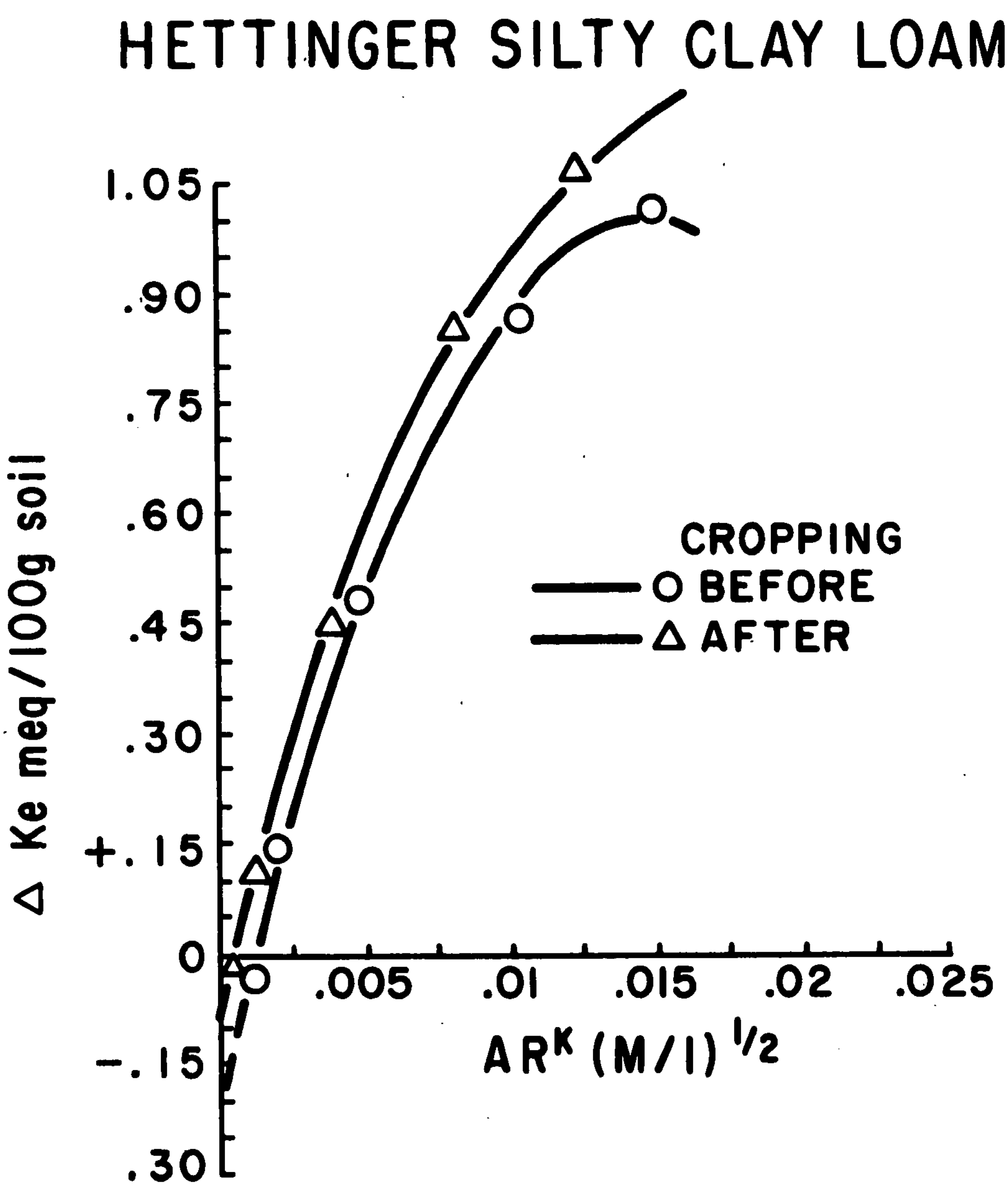

Fig. 10.--Relation of potassium activity ratio (AR_e^K) to $-\Delta K$ before and after cropping on Hettinger silty clay loam.

