米国ミシガン州の四土壌のカリ有効度に関する研究(農芸化学科)

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Evaluation of Potassium Availability of Four Michigan Soils**

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I INTRODUCTION

A great number of research papers have been devoted to potassium fixation or release of soils. The mechanisms of potassium fixation or release are now well explained (39). Soils containing montmorillonite, illite and vermiculite are capable of fixing potassium applied to the soil as fertilizer (6, 39, 94). Potassium fixed in the soil seems to become available to the plant slowly and a new equilibrium between nonexchangeable and exchangeable potassium, and exchangeable and solution potassium is established upon depletion of potassium in the soil solution (76).

From the soil fertility point of view, an accurate determination of available potassium is necessary to make effective use of soils and fertilizer. In order to discover such a measure, various methods have been employed, none of which, however, has completely satisfied soil scientists.

The determination of available potassium as indicated by uptake of the plant itself should be the most accurate, but because of the time consuming nature of the method, soil chemical extraction methods are commonly used. Examples of chemical extractions employed for this purpose are: 1 N neutral ammonium acetate (77), 1 N nitric acid (68), and sodium tetraphenylboron methods (79). Some of the methods measure only a part of the exchangeable potassium while others may measure a portion of nonexchangeable forms. Available potassium ranges from solution potassium through exchangeable to nonexchangeable forms depending on conditions. On the other hand, an activity ratio such as $^{a}K/\sqrt{^{a}(Ca+Mg)}$ has been proposed as a good measure for potassium availability (50) for certain soils, and its usefulness has been tested to some extent (1, 10). Suitability of a method for determining available potassium in a particular soil seems to be largely affected by the degree of potassium released and/or fixed by a soil.

Known factors involved in the release or fixation of soil potassium are: (a) levels of potassium in the soil (21); (b) absorptive power of plant species (90); (c) soil temperature (93); (d) soil moisture or wetting-drying conditions (8); (e) soil pH (64); (f) soil organic matter (56); (g) concentrations of coexisting cations such as Ca, Mg, and NH_4 (61, 67, 94); (h) texture of the soil (60); and (i) types of clay mineral present in the soil (75).

Potassium fixing clays, such as montmorillonite, illite, and vermiculite, have been detected in Michigan soils, and release of nonexchangeable potassium from the soil has also been studied to some extent in relation to clay mineralogy (19, 24). However, further study is considered necessary concerning the release and fixation of potassium in Michigan soils from the standpoint of soil fertility; namely, the release and fixation of potassium in relation to fertilization, cropping, and physical, chemical and mineralogical properties of the soil.

The objectives of the present thesis are to study the release and fixation of potassium in some high-potassium-fixing and low-potassium-fixing Michigan soils in relation to their physical, chemical and mineralogical properties. In order to achieve these objectives, particular emphasis was placed on the following aspects:

1. Plant yields as affected by potassium fertilization; potassium uptake of plants as related to calcium and magnesium uptake; and the effect of differential potasisum release and fixation of the soils on plant yield and potassium uptake.
2. Suitability of chemical methods for measuring plant available potassium and their relationship to uptake of potassium by plants.
3. The relationships among the physical, chemical, and mineralogical properties of the soils and their ability to release and/or fix potassium.
4. The effect of potassium fertilization and cropping on the clay mineralogy, cation exchange capacity, and potassium supplying power of the soils under investigation.

II LITERATURE REVIEW

A. IMPORTANCE OF POTASSIUM IN PLANT METABOLISM

Potassium is one of the major plant nutrients, however, the role of potassium in the plant is still not fully understood. The accumulation of knowledge indicates that potassium plays catalytic roles in the plant rather than becoming an integral part of plant components. For example, the enzyme systems related to starch synthesis from glucose, protein synthesis from various amino acids, and nucleic acid and nucleotide metabolisms are regarded as affected by the potassium ion (27). Furthermore, potassium helps promote turgor, and regulates permeability of cell walls and activities of various mineral elements as well as neutralizing physiologically important organic acids (27, 45).

Plants with an inadequate supply of potassium may show poor fruit or seed formation, yellowing of the leaves, poor growth, and low resistance to coldenss and drought (90).

Explanations of the disturbance in carbohydrate and nitrogen metabolism relative to potassium nutrition are probably that: (a) potassium deficiency results in inactivation of such enzymes as pyruvic acid kinase which is involved in the formation of energy-charged adenosine triphosphate (ATP) in the gloycolytic pathway (The insufficient energy reduces nitrogen assimilation which repuires a large amount of energy from the outside.); (b) accumulation of soluble nitrogen compounds results from insufficient energy necessary to synthesize proteins which is caused by inactivation of cytochromeoxidase in the cytochrome system with deficient potassium (28).

The respiration rate of some plants, such as rice, increases when potassium is deficient. However, this increase in respiration is useless as far as plant metabolism is concerned since the cytochrome system is disturbed by the absence of potassium (31).

B. POTASSIUM ABSORPTION BY PLANTS

It is not appropriate to generalize concerning the potassium content of plants because the ability of potassium absorption differs among plant species; moreover, it is affected by soil conditions, the level of exchangeable or available posassium, the amount of other nutrients, soil pH, soil moisture, aeration, soil temperature, and the quantity and kind of clay minerals.

1. Differential Absorption of Potassium by Plant Species

Differential absorption of potassium by various plant species was demonstrated by Newton (59), and Drake and Scarseth (25).

Newton (59) grew sunflowers, beans, barley, wheat, peas and corn for 56 days in a water culture which contained 185 ppm of potassium, and analyzed the plant tops. The potassium contents of these plants varied from the lowest 3.9% with corn to the highest 6.92% with barley. He also grew sunflower, beans, wheat and barley in a soil which contained 1.5% potassium and found that the potassium contents ranged from 1.19% with beans to 4.16% with wheat.

Drake and Scarseth (25) carried out an experiment with a Crosby silt loam in which they grew 13 different crops such as spring wheat, oats barley, Sudangrass, timothy, spinach, carrots, sugar beets, Turkish tobacco, alfalfa, sweet clover, buckwheat and salvia to near maturity. The soil received constant amounts of nitrogen and phosphorus but no potassium. When no potassium was applied on the soil, in which exchangeable soil potassium (K_2O) was 267 mg per pot, potash uptake varied from less than 100 mg with spinach to nearly 800 mg K_2O with timothy. Several explanations have been advanced to explain the differential ability to absorb potassium. Lewis and Eisenmenger (46) from their experimental results interpreted that the plants in lower orders of evolution utilized more potassium than the plants in higher orders. Other explanations are concerned with the physiological requirement and cation exchange capacity properties of the plant root. There appear to be definite differences in potassium and calcium contents of leguminous crops such as alfalfa, red clover, sweet clover and soybean, and of monocotyledon plants such as oats and corn as studied by Beeson (12). The monocots absorbed more potassium than leguminous crops but less calcium.

2. Effects of Potassium Level in soil

Plants may utilize more potassium when the available soil level of potassium is high. DeMent, *et al* (21) reported that oats absorbed the largest amount of potassium (47.3 mg for the 14-day growth period) from the quartz sand-soil mixture which received the highest amount of patassium (120 mg potassium per 200 gm of soil); whereas the oat plant grown without any addition of potassium absorbed only 10.8 mg.

Jaworske and Barber (38) showed the relationship between potassium uptake of plant and exchangeable soil potassium.

An experiment by Oya (63) with kaolinitic Hawaiian latosols showed the potassium contents of peanut leaves increased with additions of potassium up to 800 lbs per acre at lower calcium treatments.

The process of nutrient uptake and transport of potassium in the plant against a concentration gradient requires energy (30). This gradient between the plant and the soil solution will be lower for a soil high in potassium than for a soil low in this element. Consequently, if plants use the same amount of energy for potassium uptake in soils with different levels of available potassium, a plant would absorb potassium more easily from a soil rich in potassium than from a soil poor in potassium.

3. Effects of Other Nutrients in Soil on Potassium Availability

a. Nitrogen

A review by Lawton and Cook (45) showed there are some instances when applications of nitrogenous fertilizers alone or nitrogen coupled with phosphorus fertilizers decreased the potassium concentration of crops and subsequently resulted in potassium deficiency. However, such an unfavorable effect must be explained by the phenomenon of vegetative expansion of the crops by the applied fertilizers. The addition of nitrogen brings about vigorous growth of crops and plant absorbed potassium is diluted thus lowering the potassium concentration. Potassium deficiency results unless the patassium supply of the soil is sufficient to meet the rapid growth of the plants.

In general, with a sufficient supply of potassium, the addition of nitrogen promotes a rather favorable effect on the potassium uptake by plants due to its stimulative effect on plant growth as shown by Hallock, *et al.* (35).

Nitrogen in the soil is available to plants mainly in two forms; ammonium nitrogen and nitrate nitrogen. Studies have been carried out concerning the effect of ammonium rather than the nitrate on potassium absorption by plants. The ammonium ion (NH_4^+) seems to have little direct effect on the potassium uptake of the plant but has remarkable indirect effect in soils particularly where potassium fixing clay minerals are dominant (6, 49, 94).

Macleod and Carson (49) using the hydroponic culture technique grew three species of grass at three levels of ammonium and two levels of potassium (50 and 250 ppm); 12, 50, and 75% of the applied 250 ppm nitrogen was in the NH_4^+ form. The potassium concentrations of timothy, orchardgrass, and bromegrass were about 3.5% irrespective of the ammonium levels in the culture containing 50 ppm of potassium.

Bartlett and Simpson (6) studied the effect of ammonium addition on potassium uptake of a plant in a potassium-fixing soil. They found that the addition of ammonium nitrogen, after potassium was equilibrated with the soil for two weeks, did not indicate any apparent effect on the potassium uptake of corn seedlings; whereas the equilibration of ammonium with the soil before the potassium addition showed an increase in the potassium absorption by the seedlings. An ammonium application prior to a potassium application to the soil containing clays that fix both ammonium and potassium may have brought about the occupancy of potassium fixing sites by the ammonium ions, and left the potassium unfixed. The consequent result is an efficient use of potassium by the plant. It has been shown that plants absorb potassium in both exchangeable and nonexchangeable forms. However, ammonium ions block the release of nonexchangeable potassium from the clay fraction to the plant (94).

Further information concerning potassium fixation will be reviewed in the section, "Mechanisms of Potasium Release and Fixation in the Soil", below.

b. Phosphorus

Readily available soil phosphorus exists in the forms of such anions as

$H_2PO_4^-$, HPO_4^{2-} and less abundantly as PO_4^{3-} (39). Because of its anionic nature, phosphorus does not exhibit the cation exchange phenomena as does potassium. Consequently, there seems to be no direct effect of phosphorus on the release of potassium from the exchange complex of the soil; but indirectly, phosphorus promotes plant growth and absorption of potassium as well as other nutrients as mentioned by Lawton and Cook (45).

Gillinghan (33) studied potassium uptake in connection with nitrogen and phosphorus additions using the Neubauer rye seedling method with soils of Vancouver Island, British Columbia. His data appeared to show that phosphorus had a favorable effect on the potassium uptake of the rye seedlings, and his conclusion was "it was an illustration of Liebig's Law of the Minimum."

c. *Calcium and Magnesium*

The level of calcium and magnesium has a definite effect on the potassium accumulation of plants. Although relationships among potassium, calcium and magnesium are not well understood, antagonistic relationships have been observed among these elements.

In a study carried out by Burkhart and Collins (15) with the peanut plant, in water culture, a large application of potassium increased the uptake of potassium by the plant but markedly decreased the uptake of calcium and magnesium, and vice versa.

Oya (63) also found an antagonistic relationship between calcium and potassium uptake of the peanut plant grown on kaolinitic soils. However, the same relationship was not demonstrated clearly on a montmorillonitic soil. Omar and Kobbia (62) reported that the increase of soil magnesium led to a marked decrease in the potassium content of the plant whereas the magnesium content in the plant increased only slightly.

In general the antagonistic relationships among potassium, calcium and magnesium are clearly demonstrated with the use of water or sand culture, but rather insufficiently with soils. The reason is based on the factors controlling nutrient availability. Factors that are to be considered include: (a) mechanisms of contact exchange, (b) the effecttive concentration of ions in the growing medium, and (c) the renewal rate of nutrients in the growing medium (90).