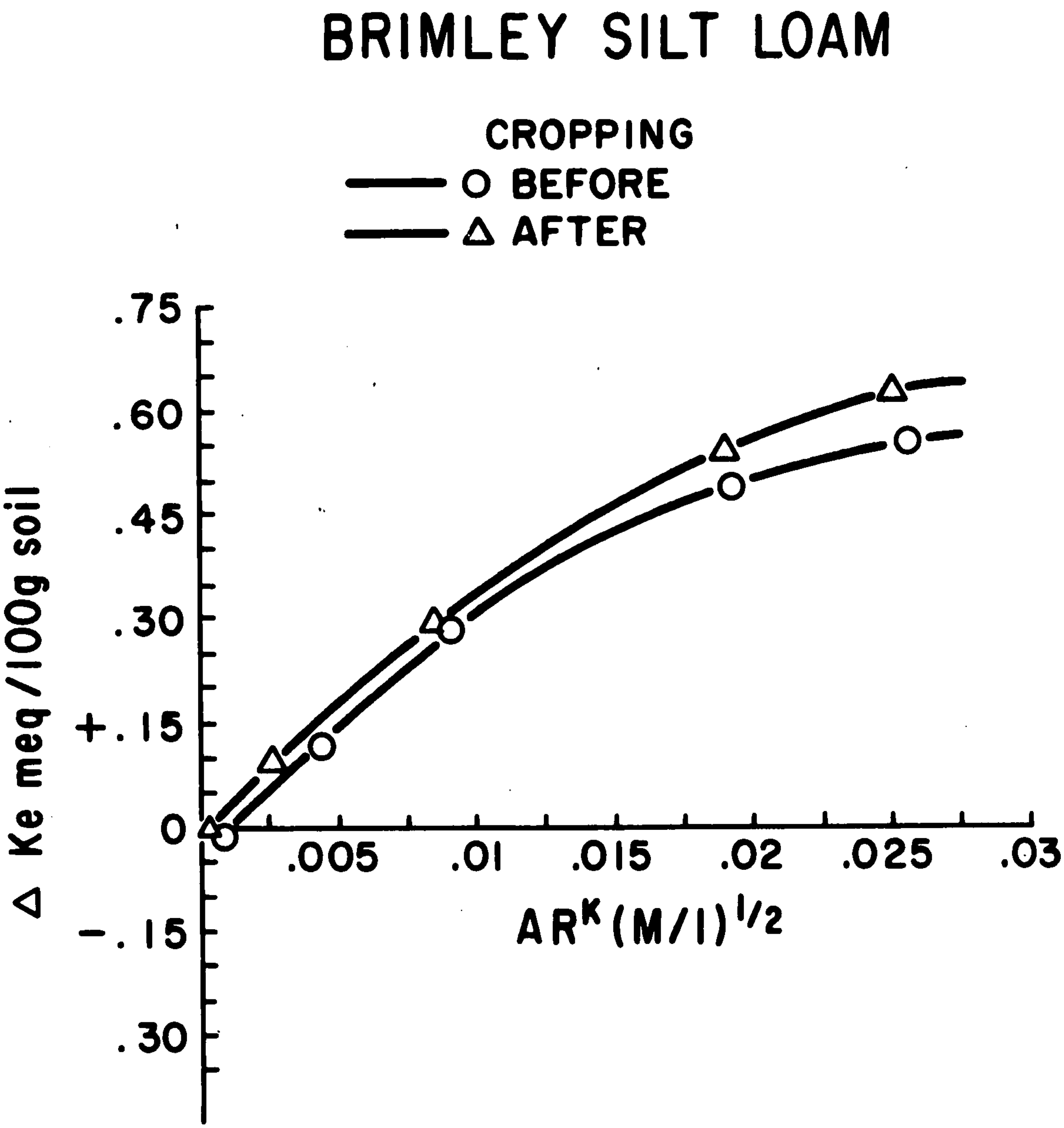

Fig. 11.--Relation of potassium activity ratio (AR_e^K) to -ΔK before and after cropping on Brimley silt loam.

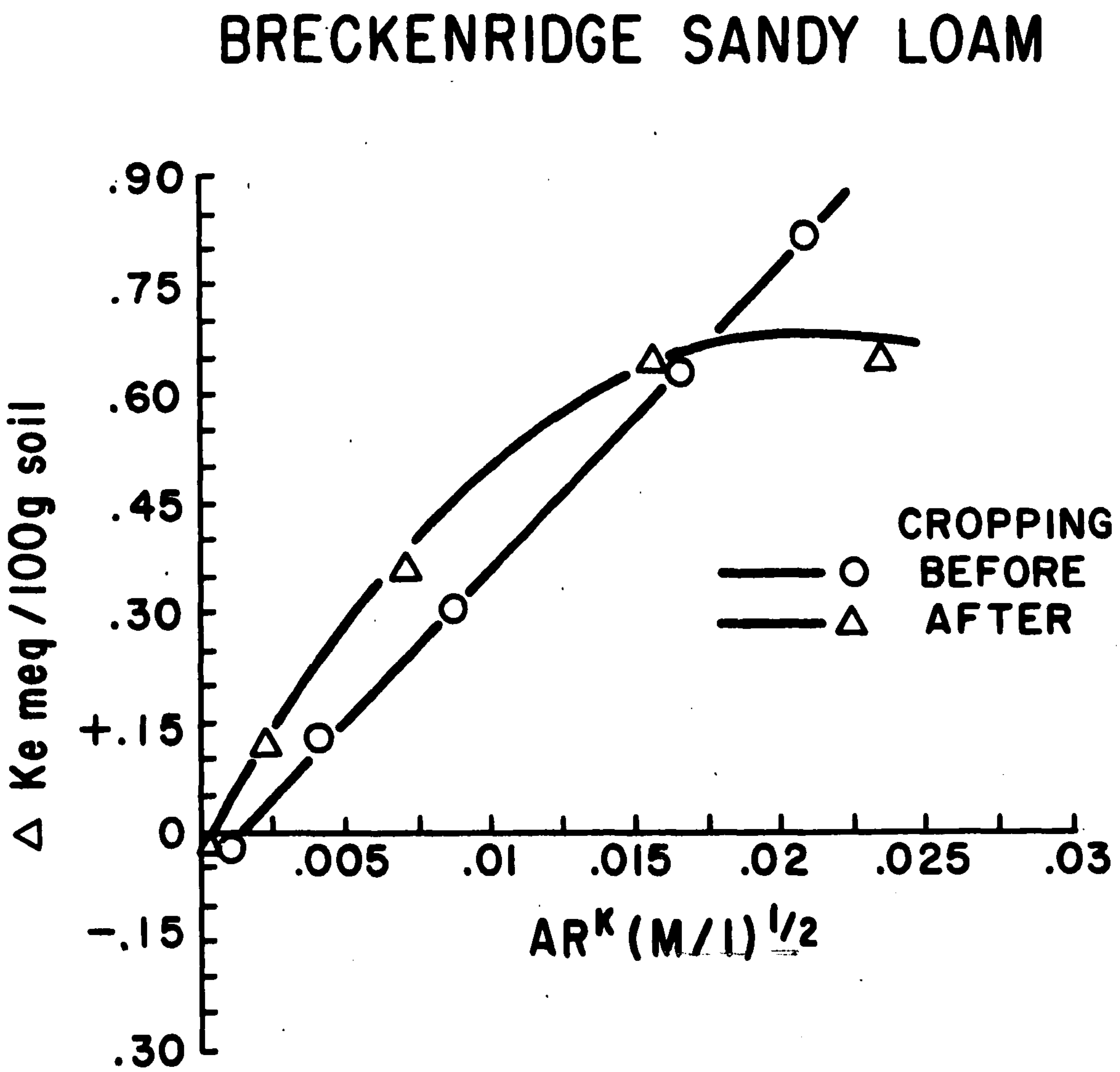

Fig. 12.--Relation of potassium activity ratio (AR_e^K) to $-\Delta K$ before and after cropping on Breckenridge sandy loam.