Contact exchange of nutrients between plant roots and soil colloids takes place in the soil but not in the water and sand cultures. The renewal rate of the nutrients in the soil is governed by much more complex conditions than that of water and sand cultures where colloidal particles of clays are not involved. Consequently the phenomena observed for the relationships among potassium, calcium and magnesium are simpler for the sand and water cultures than for soils. Among soils themselves, kaolinitic clays have larger size and lower negative charges than montmorillonitic clays, and therefore fewer interactions with these cations. The different nature of the clay minerals apparently affects plant uptake of potassium, calcium and magnesium.

d. Sodium and Boron

According to the review by Lawton and Cook (45) relative to the effects of sodium and boron on plant absorption of potassium, it is not clear whether sodium affects the uptake of this element, although sodium may partially substitute for potassium in certain crops. These workers suggested that the application of boron to tomato plants and orange trees increased the potassium absorption by the plants.

4. Effects of Physical Factors in Soil on Potassium Availability

a. Soil Moisture

Soil moisture is closely related to plant absorption of potassium as reported by Mederski and Stackhouse (52). Plant nutrients in the soil may reach the plant root by: (a) root extension, (b) mass flow, and (c) diffusion. If the speed of the root extension is a constant, the mass flow and diffusion control degrees of contact by the plant with nutrients. The supply of potassium to the plant root is mostly a diffusion controlled process; unlike calcium, magnesium and nitrogen which are supplied adequately by mass flow (5, 61). The relative rate of diffusion of potassium is expected to become greater with an increase in soil moisture (4).

Potassium uptake may be impeded by a discontinuity of the water film around the soil particles which intercepts the diffusion, and also by a high water stress in a soil of low moisture which depresses the root activity. In the experiment of Mederski and Stackhouse (52), potassium uptake by corn seedlings (25-day old) increased with soil moisture up to 16%. The soil was found to contain 25 and 6.5% moisture at 1/3 and 15 atmospheres, respectively. At moisture levels higher than 16%, plant absorption of potassium seemed to be affected by levels of soil aeration which served as a limiting condition of root respiration for the best potassium uptake.

b. Soil Aeration

Vlamis and Davis (91) and Lawton (44) demonstrated the effect of aeration on the uptake ot potassium by plants. In the water culture experiment, accumulation of potassium increased with aeration. Tomato and barley were found to require more aeration than rice in the root medium. The corn plants grown by Lawton in potassium-rich soils showed potassium defictency when the soils were either compacted or too wet.

Soil aeration seems to have specific effects on the potassium uptake of the plant. If the aeration is inadequate, root respiration (which is a process to decompose carbohydrate through pyruvate to carbon dioxide and water) is disturbed and creates less energy thus resulting in the production of ethyl alcohol. The accumulation of ethyl alcohol in the plant sap was very marked when soil aeration was restricted according to Fulton and Erickson (32).

Since potassium absorption is an energy requiring process, less potassium is absorbed under conditions of poor aeration. Furthermore, potassium is involved in pyruvate oxidase and cytochrome oxidase (27, 32), which lowers the energy output when insufficient potassium is supplied. Soil aeration, potassium absorption, and energy produced by the plant root are closely related.

c. Soil Temperature

The plant seems to absorb more potassium as the soil temperature rises. According to Worley *et al.* (98), the excised roots of Sudangrass, peas, and soybeans absorbed more potassium from 0.005 N potassium chloride solution when the solution temperature was raised from 5° to 25° C. Weber and Caldwell (93) showed that the sorghum plant absorbed more potassium as the soil temperature was raised from 60° to 90° F. The effet of temperature on potassium uptake was greater in a Floyd silty clay loam than in a Milaca sandy loam when potassium was applied. Since the release of carbon dioxide by the excised root of Worley *et al.* (98) increased linearly from 5° to 25° C, although there were variations above 25° C, soil temperature, potassium uptake, and respiration of the plant are related.

5. Effects of Clay Mineralogy of Soil on Potassium Availability

Clay minerals such as illite, montmorillonite and vermiculite are known to fix potassium (39). Soils containing these clay minerals may fix potassium applied as fertilizer and permit the plant to absorb only a fraction of it. Therefore, plants growing in a soil containing potassium-fixing minerals in quantity may take up less potassium in a short time when the soil is less saturated with potassium. Plants growing in such a potassium-fixing soil may, however, absorb more potassium than in other soils for a long period of time, because the potassium in the fixed state and in primary minerals (such as micas) becomes available slowly as potassium equilibrium moves to balance potassium absorbed by the plant.

C. DYNAMIC NATURE OF SOIL POTASSIUM

1. Origin of Soil Potassium

Soil potassium originates mainly from feldspars and micas which occur chiefly in igneous rocks. The earth's crust is composed of 95% igneous rock, 4% shale, 0.75% sandstone and 0.25% limestone, of which K_2O contents are 3.13, 3.24, 1.32, and 0.33%, respectively (16).

Soil is formed from parent materials, by the action of physical disintegration, chemical reaction and mineralogical changes under the influence of climate, drainage, and activity of life over varying periods of time.

Soils vary in their potassium content from place to place because soil forming processes occur in differing intensity. An important phase in soil formation and weathering is the formation of secondary clay minerals. The secondary clay minerals include 2 : 1, 2 : 2, and 1 : 1 type crystalline minerals and amorphous materials. Illite, vermiculite and montmorillonite are typical of 2 : 1 type clay, chlorite 2 : 2 type clay and kaolinite 1 : 1 type clay. In general clay mineral weathering proceeds from 2 : 1 and 2 : 2 types to 1 : 1 and ultimately to gibbsite, an aluminum oxide $Al(OH)_3$ (37).

Important clay minerals concerned with soil potassium are the 2:1 type clays which may hold potassium with their high cation exchange capacity, and among which illite and vermiculite carry potassium as their chemical component like the micas which are primary minerals.

Since feldspars (potassium carrying primary minerals) easily weather and do not remain in an active soil fraction clay, micas and 2:1 type clay minerals (especially illite and vermiculite) are considered to be the primary source of soil potassium. The potassium contents of most agricultural soils (0 to 6 inches in depth) in the United States range from 1 to 2% expressed as K_2O (37).

2. Factors Affecting Potassium Availability

Potassium availability in the soil would be best determined by potassium accumulation of the plant as the result of the integral condition of soil and other environmetal factors.

Soil potassium is generally divided into three broad categories: difficultly, moderately and easily available. The first group includes potassium present in the lattice of biotite, illite and vermiculite; the second group includes fixed potassium in the interlayer of potassium fixing clays such as illite, vermiculite and montmorillonite; and the last group includes exchangeable and water soluble potassium. Since these three groups of potassium are present in equilibrium in the soil, the rate of potassium change from difficultly to easily available form or vice versa upon depletion or supply of easily available potassium determines the soil potassium availability. Soil factors that affect the rate and direction of soil potassium equilibrium are: soil pH, moisture, freezing and thawing, organic matter, and complementary cations particularly in connection with potassium fixing clays.

a. Soil pH

In acid soil, potassium equilibrium is prevented from fixation because difficultly replaceable cations including H, Fe, and Al block potassium absorption sites of illite and vermiculite (64, 84).

b. Soil Moisture Level

Reitemeir *et al.* (74) and Khanna and Datta (41) reported that soils release nonexchangeable potassium in the moist condition. On the other hand Attoe (3) found potassium fixation to occur to some extent by keeping Miami silt loam and Spencer silt loam in a moist condition. Seemingly, these reports are in conflict, however, the results are well explained by clay mineralogy and potassium equilibrium in soil. In the experiment of Reitemeir *et al.* (74), exchangeable potassium was removed initially then the soil was kept in a moist condition. Consequently nonexchangeable potassium should have been released from the soil to attain the equilibrium. Potassium fixation was nil when no potassium was added to the soils studied by Attoe (3). This phenomenon would be explained in the same manner as above. Potassium fixation in a moist condition is peculiar to the soils containing vermiculite in which the interspace collapses even at low saturation with potassium in a moist state (22).

Potassium release from nonexchangeable forms was reported upon drying soils by Stanford (84), Luebs *et al.* (48) and Bates (7), whereas Stanford (84) obtained potassium fixation in drying some of his soils. Experiments with repetition of wetting and drying soil affected fixation of potassium according to Volk (92), and Powell and Hutcheson (67).

Potassium is released in drying soil by surface tension of water which curls up the fracture on the surface of micaceous minerals and releases potassium (69). Potassium fixation is caused by the contraction of montmorillonite interlayer space (39) .

Under field conditions, such drastic drying as employed in the laboratory seldom occurs except at the very surface of the soil, and release or fixation of potassium should take place only slowly.

c. *Freezing and Thawing*

Repetitions of freezing and thawing soils tended to increase exchangeable potassium. Among clays, montmorillonite and Putnam clay (a mixture of illite and montmorillonite), released potassium but illite fixed it (29). Potassium release by repetition of freezing and thawing was almost the same in quantity with that of samples kept in a moist condition when extraction was repeated during the treatment (74).

d. *Organic Matter*

Addition of organic matter to soil reduced the potassium release upon drying (7,8), because organic matter reduced the surface tension of water on the clay bearing potassium.

Mortland (56) reported that aniline hydrochloride and 2,4-diaminephenol dihydrochloride prevented potassium absorption of vermiculite by inhibiting collapsibility of the vermiculite interspace upon potassium intake.

e. *Complementary Cations*

Because of the similarity in their ionic size, ammonium and potassium ions compete for clay surface of potassium fixing sites. The ionic sizes of potassium and ammonium are 1.33 and 1.43 Å in radius respectively and hydrated sizes 5.3 and 5.4 Å as cited by Bertramson (13).

According to Page and Baver (cited by Kardos (39)), potassium and ammonium fixation by Miami colloidal clay was almost the same when the clay was saturated with the respective cations. When ammonium ion was abundant, potassium release from nonexchangeable form was blocked (94) and when ammonium was applied before potassium to the soil, potassium fixation was prevented (6) .

Calcium and magnesium, the most abundant cations in soil, also have some connection with potassium fixation or release. Powell and Hutcheson (67) reported that liming soils of micaceous mineralogy increased release of nonexchangeable potassium and prevented soils from fixing it. Their suggestion was that the calcium ion opened edges of clay mineral packet, because the calcium ion was smaller in hydrated size than potassium, i. e., the hydrated ion of calcium is 5.0 Å in radius as cited by Bertramson (13) , and easily penetrated into interstice of clays, thus releasing previously trapped potassium, and preventing entrappment of potassium by hindering potassium entrance into the interspace.

If simplified, the adsorption or replaceability of cations on clays is expected to follow the same order as the lyotropic series (96). There are, however, variations in the order of cation adsorption by soil. For instance, vermiculite adsorbed more magnesium than calcium when magnesium saturation exceeded about 35% (65) .

3. Mechanisms of Potassium Release and Fixation in the Soil

Potassium is released mainly from patassium bearing minerals such as feldspars and illite, and to a minor extent from vermiculite in the weathering process. Since feldspars, including potassium-rich orthoclase and microcline, are less resistant to weathering, micas and illite are more important sources of potassium in the clay fraction (37), which is considered to be an active constituent of the soil because of its greater specific surface accompanied by physicochemical activeness. Upon weathering micas change through illite, vermiculite to montmorillonite by releasing potassium.

The weathering action includes: (a) actions of loosening mica interlayers by the penetration of hydrated cations and by the scroll of weathered mica surface by the surface tension of water caused by drying the soil; and (b) reduction of electric charges by oxidation of the ferric ion in the octahedral layer and by proton addition of a hydronium ion to octahedrally charged oxygen (37). When potassium is continuously removed from the surrounding solution, mica releases a quantity of potassium as demonstrated in the experiment by Ellis and Mortland (26).

Potassium fixation may be explained by the "lattice hole" theory and intensity of negative charge in the interlayer surface of clay minerals (39). The explanation of the "lattice hole" theory, if vermiculite is taken as an example, is as follows.

Upon dehydration, a potassium ion, of which the unhydrated diameter is 2.66 Å, just fits in the hexagonal space of the oxygen sheet of the silica tetrahedral layer of the clay (size - 2.8 Å in diameter). The perfectness of fit of the potassium ion to the "lattice hole" pulls the adjoining tetrahedral layers so close that no other accessible cations can replace the potassium. Thus fixed potassium is difficultly rehydrated.