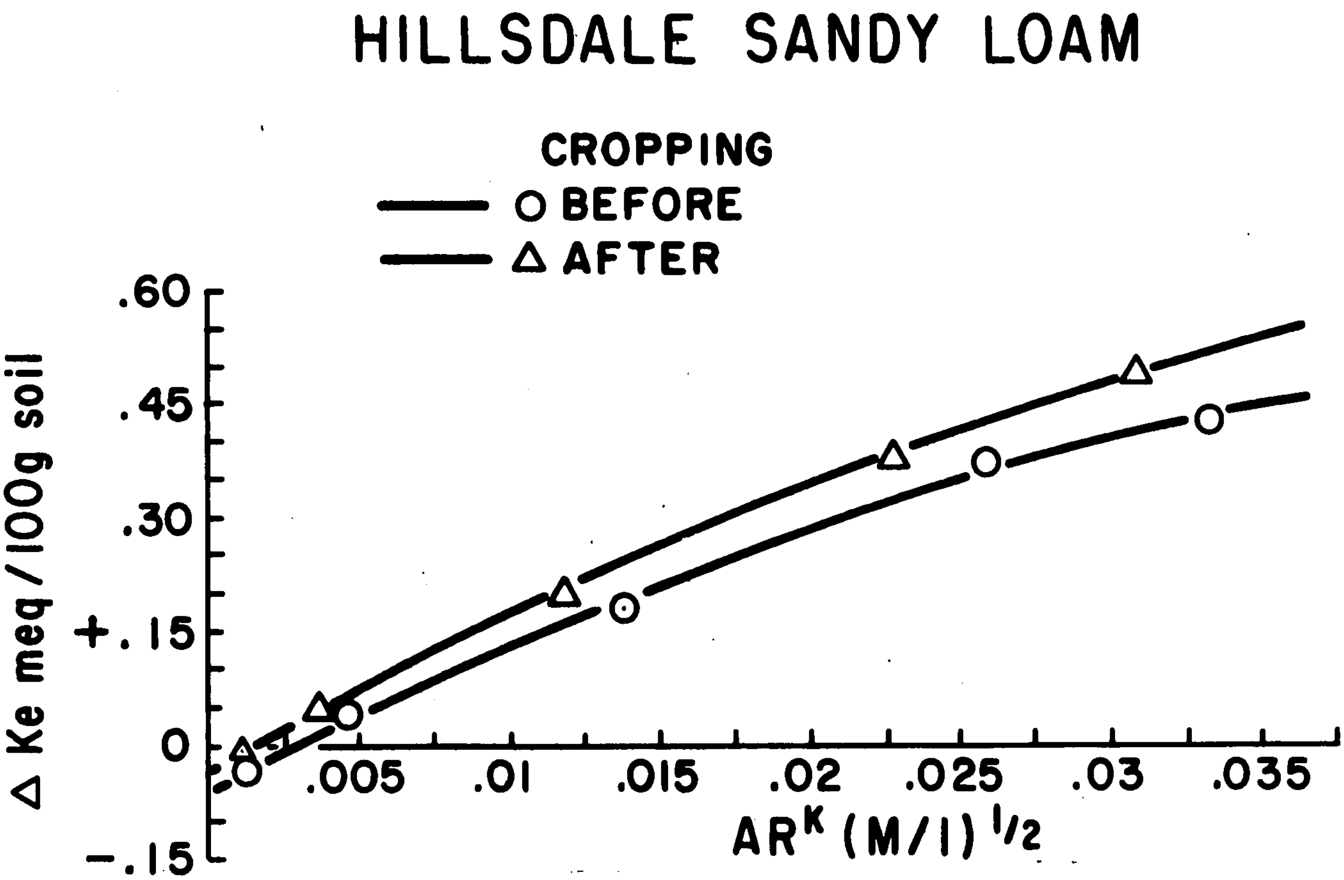

Fig. 13.--Relation of potassium activity ratio (AR_e^K) to $-\Delta K$ before and after cropping on Hillsdale sandy loam.