Differences in the intensity of negative charge on the clay surface make potassium fixation possible in different ways with respective clays. In illite and vermiculite, more negative charge is derived from the silica tetrahedral layer than the aluminum octahedral layer; in contrast, in montmorillonite more negative charge is derived from the aluminum octahedral layer than the silica tetrahedral layer for a unit surface. The potassium ion is attracted more strongly by the negative charge at the silica tetrahedral layer than the negative charge at the octahedral layer since the distances between the potassium ion, and the charges at the tetrahedral and octahedral negative sites are 2.19 and 4.99 Å respectively. Therefore, potassium fixation is observed in both moist and dry condition of the soil with illite and vermiculite but only in the dry condition with montmorillonite. The expandability of the clays with potassium fixed in this way is highest with montmorillonite and lowest with illite in accordance with the charge intensity. These factors also affect the ease of rehydration of potassium and accessibility of other ions.

D. POTASSIUM AVAILABILITY MEASUREMENT

Soil potassium is arbitrarily divided into three categories: difficultly, moderately and easily available. However, the status of the soil potassium changes by conditions. Many methods have been devised and used to measure available potassium with greater accuracy. These methods may be categorized as biological and chemical methods.

1. Biological Methods

Generally known biological methods are· (a) the Neubauer method, (b) the Stanford and DeMent method, and (c) greenhouse pot and field plot methods.

a. Neubauer Method

The Neubauer method using rye as an indicator plant was devised in Germany in 1929, and became very popular in Europe. In the United States the method was extensively tested and employed by Thornton and other investigators to test availability of potassium as well as other nutrients in the soil (51, 66, 88, 89).

b. Stanford and Dement Method

Stanford and DeMent devised an efficient way to test nutrient availability in soil by growing plant seedlings on quartz sand deficient in a nutrient and after a certain period transferring them onto a soil to be tested for the nutrient. They developed this method first for testing phosphorus (85) and then for potassium (21). Since then the method has been employed by many investigators.

C. Greenhouse and Field Methods

Field testing began with the establishment of the Rothamsted

Experiment Station in 1843, and is still a popular orthodox method because plants and nutrients are tested under natural conditions. The greenhouse method using pots with various modifications is extensively employed as well, because plants and nutrients can be tested under conditions similar to the field besides controlling desired factors.

Using biological methods, the potassium availability is demonstrated by the difference between yields or potassium contents of the plants grown with and without potassium. If the difference is small, the potassium availability of the tested soil to be high. Biological methods are the most reliable, because the plant itself is the indicator and potassium availability is related to plant production.

2. Chemical Methods

a. Extraction of Potassium with Neutral I N Ammonium Acetate Solution

Because of simplicity and rapidity, chemical methods employed in the laboratory became more popular in determining available potassium since the biological methods generally require more time and skill than chemical methods. The chemical methords are considered very useful when correlated with greenhouse and field tests. Although various chemical reagents are used to extract available potassium neutral I N ammonium acetate solution is employed as a standard because exchangeable potassium determined by this method has been successfully correlated to crop yields or potassium uptake (36, 77).

b. Extraction with Boiling I N Nitric Acid

However, the exchangeable potassium is only a portion of available forms and plants may use some portions of initial nonexchangeable potassium during the growth period. Determinations of both exchangeable and nonexchangeable forms are accomplished by using a boiling I N nitric acid extraction (23, 74, 77) .

Other methods in determining nonexchangeable potassium in micaceous soils include the extraction method with sodium tetraphenylborate (NaTPB) solution (72, 73, 79, 80, 81, 82) .

c. Quantity-Intensity Relations of Soil Potassium

Several methods of potassium availability measurements have been studied from the activity point of view. The quantity-intensity relations of labile soil potassium were studied, and the activity ratio, $^{a}K/\sqrt{a(Ca + Mg)}$, in soil solution was proposed as a measure of the intensity factor. The potential buffering capacity, $-\triangle K^0 / AR^k_e$, was proposed as a measure of soil ability to maintain the activity ratio against potassium depletion by the plant (9, 10, 50). According to Beckett (11), the labile potassium is defined as:

> ions present in the soil solution or in exchangeable form; except for 1–2% which is more difficultly exchangeable, equilibrium is very rapidly achieved within the pool of labile potassium, with a halftime measured in minutes or less.

In the calculation of potential buffering capacity (PBC^k), $-\triangle K^0$ is the exchangeable potassium supposed to be measured at zero value of chemical activity of potassium in the soil solution (which is measured in the presence of exchangeable potassium of the soil proper) and AR^k_e is the activity ratio at an equilibrium where no gain or loss of potassium by soil takes place ($\triangle K_e = 0$).

Since the values for $-\triangle K^0$ and AR^k_e were difficult to determine, they were obtained from a graph drawn with various activity ratios $AR^k = {}^aK / \sqrt{{}^a(Ca+Mg)}$ against changes in the exchangeable posassium ($\triangle K_e$) by extrapolating the linear portion of asymptotic curve to cross the ordinate for $-\triangle K^0$ value and by interpolating the curve to cross the $\triangle K_e = 0$ line for AR^k_e value. Calcium and magnesium are used in the activity ratio calculation because they are considered most abundant in the soil; although in some cases other ions such as Al in acid soils and Na in alkali soils must also be included in the calculation.

The Beckett method seems to have the advantage of not disturbing the potassium equilibrium in the soil; many investigators have tested the method. Acquaye and MacLean (1) found good correlations ($r = +0.92$) between potassium uptake by plants and $-\triangle K^0$ values on Canadian soils as well as between potassium uptake and exchangeable potassium measured with the ammonium acetate method ($r = +0.91$), however, low correlation ($r = +0.56$) between potassium uptake and AR^k_e. Correlation between PBC^k and non-exchangeable potassium measured with boiling I N nitric acid was $+0.52$.

Wild *et al.* (97) found no correlation between potassium uptake by plants and activity ratio expressed as $(K)/\sqrt{(Ca)}$ in sand culture which also contained various amounts of magnesium.

Better correlations were obtained between potassium uptake and potassium potential, calculated by multiplying $-\triangle K^0$ value by PBC^k value, than between potassium uptake and exchangeable patassium (99). When the $-\triangle K^0$ is multiplid by PBC^k value, the $-\triangle K^0$ value is to be magnified.

However, this may benefit the relationship, because exchangeable potassium is slowly supplemented by nonexchangeable potassium during cropping period in potassium fixing soils.

III SOIL CROPPING EXPERIMENTS IN THE GREENHOUSE EMPLOYING WHEAT, SORGHUM AND TOMATO AS THE INDICATOR PLANTS

A. EXPERIMENTAL METHODS AND MATERIALS

1. SOILS

Four different soils were used in the experiments: Brookston loam, Genesee loam, Kalamazoo sanday loam, and Landes-Abscota sandy loam. A soil suspected of having a high capacity for the fixation of potassium was first chosen for the experiment and tentatively named Landes-Abscota because its characteristics were identified between Landes and Abscota series.[1] Genesee loam was similar to the Landes-Abscota sandy loam in terms of soil genesis. Kalamazoo sandy loam was adjacent to the Landes-Abscota sandy loam but located on a higher terrace. Similarity was anticipated among the three soils concerning potassium release and fixation properties. The Brookstoon loam, of which potassium release and fixation properties were little known, was also chosen to provide a comparison with the other three soils. The characteristics of the four soils are described in Appendix A.

a. Soil Collection

Brookson loam was collected on June 13, 1968, from the surface layer (0-6.5 inches) of a field planted to navy beans which had not begun to germinate. The field is located at SW ¼ of SW ¼, Sec. 15, Sebewa Township (T5N, R6W), Ionia County, Michigan.

Genesee loam was collected on June 11, 1968, from the plowed layer (0-6.5 inches) of the harvested corn field which is located at NE ¼ of SW ¼ of NW ¼, Sec. 33, Danby Township (T5N, R5W), Ionia County, Michigan.

Kalamazoo sandy loam was collected on September 18, 1968, from the surface (0-6.5 inches) of the plowed harvested Sudangrass field. The collection site is about 30 meters east of the barn and 7 meters south of the entrance road in the Sodus Experimental Farm of Michigan State University

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[1] Personal communication with Dr. E. P. Whiteside, Crop and Soil Sciences Department, Michigan State University

located in section 16 of Berrien County, Michigan.

Landes-Abscota sandy loam was collected on September 18, 1968, from the surface (0-6.5 inches) of a harvested tomato field at 10' E of the tomato plot of the Sodus Experimental Farm. The collection site was located at a raised part of the flat along the St. Joseph River, and about 80 meters east of the river.

b. Chemical Analysis

Soil samples were submitted to the Soil Test Laboratory at the Department of Crop and Soil Sciences, Michigan State University to examine the chemical properties before starting the greenhouse experiment. The result of the chemical analysis is shown in Table 1.

Table 1. Chemical analysis of the experimental soil[a]

Soil	pH	CEC	P	K	Ca	Mg	Zn	Mn	Cu	Organic matter
		me／100g	―――Ibs／A―――				―――ppm―――			%
Brookston loam	6.5	20.7	38	151	6551	723	18	76	10	3.7
Genesee loam	6.3	15.8	14	93	4899	394	16	160	8	3.4
Kalamazoo sandy loam	7.3	7.0	121	275	2239	379	13	68	13	1.4
Landes-Abscota sandy loam	6.3	13.2	97	75	4658	404	13	60	12	2.4

[a] All values are averages of 3 determinations on air-dried samples except for CECs (cation exchage capacities) which are means of 2 determinations and converted to the oven-dry basis.

1) Soil acidity

Determination of pH was done with a glass electrode pH meter on 1:1 soil-water suspension.

2) Cation exchange capacity

Cation exchange capacity was determined by the author on a 10 g sample of soil which was saturated with calcium by repeated centrifugings with 1 N calcium chloride solution. Excess salt was removed with water and then methyl alcohol and the calcium held on the sample was replaced by magnesium by repeated centrifugings with 1 N magnesium chloride solution. The calcium in the collected supernatant representing cation exchange capacity was determined on a Coleman Flame Photometer

Model 21.

3) Phosphorus

Phosphorus was extracted from a 2.5 g sample with 20 ml of Bray P_1 solution consisting of 0.3 N ammonium fluoride and 0.25 N hydrochloric acid. To the extractant 5 drops of ammonium molybdate solution and 5 drops of F-S reducing solution, which consisted of 1-amino-2-nappthol-4-sulfonic acid (Eastman 360), sodium sulfite and sodium metabisulfite ($Na_2 S_2 O_5$), were added to develop a blue color the intensity of which was compared on a colorimeter at a wave length of 500 mμ with a set of standard phosphorus solutions.

4) Potassium, calcium, and magnesium

Potassium, calcium, and magnesium were extracted from the soil with 1.0 N neutral ammonium acetate solution. Potassium in the extract was determined on a Coleman Flame Photometer. Calcium was determined on a Beckman model DU flame emission spectrophotometer with 1,500 ppm lanthanum im the extract. Magnesium also with lanthanum was determined on a Perkin-Elmer Model 290 Atomic Absorption Spectrophotometer. Each determination was calibrated against a set of standard solutions of the respective elements.

5) Zinc, Manganese, and Copper

Zinc and manganese were extracted from a 2.0 g sample by shaking for 10 minutes with 20 ml of 0.1 N hydrochloric acid. Copper was extracted by shaking a 2 g sample of the soil for 1 hour with 20 ml of 1.0 N hydrochloric acid. The three elements were determined on a Perkin-Elmer Model 290 Atomic Absorption Spectrophotometer.

6) Organic matter

Carbon was analyzed by a Leco carbon analyzer which ignited organic matter with an induction furnace, and the carbon contents were converted to organic matter content (%) by multiplying percentage of carbon by a factor of 1.724.

c. *Soil Preparation and Treatment*

The soil was air-dried and mixed thoroughly in order that the soil became homogeneous. The soil was then sieved through a wire screen of quarter inch (6 mm) openings to remove larger stones and plant roots, and was put into pots (1 gallon cans) lined with plastic bags so that each pot contained 2.7 kg (6 lbs) of oven-dry weight.

On a sheet of wrapping paper each soil was mixed thoroughly with three nutrient elements: nitrogen as calcium nitrate; phosphorus as monocalcium phosphate; and potassium as potassium chloride; and returned to the pot.

Table 2 shows the amounts of the nutrient elements applied per pot expressed as equivalents of pounds per acre of each element converted on the basis of soil weight in the pot.

Table 2. Applied rates of nitrogen, phosphorus, potassium and manganese

Crop	Nutrient element	Soil			
		Brookston loam	Genesee loam	Kalamazoo sandy loam	Landes-Abscota sandy loam
1st crop (Wheat)	N	50	50	50 (25) [a]	50 (25) [a]
	P	44	66	22	22
	K	(0, 200, 400, 800, and 1,600 to all soils)			
2nd crop (Wheat)	N	100	100	100	100
	P	88	99	44	44
3rd crop (Wheat)	N	100	100	100	100
	P	83	99	44	44
	Mn	10	10	10	10
4th crop (Sorghum)	N	100 (50) [a]	100 (50) [a]	100 (50) [a]	100 (50) [a]
	P	88	99	44	44
	Mn	5	5	5	5
5th crop (Sorghum)	N	100 (25) [a]	100 (25) [a]	100 (25) [a]	100 (25) [a]
	P	88	99	44	44
	Mn	5	5	5	5
6th crop (Tomatoes)	N	70 [b]	70 [b]	70 [b]	70 [b]
	P	100	100	100	100
	Mn	20	20	20	20

[a] Additional nitrogen applied.

[b] Split application; 35 lbs before planting and the remainder during the growing period.

Only nitrogen was applied in solution; other nutrient elements were applied in the solid form. Since the phosphorus content of the soils varied (Table 1), phosphorus rates equivalent to 44 lbs per acre were added to Brookson loam, 66 lbs per acre were applied to Genesee loam, and 22 lbs per acre were applied to both Kalamazoo sandy loam and Landes-Abscota sandy loam to insure this clement was not limiting on the basis of recommendation in the Michigan State University Extension Bullletion E-550 (53).

Potassium was applied as ptassium chloride to the respective soils at five levels equivalent to 0, 200, 400, 800, and 1,600 lbs of potassium (K) per acre. Each potassium treatment was replicated four times for all crops except for the 6th crop (tomatoes) which employed two replicates. An additional replicate was prepared for the incubation study which was uncropped during the entire greenhouse experiment.

After harvesting each crop, the soils were sieved through a wire screen with openings of a quarter of an inch to remove crop roots, and mixed with given amounts of nutrients, excluding potassium. The amounts of nutrients supplied to the soils for the 2nd and succeeding crops are also presented in Table 2.

Calcium nitrate and monocalcium phosphate were used as nitrogen and phosphorus sources throughout the experiment. Potassium was applied to the lst crop only. Manganese was applied in a band as a solution of manganese sulfate to the 3rd crop and the succeeding crops, since manganese deficiency was suspected with the 2nd crop at a later stage of growth.

The pots were arranged in a randomized complete block design on the benches in the greenhouse.

2. PLANTS

a. Plants Used for the Experiment

Three different Plants were used in the experiment; wheat (***Triticum aestivum var. avon***) for the lst through the 3rd crops; sorghum (***Sorghum vulgae var. Pioneer*** 884) for the 4th and 5th crops; and tomato (***Lycopersicon esculentum var. Campbell*** 1327) for the 6th crop.

Wheat, sorghum and tomatoes are considered relatively high absorbers of potassium as suggested by Newton (59), Lewis and Eisenmenger (46) and Drake and Scarseth (25).

In growing the plants, 25 wheat seeds were planted in each pot and later thinned to 20 plants per pot. Ten sorghum seeds were grown per pot and thinned to 6 plants per pot. Tomato seeds were sown in wooden flats consisting of 2 parts of unfertilized loamy soil, 1 part of sand and 1 part of shredded peat. Fifteen-day old seedlings bearing 2 true leaves were transplanted to each pot, and later thinned to 4 plants.

b. Management and Growth of the Plants

The lst crop (wheat) was grown for 71 days, planted on December 5, 1968, and harvested on February 13, 1969. Distilled water was applied as needed. However, the moisture of the soil was brought up to a pot capacity at 7 to 10 day intervals to maintain the proper moisture level. The pot capacity measured with separate pots was the percentage of water retained after the gravitational water had been removed.

Since the wheat plants grown in Kalamazoo sandy loam and Landes-Abscota sandy loam showed nitrogen deficiency during the 6th week of growth, additional nitrogen, equivalent to 25 lbs of nitrogen per acre, was applied to those soils (Table 2).

The 2nd crop (wheat) was grown for 72 days from March 26 to June 5, 1969. The wheat plants showed chlorotic symptoms as observed in the lst crop. The symptom was suspected as manganese deficiency. Therefore, manganese was applied to the subsequent crops (Table 2). The growth of the plants is depicted in Appendices B to E.

The 3rd crop (wheat) was grown for 47 days from June 7 to July 23, 1969. The daytime temperature in the greenhouse sometimes rose to 90° F in July and seemed to have unfavorable effects on the growth of the plants. Therefore, the 3rd crop was harvested with a shorter period of growth than the previous two crops.

The 4th crop (shorghum) was grown for 61 days from July 29 to September 27, 1969. Since the sorghum plants showed symptoms of nitrogen starvation, nitrogen, equivalent to 50 lbs per acre, was applied in solution in addition to the basic treatment (Table 2). Daytime greenhouse temperatures sometimes rose above 90° F during the growing period of the 4th crop. This appeared favorable for plant growth, since sorghum prefers rather warm temperatures (2).

The 5th crop (sorghum) was grown for 72 days from October 11 to December 21, 1969. From the 3rd week, differences in plant growth were visibly observable among the potassium treatments. Plants subjected to the 0 potassium (no K added) and 200 potassium (200 lbs K/A) treatments showed potassium deficiency symptoms resulting in yellowing of the older leaves, burned edges, and less vigorous growth. The 800 and 1,600 potassium treatments resulted in larger, healthier plants. The 400 patassium treatment produced plants intermediate in growth. Additional nitrogen equivalent to 25 lbs of nitrogen per acre was applied during the 5th week before nitrogen deficiency developed. The growth difference of the 5th crop are shown in Appendices B to E.

The 6th crop (tomatoes) was grown for 42 days; being transplanted on March 18, and harvested on April 28, 1970. The tomato plants showed potassium deficiency two weeks after being transplanted in the soils containing 0 lbs per acre applied potassium. Prior to harvest, the plants grown on Brookston loam showed chlorosis of the older leaves with slight burning at the edges on the 0 potassium treatment. The plants grown on Genesee loam showed potassium deficiency following the 0, 200, and 400 potassium treatments. The deficiency was most prominent on the 0 patassium treatment where excessive drop of the older leaves occurred and the middle leaves showed chlorosis on the entire leaf with marginal leaf burn. Rusty black specks irregular in shape 2/5 to 1 mm in diameter were observed on and between the veins of the older leaves of the potassium deficient plants. This symptom appeared to be associated potassium deficiency since examination by Mr. Bockstahler, Department of Botany and Plant Pathology, Michigan State University, confirmed the absence of fungus causing this symptom.

The plants growing on Kalamazoo sandy loam and Landes-Abscota sandy loam showed the same tendency for potassium deficiency as described for those growing on Genesee loam. In general, better plant growth was observed on the higher potassium treatments. The temperature of the greenhouse was maintained at approximately 70° F during night but periodically rose above 80° F in the daytime. The growth of crop is illustrated in Appendices B to E.

3. Plant Analysis for Potassium, Calcium and Magnesium

a. Chemical Analysis

The harvested plant material was ground in a Willey mill after having been dried in an oven at 160° F. One gram samples of the ground tissue were placed in 50 ml beakers and ashed in a muffle furnace at 400° C for 8 hours. To insure the ashing 20 ml of I N nitric acid was added to the beakers and evaporated to dryness on a hot plate. The residue in the beakers was ashed again at 400° C for 10 minutes. The ashed material was taken up with 0.1 N hydrochloric acid in 100 ml volumetric flasks and the extract used for potassium, calcium, and magnesium determination.

Potassium was determined on a Coleman Flame Photometer Model 21. Calcium and magnesium were determined with a Perkin-Elmer 303 Atomic Absorption Spectrophotometer. The plant uptake of each element was obtained by multiplying the concentration (%) of the element by the plant yield (dry matter), and expressed as a milligram of the element per pot.

b. Electron Microprobe X-Ray Analysis

The electron microprobe X-ray analysis was used for the determination and distribution of potassium, calcium, and magnesium in wheat stem tissue. Stem segments of 9-week old wheat plants were obtained 1-inch above the ground from the 2nd crop grown on Brookston loam receiving 400 lbs of potassium per acre and on the 0 potassium treatment of Genesee loam.

The stem segments were immediately frozen and sectioned after embedding them in Optimum Cutting Temperature compound (Tissue-Tek, -15° to -30° C; Fisher Scientific Company) on the cryostat at -18° C. The thin cross sections (16 μm thick) were mounted on polished carbon discs at room temperature, allowed to air-dry, and then submitted for electron microprobe X-ray analysis.

B. RESULTS AND DISCUSSION

1. Plant Yields

a. Plant Yields Obtained on Brookston, Genesee, Kalamazoo, and Landes-Abscota Soils

The plant yields of the lst through the 6th crops are presented in Tables 3 to 6 for Brookston loam, Genesee loam, Kalamazoo sandy loam, and Landes-Abscota sandy loam. The values are averages of 4 replications except for the 6th crop which had only 2 replications.

The LSD (least signifcant difference) values were calculated only where F test by the analysis of variance showed significant treatment effects at less than 5 percent probability levels as suggested by Steel and Torrie (86). In addition, regression analyses were carried out to determine the relationships between plant yields and potassium treatments, and are presented in Table 7.

The general trends on all soils show that the plants responded favorably to the potassium treatments when potassium became exhausted by continuous cropping. Also shown are the differential responses of the plants to applied potassium.

Table 3. Yields of wheat, sorghum, and tomato crops as affected by potassium treatments on Brookston loam

K treatment	Wheat crop			Sorghum crop		Tomato crop	Total
	1	2	3	4	5	6	
(lbs/A)				(gm/pot)			
0	9.0	21.0	6.1	23.5	6.4	6.1	72.8
200	7.1	23.8	6.6	23.5	7.3	6.2	74.5
400	9.9	22.9	7.0	24.0	7.4	5.9	77.1
800	11.1	20.4	7.4	23.9	7.4	7.3	77.5
1,600	9.5	21.3	7.8	24.6	7.8	8.0	79.0
L.s.d.[a]							
(.05)	N.s.[b]	N.s.	0.73	N.s.	N.s	0.76	
(.01)			1.02			1.26	

[a] The least significant difference at 5% and 1% levels of probability, respectively.

[b] No significant difference in plant yields as detected by F test with analysis of variance.

Table 4. Yields of wheat, sorghum, and tomato crops as affected by potassium treatments on Genesee loam

K treatment	Wheat crop			Sorghum crop		Tomato crop	Total
	1	2	3	4	5	6	
(lbs/A)				(gm/pot)			
0	8.1	15.8	4.8	20.0	6.4	1.7	56.8
200	8.4	16.1	5.5	19.5	6.6	2.6	58.7
400	8.1	17.1	5.9	22.0	7.6	3.6	64.3
800	8.1	17.6	6.4	22.4	8.5	5.4	68.4
1,600	8.3	17.3	6.9	26.6	9.4	6.7	75.2
L.s.d.[a]							
(.05)	N.s.[b]	N.s.	0.39	1.94	1.09	0.95	
(.01)			0.55	2.72	1.52	1.57	

[a] The least significant difference at 5% and 1% levels of probability, respectively.

[b] No significant difference in plant yields as detected by F test with analysis of variance.

Table 5. Yields of wheat, sorghum, and tomato crops as affected by potassium treatments on Kalamazoo sandy loam

K treatment	Wheat crop			Sorghum crop		Tomato crop	Total
	1	2	3	4	5	6	
(lbs/A)				(gm/pot)			
0	8.5	16.4	5.1	17.6	6.1	2.9	56.6
200	8.4	16.1	6.0	20.9	7.3	4.3	63.0
400	8.6	14.8	6.0	22.1	8.1	5.0	64.6
800	8.0	13.0	6.6	20.8	8.3	6.0	62.7
1,600	8.1	13.8	6.3	24.0	9.9	6.8	68.9
L.s.d.[a]							
(.05)	N.s.[b]	1.33	0.47	1.88	0.98	0.58	
(.01)		1.86	0.66	2.64	1.38	0.97	

[a] The least significant difference at 5% and 1% levels of probability, respectively.

[b] No significant difference in plant yields as detected by F test with analysis of variance.