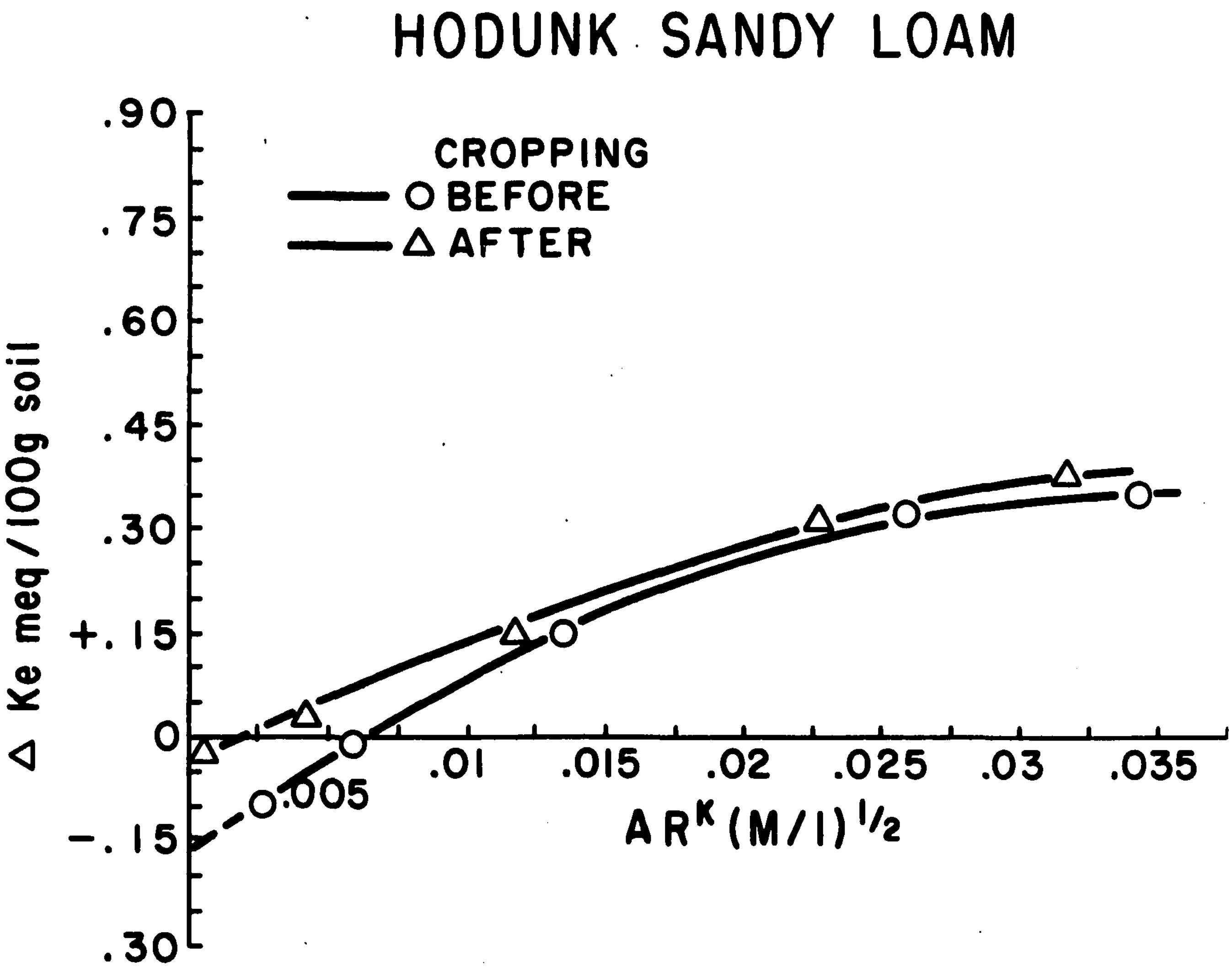

Fig. 14.--Relation of potassium activity ratio (AR_e^K) to -ΔK before and after cropping on Hodunk sandy loam.