Table 6. Yields of wheat, sorghum, and tomato crops as affected by potassium treatments on Landes-Abscota sandy loam

K treatment	Wheat crop			Sorghum crop		Tomato crop	Total
	1	2	3	4	5	6	
(lbs/A)				(gm/pot)			
0	9.0	15.3	5.4	20.6	7.0	2.9	60.2
200	10.4	15.1	5.5	21.8	7.4	2.6	62.8
400	10.5	15.4	6.0	22.4	7.9	4.3	66.5
800	10.1	15.4	6.6	22.9	7.9	5.5	68.4
1,600	10.8	16.1	7.0	25.8	8.5	7.1	75.3
L.s.d.[a]							
(.05)	0.42	N.s.[b]	0.48	2.03	0.38	1.67	
(.01)	0.58		0.68	2.85	0.53	2.76	

[a] The least significant difference at 5% and 1% levels of probability, respectively.

[b] No significant difference in plant yields as detected by F test with analysis of variance.

Table 7. Relationships between plant yields and potassium treatments on Brookston loam, Genesee loam, Kalamazoo sandy loam and Landes-Abscota sandy loam

Crop[a]	Linear regression equation	Simple correlation coefficient[b] (r)
	Brookston loam	
Wheat (1st crop)	$\hat{Y} = 6{,}490 + 0.69X$	0.19
Wheat (2nd crop)	$\hat{Y} = 16{,}559 - 0.62X$	−0.22
Wheat (3rd crop)	$\hat{Y} = 4{,}946 + 0.52X$	0.68**
Sorghum (4th crop)	$\hat{Y} = 17{,}397 + 0.51X$	0.24
Sorghum (5th crop)	$\hat{Y} = 5{,}067 + 0.47X$	0.42
Tomato (6th crop)	$\hat{Y} = 4{,}358 + 1.00X$	0.89**
	Genesee loam	
Wheat (1st crop)	$\hat{Y} = 6{,}066 + 0.01X$	0.02
Wheat (2nd crop)	$\hat{Y} = 12{,}022 + 0.67X$	0.48*
Wheat (3rd crop)	$\hat{Y} = 3{,}817 + 0.89X$	0.90**
Sorghum (4th crop)	$\hat{Y} = 14{,}971 + 1.34X$	0.60**
Sorghum (5th crop)	$\hat{Y} = 4{,}849 + 1.42X$	0.86**
Tomato (6th crop)	$\hat{Y} = 1{,}563 + 2.30X$	0.96**
	Kalamazoo sandy loam	
Wheat (1st crop)	$\hat{Y} = 6{,}291 - 0.21X$	−0.37
Wheat (2nd crop)	$\hat{Y} = 11{,}760 - 1.33X$	−0.62**
Wheat (3rd crop)	$\hat{Y} = 4{,}194 + 0.42X$	0.56*
Sorghum (4th crop)	$\hat{Y} = 14{,}276 + 2.22X$	0.71**
Sorghum (5th crop)	$\hat{Y} = 4{,}946 + 1.54X$	0.83**
Tomato (6th crop)	$\hat{Y} = 2{,}707 + 1.65X$	0.92**
	Landes-Abscota sandy loam	
Wheat (1st crop)	$\hat{Y} = 7{,}206 + 0.52X$	0.58**
Wheat (2nd crop)	$\hat{Y} = 11{,}187 + 0.43X$	0.50*
Wheat (3rd crop)	$\hat{Y} = 4{,}046 + 0.79X$	0.86**
Sorghum (4th crop)	$\hat{Y} = 15{,}469 + 2.21X$	0.83**
Sorghum (5th crop)	$\hat{Y} = 5{,}347 + 0.62X$	0.82**
Tomato (6th crop)	$\hat{Y} = 2{,}024 + 2.11X$	0.94**

[a] Each crop had 4 replicates except for the 6th crop which had only 2.

[b] * and ** indicate significance at 5% and 1% probability levels respectively.

b. Effect of Potassium Treatment on the Yield of Plants Grown on Brookston Loam

In Brookston loam, the initial exchangeable potassium, 151 lbs per acre (Table 1), and nonexchangeable potassium, 31.9 mg per 100 g (Table 21), seemed to be sufficient to supply the lst and 2nd crops since the two crops did not respond to applied potassium (Tables 3 and 7, and Figure A1). The 3rd crop responded to potassium application but the 4th and 5th crops did not. This may have been the result of the difference in the potassium absorbing power of the plants and envrironmental effects. Sorghum plants appeared to be higher than wheat in potassium absorbing power as suggested by Drake and Scarseth (25) in which Sudangrass absorbed more potassium than spring wheat on Crosby silt loam. The greenhouse temperature in the daytime rose to more than 90° F during the growing period of the 3rd crop (June 7 to July 23, 1969), at which temperature the 3rd crop, wheat, performed poorly but seemed to have received beneficial effect from the applied potassium. Plant respiration is generally stimulated by higher temperatures and the applied potassium might have affected plant metabolism since plant respiration and potassium consumption are closely related. The 4th crop, sorghum, showed a more favorable growth response under high temerature and high sunlight intensities during the growing period of July 29 to September 27, 1969 than the 5th crop, sorghum, which was grown from October 11 to December 21, 1969 (Tables 3 and 7, and Figure A2).

For the 6th crop, tomatoes, native potassium seemed to be exhausted and available quantities were not sufficient to support the crop without the addition of potassium, even though the tomato plant has a relatively strong absorption power for potassium, as shown by Lewis and Eisenmenger (46). The differential response between sorghum (the 5th crop) and tomatoes (the 6th crop) may not be explained fully by plant differences but by the depletion of soil potassium, since the tomato crop did not show significant yield differences with potassium application when grown on the newly treated (uncropped) soils, as shown in Table 8 and Figure A4 of Appendix B.

Table 8. Yields of tomato plants on newly treated (uncropped) Brookston, Genesee, Kalamazoo, and Landes-Abscota soils

K treatment	Soil			
	Brookston loam	Genesee loam	Kalamazoo sandy loam	Landes-Abscota sandy loam
(lbs/A)			(gm/pot) [a]	
0	11.1	10.3	9.6	10.9
200	10.8	10.4	10.2	12.0
400	10.1	10.8	10.4	12.4
800	10.8	11.2	10.1	11.9
1,600	10.4	10.0	8.6	10.2
L. s. d. (.05) [b]	N.s.[c]	N.s.	N.s.	N.s.

[a] All values are averages of 2 replicates.

[b] The least significant difference at 5% level of probability.

[c] No significant difference.

c. *Effect of Potassium Treatment on the Yield of Plants Grown on Genesee Loam*

Genesee loam contained only 93 lbs of exchangeable potassium per acre (Table 1) which, however, appeared to be sufficient to supply adequate to the lst and 2nd crops (Tables 4 and 7, Figure A5). The 3rd and successive crops responded positively to applied potassium due to the exhaustion of native soil potassium which was consequently considered to be lower in this soil than in Brookston loam. The good yield of the 4th crop in Genesee loam may be explained in the same manner as the 4th crop grown on Brookston loam.

The tomato plants grown on newly treated (uncropped) Genesee loam did not respond to application of potassium as indicated in Table 8 and Figure A8 in contrast wtih the 6th crop (tomatoes) which showed remarkable benefit from the potassium treatments (Tables 4 and 7, and Figure A7).

d. *Effect ot Potassium Treatment on the Yield of Plants Grown on Kalamazoo Sandy Loam*

Since the initial exchangeable potassium was as high as 275 lbs per acre (Table 1), potassium application seemed to have created detrimental effects on the yields of the 2nd crop on this soil by supplying the plants with an excess amount of potassium which was apparently not alleviated by potassium fixation. The fixation of potassium was very low in this soil in contrast with the other three soils (Table 23).

Sunlight stimulates plant metabolism and respiration leading to the activation of root uptake of nutrients. The unfavorable effect of excess potassium was not clearly indicated with the 1st crop because the intensity of sunlight was low during the growing period (December 5, 1968 to February 13, 1969). On the other hand, during its growing period (March 26 to June 4, 1969) the 2nd crop received more sunlight causing more plant uptake of potassium and decreasing the yields by the increased levels of potassium application (Tables 5 and 7).

The 3rd and succeeding crops responded positively to applied potassium. The discussion of the 4th crop grown on Brookston loam would also be applied to the 4th crop of Genesee loam.

In contrast with the tomatoes (6th crop) which showed a remarkable yield increase due to the residual potassium, the tomato plants grown on the newly prepared (uncropped) soil did not respond to any of the potassium treatments (Tables 7 and 8, and Figures A11 and A12).

e. *Effect of Potassium Treatment on the Yield of Plants Grown on Landes-Abscota Sandy Loam*

Landes-Abscota sandy loam soil was initially low (75 lbs/A) in exchangeable potassium (Table 1). It appeared to be partly due to the influence of the previous tomato crop grown at the sample collection site. Tomato plants are generally believed to absorb large quantities of potassium (30). The application of potassium was effective in increasing plant yields of the 1st crop (Table 6). However, the 2nd crop seemed to have absorbed sufficient native potassium possibly due to more favorable environmental conditions as previously discussed. When the native potassium became exhausted, the 3rd and successive crops responded to applied potassium (Tables 6 and 7, and Figures A13 to A15). The discussion on the general high yield of the 4th crop in Brookston loam may also apply.

The tomato plants grown on the newly prepared (uncropped) soil showed no significant difference in plant yields due to potassium treatments (Table 8, and Figure A16 of Appendix C). The difference in response to applied potassium between the 1st wheat crop, which responded to applied potassium, and the tomato plants (also the 1st crop on the newly prepared soil), which did not respond to applied potassium, may be considered as the result of the differential potassium absorbing power between these two plants, i. e., the wheat plants needed applied potassium to meet increasing growth but the tomato plants used sufficient native potassium when potassium application was low.

2. Potassium, Calcium, and Magnesium Concentration in the Plants

a. Potassium, Calcium, and Magnesium Concetrations, and Relations among the Concentrations of These Elements

1) Potassium, calcium, and magnesium concentrations in the plants

The plant concentration of potassium, calcium, and magnesium were obtained by plant analysis for each crop, and the results are summarized in Tables 9 to 12 on the basis of dry weight. The potassium concentration of plants grown on all the soils rose with the increasing level of applied potassium, which agreed with the work of DeMent *et al.* in 1959. Since it has been reported that antagonistic relationships exist between potassium and calcium or potassium and magnesium, relationships among the three elements were examined (Table 13).

Table 9. Potassium, calcium, and magnesium concentrations of plant material as affected by potassium treatments on Brookston loam[a]

K treatment[b]	K	Ca	Mg	K	Ca	Mg	K	Ca	Mg
lbs/A		%			%			%	
		1 t crop-wheat			*2nd crop-wheat*			*3rd crop-wheat*	
0	2.73	0.96	0.39	2.78	0.62	0.33	1.30	0.74	0.46
200	3.88	0.87	0.34	3.15	0.55	0.29	1.30	0.75	0.45
400	3.75	0.71	0.27	4.18	0.58	0.25	1.65	0.68	0.43
800	4.65	0.70	0.28	5.43	0.56	0.22	2.60	0.60	0.34
1,600	4.55	0.83	0.31	5.08	0.64	0.20	4.03	0.56	0.21
		4th crop-sorghum			*5th crop-sorghum*			*6th crop-tomato*	
0	0.24	0.68	0.84	0.58	2.22	1.16	1.02	3.42	0.76
200	0.22	0.70	0.87	0.62	2.06	1.17	1.23	2.95	0.70
400	0.18	0.66	0.82	0.54	1.81	1.04	1.33	3.54	0.73
800	0.22	0.62	0.71	0.67	1.75	1.02	1.50	3.19	0.67
1,600	1.46	0.42	0.39	1.27	1.56	0.98	2.09	3.07	0.58

[a] All values are averages of 4 replicates except for the 6th crop which had only 2.

[b] Potassium was given only to the 1st crop.

Table 10. Potassium, calcium, and magnesium concentrations of plant material as affected by potassium treatments on Genesee loam[a]

K treatment[b]	K	Ca	Mg	K	Ca	Mg	K	Ca	Mg
lbs/A		%			%			%	
		1st crop-wheat			*2nd crop-wheat*			*3rd crop-wheat*	
0	1.40	0.72	0.43	1.10	0.74	0.42	0.85	1.03	0.48
200	2.78	0.51	0.25	2.13	0.71	0.40	1.08	0.99	0.46
400	3.70	0.59	0.23	3.53	0.69	0.34	1.30	0.90	0.43
800	3.88	0.62	0.22	5.28	0.59	0.23	2.28	0.74	0.33
1,600	4.33	0.86	0.25	5.93	0.64	0.20	3.83	0.62	0.19
		4th crop-sorghum			*5th crop-sorghum*			*6th crop-tomato*	
0	0.17	0.88	0.64	0.42	2.70	0.96	0.91	3.90	1.06
200	0.17	0.93	0.71	0.44	2.50	0.94	0.75	4.02	0.90
400	0.12	0.72	0.65	0.48	2.23	0.93	0.82	3.78	0.64
800	0.19	0.65	0.63	0.56	1.94	0.86	0.85	3.07	0.48
1,600	1.05	0.51	0.39	0.88	1.60	0.80	1.59	3.13	0.48

[a] All values are averages of 4 replicates except for the 6th crop which had only 2.

[b] Potassium was given only to the 1st crop.

Table 11. Potassium, calcium, and magnesium concentrations of plant material as affected by potassium treatments on Kalamazoo sandy loam[a]

K treatment[b]	K	Ca	Mg	K	Ca	Mg	K	Ca	Mg
lbs/A		%			%			%	
		1st crop-wheat			*2nd crop-wheat*			*3rd crop-wheat*	
0	3.20	0.45	0.25	3.50	0.39	0.27	1.38	0.71	0.47
200	3.38	0.44	0.24	4.20	0.39	0.25	2.35	0.48	0.34
400	3.95	0.57	0.29	4.95	0.46	0.24	3.30	0.40	0.26
800	3.93	0.61	0.31	6.08	0.79	0.36	3.85	0.40	0.21
1,600	3.88	0.66	0.31	6.43	0.74	0.30	4.33	0.55	0.23
		4th crop-sorghum			*5th crop-sorghum*			*6th crop-tomato*	
0	0.21	0.65	0.71	0.41	2.23	1.14	0.69	3.01	1.04
200	0.31	0.54	0.69	0.49	1.90	1.09	0.61	3.25	0.90
400	0.44	0.45	0.57	0.59	1.58	1.02	1.07	3.25	0.78
800	1.24	0.45	0.34	0.99	1.32	0.78	1.59	3.13	0.71
1,600	2.13	0.43	0.24	1.60	1.09	0.63	2.85	3.37	0.66

[a] All values are averages of 4 replicates except for the 6th crop which had only 2.

[b] Potassium was given only to the 1st crop.

Table 12. Potassium, calcium, and magnesium concentrations of plant material as affected by potassium treatments on Landes-Abscota sandy loam[a]

K treatment[b]	K	Ca	Mg	K	Ca	Mg	K	Ca	Mg
lbs/A		%			%			%	
		1st crop-wheat			*2nd crop-wheat*			*3rd crop-wheat*	
0	1.35	0.88	0.46	1.65	0.80	0.46	1.10	1.05	0.48
200	2.88	0.62	0.31	2.15	0.70	0.43	1.15	0.90	0.48
400	3.78	0.64	0.24	3.10	0.70	0.38	1.38	0.85	0.47
800	3.98	0.75	0.24	5.28	0.65	0.28	2.43	0.74	0.37
1,600	4.15	0.85	0.25	5.55	0.86	0.26	3.88	0.65	0.22
		4th crop-sorghum			*5th crop-sorghum*			*6th crop-tomato*	
0	0.20	0.87	0.63	0.36	2.36	0.89	0.81	3.84	0.75
200	0.14	0.74	0.60	0.38	2.49	0.97	0.68	3.45	0.69
400	0.15	0.72	0.64	0.45	2.15	0.90	0.62	3.43	0.53
800	0.22	0.67	0.61	0.53	1.85	0.78	1.00	3.42	0.49
1,600	0.83	0.56	0.43	0.83	1.66	0.68	1.73	3.36	0.43

[a] All values are averages of 4 replicates except for the 6th crop which had only 2.

[b] Potassium was given only to the 1st crop.

Table 13. **Relationships among concentrations of potassium, calcium and magnesium in plants grown on Brookston, Genesee, Kalamazoo and Landes-Abscota soils**

Comparison	Crop 1	2	3	4	5	6
			Simple correlation coefficiet(r)			
			Brookston loam			
K vs. Ca	−0.27	0.06	−0.87**	−0.84**	−0.47*	−0.37
K vs. Mg	−0.40	−0.81**	−0.98**	−0.88**	−0.37	−0.82**
Ca vs. Mg	0.93**	0.26	0.88**	0.93**	0.63**	0.51
K vs. Ca+Mg	−0.27	0.06	−0.87**	−0.84**	−0.47*	−0.37
K vs. $\sqrt{Ca+Mg}$	−0.30	−0.37	−0.95**	−0.90**	−0.49*	−0.50
			Genesee loam			
K vs. Ca	0.18	−0.76**	−0.93**	−0.69**	−0.78**	−0.33
K vs. Mg	−0.87**	−0.95**	−0.99**	−0.89**	−0.64**	−0.26
Ca vs. Mg	0.25	0.85**	0.96**	0.78**	0.80**	0.80**
K vs. Ca+Mg	0.18	−0.76**	−0.93**	−0.69**	−0.78**	−0.33
K vs. $\sqrt{Ca+Mg}$	−0.25	−0.91**	−0.97**	−0.84**	−0.80**	−0.31
			Kalamazoo sandy loam			
K vs. Ca	0.73**	0.88**	−0.56*	−0.60**	−0.87**	0.02
K vs. Mg	0.68**	0.55*	−0.95**	−0.95**	−0.91**	0.62**
Ca vs. Mg	0.87**	0.87**	0.78**	0.72**	0.87**	0.01
K vs. Ca+Mg	0.73**	0.88**	−0.57**	−0.60**	−0.87**	0.02
K vs. $\sqrt{Ca+Mg}$	0.74**	0.83**	−0.76**	−0.91**	−0.93**	0.02
			Landes-Abscota sandy loam			
K vs. Ca	−0.28	0.13	−0.81**	−0.56**	−0.80**	−0.48
K vs. Mg	−0.93**	−0.94**	−0.99**	−0.78**	−0.73**	−0.58
Ca vs. Mg	0.51*	0.05	0.80**	0.78**	0.91**	0.79**
K vs. Ca+Mg	−0.28	0.13	−0.81**	−0.56**	−0.80**	−0.48
K vs. $\sqrt{Ca+Mg}$	−0.63**	−0.49*	−0.95**	−0.71**	−0.80**	−0.52

2) Relationship between concentrations of potassium and calcium in the plants

Calcium concentrations seemed to decrease while potassium concentrations increased with higher potassium levels although this relationship seemed to be influenced by the initial level of the elements in the soil and also by the plant. Only in Kalamazoo sandy loam did the relationship between potassium and calcium differ from the other three soils.

3) Relationship between potassium and magnesium in the plants

The general relationship between potassium and magnesium concentrations was similar to that of potassium and calcium.

4) Relationship between calcium and magnesium in the plants

These two elements seemed to be closely related and to behave similarly when related to potassium.

5) Relationship between potassium and calcium plus magnesium in the plants

This relationship coincides with that of potassium versus calcium.

6) Relationship between potassium and the square root of calcium plus magnesium concentrations in the plants

Activity ratios such as ${}^{a}K/\sqrt{a(Ca + Mg)}$ in the soil has been proposed as an availability measure of soil potassium by Beckett (9). The relation of potassium concentration and the square root of calcium plus magnesium concentrations in the plants was used to replace the activity of the elements for the convenience of calculation. The relation was found to be similar to that of potassium and calcium concentrations, and in general indicated that the order of the activity ratios in the soil was comparable to the absorption of these elements by the plants if Beckett's proposal was significantly applicable.

b. Electron Microprobe X-Ray Analysis of Wheat Stem Tissue for Potassium, Calcium, and Magnessium

The electron microprobe *X*-ray analyzer was used to determine the relative intensity of potassium, calcium and magnesium, and the distribution of these elements in wheat stems (2nd crop) harvested from Brookston loam and Genesee loam which received 400 and 0 lbs per acre potassium, respectively. The following instrumental parameters were employed: 25 kv accelerating voltage, and 0.025 μa sample current.

The concentration and distribution of potassium, calcium, and magnesium in the stem tissues are presented by the X-ray oscillograms (Figures 2 to 4 and 6 to 8) and by line scans (which are not presented here because of infeasibility of printing color plates). The cellular detail of 200 μm portions of the stems obtained from Brookston and Genesee soils are shown in Figures 1 and 5, respectively.

Fig. 1. **Cellular detail of a 200 μm portion of wheat stem obtained from Brookston loam receiving 400 pounds of potassium per acre (Reverse sample current, magnification 425×)**

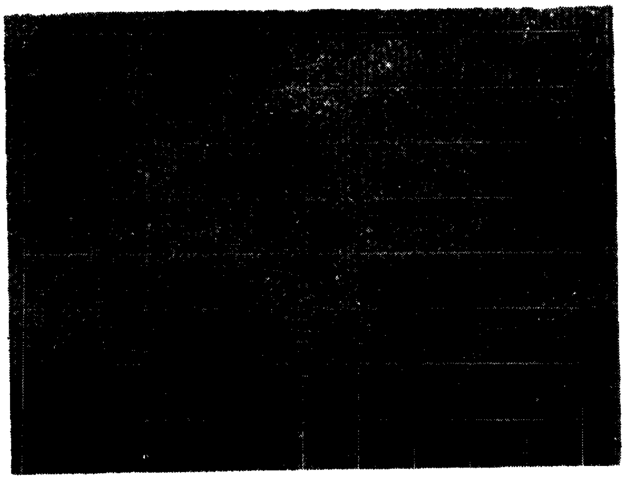

Fig. 2. **Potassium X-ray oscillogram showing the distribution of potassium in a 200 μm portion of wheat stem obtained from Brookston loam receiving 400 pounds of potassium per acre**

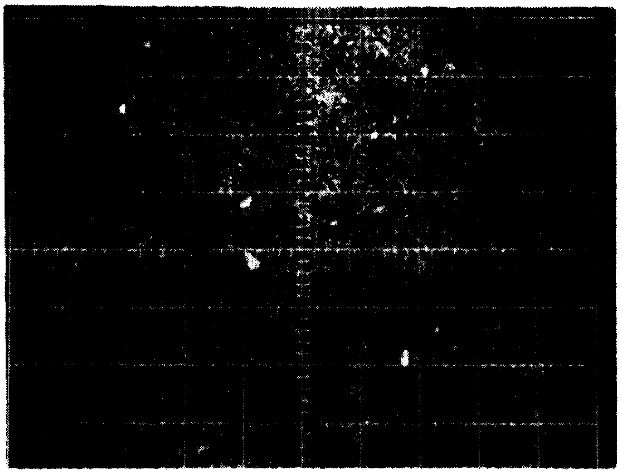

Fig. 3. **Calcium X-ray oscillogram showing the distribution of calcium in a 200μm portion of wheat stem obtained from Brookston loam receiving 400 pounds of potassium per acre**

Fig. 4. **Magnesium X-ray oscillogram showing the distribution of magnesium in a 200μm portion of wheat stem obtained from Brookston loam receiving 400 pounds of potassium per acre**

Fig. 5. Cellular detail of a 200μm portion of wheat stem obtained from Genesee loam receiving 0 pounds of potassium per acre (Reverse sample current, magnification 425×)

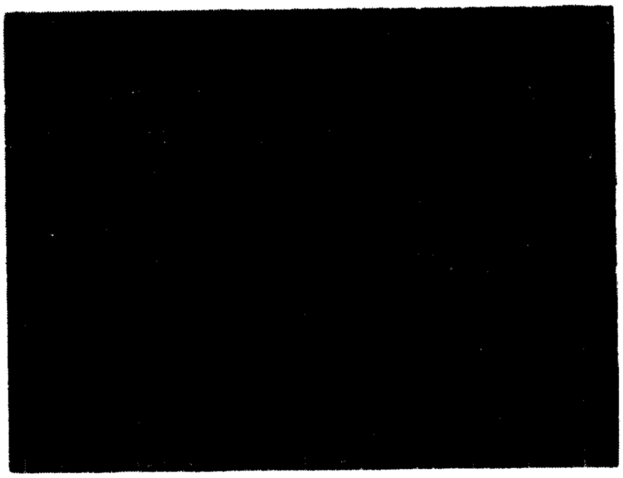

Fig. 6. Potassium X-ray oscillogram showing the distribution of potassium in a 200μm portion of wheat stem obtained from Genesee loam receiving 0 pounds of potassium per acre

Fig. 7. Calcium X-ray oscillogram showing the distribution of calcium in a 200μm portion of wheat stem obtained from Genesee loam receiving 0 pounds of potassium per acre

Fig. 8. Magnesium X-ray oscillogram showing the distribution of magnesium in a 200μm portion of wheat stem obtained from Genesee loam receiving 0 pounds of potassium per acre

A contrast is shown in these figures. The potassium concentration of the stem tissue obtained from Brookston loam is greater than calcium or magnesium (Figures 2 to 4). These results are in good agreement with the following chemical analysis obtained on the plant tissue (2nd crop). 4.18% K, 0.58% Ca, and 0.25% Mg (Table 9).