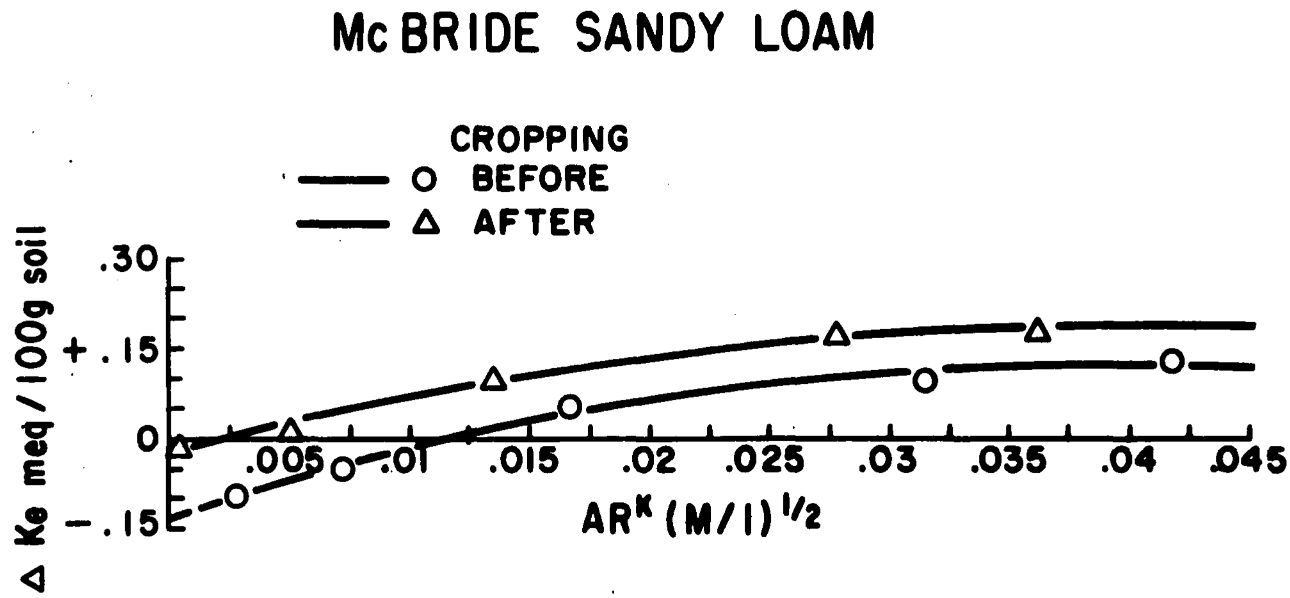

Fig. 15.--Relation of potassium activity ratio (AR_e^K) to $-\Delta K$ before and after cropping on McBride sandy loam.

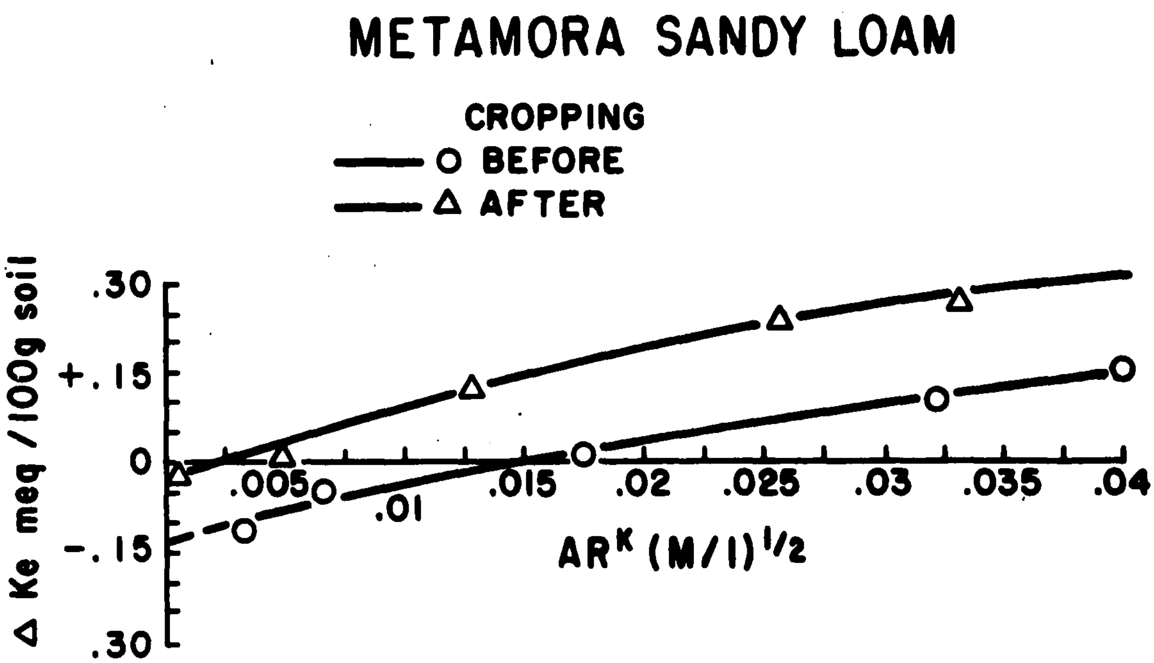

Fig. 16.--Relation of potassium activity ratio (AR_e^K) to $-\Delta K$ before and after cropping on Metamora sandy loam.