On the other hand, the potassium concentration was considerably lower than calcium and similar to magnesium for the stem tissue from the 0 potassium treatment on Genesee loam (Figures 6 to 8). The relative intensity of these elements seems to be inconsistent with the chemical analysis of the plant material (2nd crop), as shown in Table 10, which indicated 1.1% K, 0.74% Ca and 0.42% Mg. However, because of the potassium stress in the soil, the potassium contained in the stem tissue was rapidly translocated to the younger leaves. Consequently the concentration of potassium in the stem was lower than that of calcium even though the concentration of potassium in the whole plant was higher than calcium, as shown by the chemical analysis.

The traverse profiles of line scan represent the relative intensity of potassium, calcium, and magnesium across the 200 μm portion of the stem tissues from points A to B of Figures 1 and 5, respectively. These data confirm the interrelationships among the three elements contained in the stem tissue obtained from Brookston loam (K=400 treatment) and Genesee loam (K=0 treatment). Moreover, as shown by the line scans, the distribution of potassium, calcium, and magnesium in the stem tissue suggests that the three elements are distributed at similar loci in the stem tissue. The three elements are apparently concentrated at xylem, phloem, and their related tissue, through which inorganic ions and matabolic products are translocated respectively as known in plant physiology (14, 47).

It is believed that nutrient elements are translocated to the upper parts of plants through the ion carrier after entrance to the free space of the root (30). However, it appears necessary to characterize the specificity of the carriers for certain elements at different conditions. The mode of entrance of potassium, calcium, and magnesium to the plant root and translocation to the shoots may be studied in detail by the use of the electron microprobe *X*-ray method as that carried out for aluminium (70, 71) with sufficient knowledge of plant anatomy as well as physiology.

c. Relationship between Plant Yields and Concentrations of Potassium, Calcium and Magnesium

In order to examine possible relationships between plant yields and concentrations of potassium, calcium, and magnesium in the plants, simple correlation coefficients were calculated and presented in Table 14.

Table 14. Relationships between plant yields and potassium, calcium, and magnesium concentrations of the plants grown on Brookston, Genesee, Kalamazoo, and Landes-Abscota soils

Relationships of plant yields and concs. of elements	Crop					
	Wheat			Sorghum		Tomato
	1	2	3	4	5	6
	Simple correlation coefficient (r)					
	Brookston loam					
K	0.02	−0.25	0.75**	0.26	0.20	0.88**
Ca	−0.85**	−0.48*	−0.73**	−0.45*	−0.70**	−0.44
Mg	−0.78**	−0.16	−0.73**	−0.33	−0.18	−0.79**
K+Ca+Mg	−0.23	−0.30	0.74**	0.07	−0.47*	0.37
K/Ca	0.56*	0.01	0.75**	0.29	0.38	0.88**
K/Mg	0.49*	−0.13	0.69**	0.26	0.19	0.90**
K/Ca+Mg	0.54*	−0.04	0.73**	0.27	0.31	0.88**
$\mathrm{K}/\sqrt{\mathrm{Ca+Mg}}$	0.36	−0.14	0.74**	0.27	0.26	0.89**
	Genesee loam					
K	0.02	0.60**	0.87**	0.36	0.83**	0.57
Ca	0.001	−0.51*	−0.91**	−0.74**	−0.84**	−0.81**
Mg	−0.02	−0.60**	−0.87**	−0.57**	−0.71**	−0.92**
K+Ca+Mg	0.02	0.60**	0.85**	−0.33	−0.71**	−0.60
K/Ca	−0.0001	0.60**	0.86**	0.36	0.85**	0.71*
K/Mg	−0.01	0.55*	0.80**	0.36	0.85**	0.99**
K/Ca+Mg	−0.01	0.58**	0.84**	0.36	0.85**	0.76*
$\mathrm{K}/\sqrt{\mathrm{Ca+Mg}}$	0.01	0.59**	0.86**	0.35	0.85**	0.68*
	Kalamazoo sandy loam					
K	−0.19	−0.86**	0.72**	0.63**	0.84**	0.87**
Ca	−0.21	−0.87**	−0.73**	−0.73**	−0.85**	0.14
Mg	−0.09	−0.69**	−0.84**	−0.62**	−0.78**	−0.94**
K+Ca+Mg	−0.20	−0.88**	0.66**	0.53*	−0.51*	0.72*
K/Ca	0.13	0.54*	0.80**	0.64**	0.85**	0.83**
K/Mg	−0.13	−0.28	0.76**	0.63**	0.83**	0.88**
K/Ca+Mg	0.04	0.24	0.80**	0.63**	0.85**	0.85**
$\mathrm{K}/\sqrt{\mathrm{Ca+Mg}}$	−0.13	−0.51*	0.78**	0.63**	0.85**	0.87**

Table 14 (cont'd)

Relationships of plant yields and concs. of elements	Crop					
	1	2	3	4	5	6
	Wheat			Sorghum		Tomato
	Simple correlation coefficient (r)					
	Landes-Abscota sandy loam					
K	0.80**	0.38	0.84**	0.68**	0.75**	0.84**
Ca	−0.43	0.24	−0.86**	−0.82**	−0.81**	−0.75*
Mg	−0.79**	−0.53*	−0.83**	−0.69**	−0.69**	−0.83**
K+Ca+Mg	0.77**	0.39	0.81**	0.07	−0.66**	−0.24
K/Ca	0.81**	0.30	0.84**	0.73**	0.81**	0.89*
K/Mg	0.76**	0.45*	0.77**	0.68**	0.78**	0.91**
K/Ca+Mg	0.81**	0.36	0.82**	0.70**	0.80**	0.89**
$K/\sqrt{Ca+Mg}$	0.81**	0.37	0.83**	0.70**	0.78**	0.87**

1) Relationship between plant yields and potassium concentrations

The potassium concentrations of the plant were generally positively related to the plant yields obtained from all the soils except for the earlier crops in Brookston loam and Kalamazoo sandy loam. The relationship between potassium concentrations in the plant and the yields generally increased with cropping of the soils due to the depletion of available soil potassium in Kalamazoo and Landes-Abscota sandy loam soils.

2) Relationship between plant yields and calcium concentrations

The calcium concentrations of the plants seemed to be negatively related to the plant yields for all soils generally, except for the 1st crop grown on Genesee loam, the 6th crop on Kalamazoo sandy loam, and the 2nd crop on Landes-Abscota sandy loam.

3) Relationship between plant yields and magnesium concentrations

The relationship between magnesium levels of the plant tissue and yields of the crop was similar to that of calcium.

4) Relationship between plant yields and potassium, calcium, and magnesium concentrations

No general tendencies in the relationship between the plant yields and the concentrations of potassium, calcium, and magnesium became obvious in all the soils employed.

5) Relationship of plant yields and concentration ratios of potassium to calcium

The concentration ratios of potassium to calcium were somewhat positively related to plant yields, especially for Kalamazoo and Landes-Abscota sandy loam soils.

6) Relationship of plant yields and concentration ratios of potassium to magnesium

A positive relationship between plant yields and concentration ratios of potassium to magnesium generally existed for all soils. This relationship was best correlated with the yields of the 3rd (wheat) and 6th (tomato) crops on all soils.

7) Relationship of plant yields and concentration ratios of potassium to calcium plus magnesium

A similar trend was observed for plant yields as a function of the concentration ratios of potassium to calcium plus magnesium as was cited for the concentration ratios of potassium to calcium.

8) Relationship of plant yields and concentration ratios of potassium to the square root of calcium plus magnesium

The relationship between plant yields and concentration of potassium divided by the square root of calcium plus magnesium of the plants was positivety correlated for the 3rd and 6th crops grown on Brookston loam. This relationship was generally more meaningful for the other soils.

Plants may absorb more nutrients than required for optimum yields when the nutrients are in abundant supply. This phenomenon is called "luxury consumption". Excessive amounts of potassium are commonly absorbed by plants when present in large supply. The concept of luxury consumption can easily be understood in connection with Marcy's "critical percentage" (87). Additions of a certain nutrient element increase the yields of a plant without a great increase in the element to a cetain point in the plant tissue. Beyond this point the yield increases little, but the concentration of the element in the plant tissue increases greatly, corresponding to the addition of the element. Accordingly, Marcy defined the point at which yields were no longer increased as the "critical percentage", which can also be defined as the point above which luxury consumption takes place.

The poor correlations between the plant yields and the potassium concentrations of the plants observed with the 1st crop (wheat) grown on Genesee loam and the 1st and 2nd (wheat) crops grown on Brookston loam and Kalamazoo sandy loam are probably explained by luxury consumption.

3. Potassium, Calcium, and Magnesium Uptake of the Plants

It is important to consider the amount of nutrients taken up by plants, or that removed by plants from the soil for plant nutrient economy. The uptake of potassium, calcium, and magnesium by the plants are presented in Tables 15 to 17.

Table 15. Plant uptake of potassium as affeccted by potassium treatments on Brookston, Genesee, Kalamazoo, and Landes-Abscota soils

K treatment[a]	Crop						
	1	2	3	4	5	6	Total
	Wheat			Sorghum		Tomato	
(lbs K/A)	(mg K/pot)[b]						
	Brookston loam						
0	241.5	581.0	89.5	56.0	37.0	61.9	1,066.9
200	264.0	750.8	86.5	52.1	42.9	76.0	1,272.3
400	369.0	957.5	115.5	43.6	40.1	77.9	1,603.6
800	520.5	1,105.5	191.8	53.7	49.9	109.8	2,031.2
1,600	431.3	1,078.3	312.0	361.8	78.9	167.3	2,429.6
L.s.d.[c]							
(0.05)	160.35	163.68	34.82	65.10	16.00	38.23	
(0.01)	224.83	229.49	48.82	91.28	22.44	63.56	
	Genesee loam						
0	114.0	175.3	40.4	33.1	26.9	15.0	404.7
200	232.5	343.5	59.1	32.4	29.5	18.8	715.7
400	311.5	605.3	76.4	24.9	37.1	29.8	1,074.0
800	315.8	929.0	145.1	42.2	47.8	45.3	1,525.2
1,600	356.5	1,018.0	263.0	237.2	82.7	105.2	2,062.6
L.s.d.[c]							
(0.05)	30.08	76.07	13.23	15.83	11.88	34.55	
(0.01)	42.18	106.65	18.55	22.19	16.65	57.30	

Table 15 (cont'd.)

K treatment[a]	Crop						Total
	1	2	3	4	5	6	
	Wheat			Sorghum		Tomato	
(lbs K/A)	(mg K/pot)[b]						
	Kalamazoo sandy loam						
0	272.0	574.5	70.0	37.5	25.4	20.5	999.9
200	282.5	677.5	141.0	64.7	35.3	25.9	1,226.9
400	341.8	727.3	197.6	96.3	48.8	53.5	1,465.3
800	314.3	793.3	254.9	257.1	82.4	95.6	1,797.6
1,600	313.3	878.5	270.0	511.3	159.0	193.7	2,325.8
L.s.d.[c] (0.05)	N.s.[d]	50.82	15.25	34.81	22.51	18.99	
(0.01)		71.24	21.39	48.81	31.56	31.50	
	Landes–Abscota sandy loam						
0	122.8	253.0	59.5	40.8	24.9	23.7	524.7
200	298.3	325.0	63.3	29.7	27.8	17.3	761.4
400	396.3	476.3	82.5	33.1	35.9	27.5	1,051.6
800	402.5	809.8	160.4	49.7	41.8	54.5	1,518.7
1,600	446.5	895.3	271.3	211.4	70.4	121.7	2,016.6
L.s.d.[c] (0.05)	31.29	48.84	17.30	24.24	8.63	8.98	
(0.01)	43.89	68.47	24.25	33.98	12.11	14.90	

[a] Potassium was applied to the first crop only.

[b] All values of uptake are averages of 4 replicates except for the 6 th crop which had 2.

[c] The least significant difference at 5 % and 1 % levels of probability, respectively.

[d] No significant difference in potassium uptake as detected by F test with analysis of variance.

Table 16. Plant uptake of calcium as affected by potassium treatments on Brookston, Genesee, Kalamazoo and Landes-Abscota soils

K treatment[a]	Crop						
	1	2	3	4	5	6	
	Wheat			Sorghum		Tomato	Total
(lbs K/A)	(mg Ca/pot)[b]						
	Brookston loam						
0	84.3	130.9	49.5	160.3	141.0	208.5	774.5
200	56.4	130.8	49.6	163.0	148.0	182.6	730.4
400	63.7	129.9	47.8	157.0	133.3	207.0	735.7
800	77.3	113.5	44.0	148.3	128.8	232.9	744.8
1,600	78.3	136.1	43.5	102.3	119.3	244.3	723.8
L.s.d.[c] (0.05)	N.s.[d]	N.s.	N.s.	16.12	N.s.	N.s.	
(0.01)				22.59			
	Gneseeee loam						
0	58.1	116.1	49.1	175.0	171.8	66.3	636.4
200	42.6	115.0	54.3	181.0	165.8	102.2	660.9
400	47.7	118.3	52.6	158.8	170.8	136.3	684.5
800	50.4	103.1	47.3	144.3	165.0	163.3	673.4
1,600	70.8	110.0	42.4	115.3	149.3	207.9	693.7
L.s.d.[c] (0.05)	11.49	N.s.[d]	4.32	21.48	N.s.	53.81	
(0.01)	16.11		6.06	30.11		89.24	
	Kalamazoo sandy loam						
0	38.4	63.5	36.5	115.0	136.8	86.6	476.8
200	36.4	62.1	28.5	113.0	138.0	137.3	515.3
400	49.0	66.9	24.1	99.8	127.8	162.1	529.7
800	48.7	102.5	26.5	92.8	108.0	187.4	565.9
1,600	53.3	101.0	34.5	103.0	107.3	228.2	627.5
L.s.d.[c] (0.05)	11.20	17.34	3.14	N.s.[d]	16.57	83.09	
(0.01)	15.70	24.32	4.40		23.24	137.80	

Table 16 (cont'd.)

K treatment[a]	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Crop 6	Total
	Wheat			Sorghum		Tomato	
(lbs K/A)	(mg Ca/pot)[b]						
	Landes-Abscota sandy loam						
0	79.5	121.9	56.0	178.3	165.3	108.4	709.4
200	64.3	105.1	49.1	159.3	183.8	113.3	674.9
400	67.2	106.1	50.6	160.8	169.0	144.5	698.2
800	75.4	99.3	49.0	152.5	145.3	186.4	707.9
1,600	91.1	139.0	45.3	144.0	140.5	169.2	729.1
L.s.d.[c] (0.05)	6.80	18.95	N.s.[d]	N.s.	13.30	N.s.	
(0.01)	9.53	26.57			18.65		

[a] Potassium was applied to the first crop only.

[b] All values of uptake are averages of 4 replicates except tor the 6th crop which had 2.

[c] The least significant difference at 5% and 1% levels of probability, respectively.

[d] No significant difference in calcium uptake as detected by F test with analysis of variance.

Table 17. Plant uptake of magnesium as affected by potassium treatments on Brookston, Genesee, Kalamazoo and Landes-Abscota soils

K treatment[a]	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Crop 6	Total
	Wheat			Sorghum		Tomato	
(lbs K/A)	(mg Mg/pot)[b]						
	Brookston loam						
0	34.1	68.8	30.6	197.3	74.0	46.4	451.2
200	22.8	67.3	29.6	202.8	84.9	43.4	450.8
400	24.6	56.0	30.1	195.8	77.0	42.7	426.2
800	31.0	45.3	25.3	169.8	74.9	48.5	394.8
1,600	29.4	42.5	16.1	95.5	76.2	46.3	306.0
L.s.d.[c] (0.05)	N.s.[d]	7.08	2.80	19.76	N.s.	N.s.	
(0.01)		9.92	3.92	27.71			

Table 17 (cont'd.)

K treatment[a]	Crop						
	1	2	3	4	5	6	Total
	Wheat			Sorghum		Tomato	
(lbs K/A)	(mg Mg/pot)[b]						
	Genesee loam						
0	35.0	65.3	22.7	128.0	61.1	17.6	329.7
200	21.0	64.2	25.1	138.0	62.4	22.6	333.3
400	18.7	57.4	25.2	143.0	70.8	23.0	338.1
800	17.9	39.6	21.2	140.5	72.9	25.3	317.4
1,600	20.2	34.5	13.2	88.7	74.6	31.9	263.1
L.s.d.[c]							
(0.05)	3.00	7.07	2.45	11.58	10.60	7.90	
(0.01)	4.21	9.92	3.43	16.24	14.86	13.10	
	Kalamazoo sandy loam						
0	21.6	44.7	23.8	124.3	69.9	29.8	314.1
200	20.3	39.4	20.4	144.5	78.8	38.2	341.6
400	25.1	35.1	15.4	125.0	82.6	38.8	322.0
800	24.8	46.5	13.9	70.0	64.2	42.2	261.6
1,600	25.4	41.2	14.2	57.0	61.5	44.8	244.1
L.s.d.[c]							
(0.05)	N.s.[d]	N.s.	1.32	11.29	11.14	6.73	
(0.01)			1.85	15.83	15.62	11.16	
	Landes-Abscota sandy loam						
0	41.3	70.0	25.9	129.0	62.5	21.1	349.9
200	31.6	64.2	26.1	130.6	71.4	17.7	341.6
400	24.9	58.4	27.9	143.0	71.0	22.7	347.9
800	23.8	42.6	24.4	140.0	61.2	26.7	318.7
1,600	27.2	41.1	15.2	110.9	57.7	30.3	282.4
L.s.d.[c]							
(0.05)	2.87	4.77	2.48	21.55	4.03	6.46	
(0.01)	4.02	6.69	3.48	30.22	5.65	12.15	

[a] Potassium was applied to the first crop only.

[b] All values of uptake are avevages of 4 replicates except for the 6th crop which had 2.

[c] The least significant difference at 5% and 1% levels of probability, respectively.

[d] No significant difference in magnesium uptake as detected by F test with analysis of variace.

a. Relationships between Potassium Treatment and Plant Uptake of Potassium, Calcium, and Magnesium

1) Relationship between potassium treatment and potassium uptake of the plants

As shown in Table 15, potassium treatment affected the plant uptake of potassium on all soils. Plant uptake of potassium generally decreased with successive cropping. However, seasonal and plant differences were found to affect the potassium uptake. The 2nd crop (wheat) absorbed more potassium than the lst crop (wheat) in all soils since the 2nd crop was grown in the spring season during more favorable conditions than the lst crop.

Tomatoes (6th crop) absorbed more potassium than sorghum (5th crop) on all potassium treatments applied to Brookston loam, on the 1,600 potassium (1,600 lbs K/A) treatment in Genesee loam, on the 400, 800 and 1,600 potassium treatments in Kalamazoo sandy loam, and on the 800 and 1,600 potassium treatments in Landes-Abscota sandy loam. This may indicate that the tomato plants have a greater capacity for the absorption of potassium than sorghum. Since the soil was the highest in nonexchangeable potassium among the soils, Brookston loam appeared to have met the tomatoes' high capacity for absorbing potassium by supplying sufficient potassium. Since their nonexchangeable potassium was lower, Genesee loam, Kalamazoo sandy loam, and Landes-Abscota sandy loam appeared to have supplied enough potassium only when potassium was applied in larger quantities to meet the tomatoes' high capacity for absorbing potassium.

2) Relationship between potassium treatment and plant uptake of calcium

It seems to be improper to generalize the influence of potassium treatment to the plant uptake of calcium because the uptake of calcium varied. Calcium absorption decreased with the 4th crop grown on Brookston loam and Genesee loam, and with the 5th crop grown on Kalamazoo sandy loam and Landes-Abscota sandy loam but tended to increase with the 6th crop grown on Genesee loam, and with the lst, 2nd, and 6th crop grown on Kalamazoo sandy loam while no such trend was shown with the other crops. However, the total uptake of calcium by the 6 succeeding crops tended to increase with high levels of patassium treatment on all the soils except for Brookston loam. This may be an indication of nutrient balance in the plant for a long range: plants absorb more nutrient elements and grow better when soil fertility is high (18).

Further studies seem to be necessary on Brookston loam.

3) Relationship between potassium treatment and plant uptake of magnesium

The plant uptake of magnesium tended to decrease with increasing levels of potassium treatment in the 2nd, 3rd, and 4th crops grown on Brookston loam; in the 1st, 2nd and 3rd crops on Genesee loam; in the 3rd, 4th and 5th crops on Kalamazoo sandy loam; and in the 2nd crop grown on Landes-Abscota sandy loam. Magnesium absorption tended to increase in the 5th and 6th crops grown on Genesee loam; in the 1st and 6th crops on Kalamazoo sandy loam; and in the 6th crop on Landes-Abscota sandy loam. The other crops did not show any such trends. Consequently it may be irrelevant to generalize the influence of potassium treatment on the plant uptake of magnesium in this research.

A long range of nutrient balance by the 6 succeeding crops as found in the case of calcium uptake was not shown in magnesium uptake. A stronger nutrient balance for a long range may be obtained between potassium and calcium rather than between potassium and magnesium.

b. Relationships between Plant Yields and Uptake of Potassium, Calcium, and Magnesium

1) Plant yields and potassium uptake

In general, the crops which demonstrated favorable effects from the potassium treatment showed correlation between the yields and potassium uptake (Table 18).

The negative correlation with the 2nd crop on Kalamazoo sandy loam was probably due to excess uptake of potassium by the plants. The soil was originally rich in exchangeable potassium containing 275 lbs per acre (Table 1) and the 1st crop did not absorb much of the applied potassium because of the low intensity of winter sunlight during the growth period (December 5, 1968 to February 13, 1969). The 2nd crop absorbed more potassium leading to more than 6% potassium in the plant tissue at high levels of potassium treatment (Table 11) under influence of high intensity of sunlight and warm temperatures during the growth period (March 26 to June 5, 1969).

Table 18. **Relationship between plant yields and potassium, calcium, and magnesium uptake of the plants**

Relationship of plant yield and elements	Crop					
	1	2	3	4	5	6
	Wheat			Sorghum		Tomato
	Simple correlation coefficient (r)[a]					
	Brookston loam					
K	0.81**	0.01	0.80**	0.35	0.46**	0.94**
Ca	0.75**	0.05	−0.11	−0.14	0.01	0.73*
Mg	0.80**	0.10	−0.51*	−0.10	0.63**	0.41
K+Ca+Mg	0.86**	0.16	0.83**	0.47*	0.80**	0.94**
	Genesee loam					
K	0.21	0.66**	0.88**	0.38	0.91**	0.86**
Ca	0.27	0.22	−0.43	−0.49*	−0.08	0.96**
Mg	0.18	−0.39	−0.60**	−0.18	0.87**	0.84**
K+Ca+Mg	0.26	0.68**	0.91**	0.31	0.82**	0.95**
	Kalamazoo sandy loam					
K	0.17	−0.58**	0.82**	0.68**	0.89**	0.89**
Ca	0.05	−0.78**	−0.41	−0.16	−0.38	0.90**
Mg	0.28	−0.20	−0.70**	−0.38	−0.10	0.91**
K+Ca+Mg	0.16	−0.65**	0.81**	0.73**	0.91**	0.94**
	Landes-Abscota sandy loam					
K	0.85**	0.45*	0.86**	0.73**	0.83**	0.92**
Ca	0.07	0.48*	−0.35	−0.53*	−0.52*	0.69*
Mg	−0.64**	−0.37	−0.52*	−0.23	−0.19	0.92**
K+Ca+Mg	0.85**	0.47*	0.88**	0.65**	0.22	0.92**

[a] * and ** indicate significance at 5% and 1% probability levels respectively.

2) Relationship between plant yields and calcium uptake

The relationship between plant yields and calcium uptake appeared slightly negative except for the 6th crop, tomatoes, in which yields showed as good correlation with calcium uptake as with potassium uptake (Table 18).

3) Relationship between plant yields and magnesium uptake

The relationship between plant yields and magnesium uptake appeared slightly negative except for the 6th crops, tomatoes, as between plant yields and calcium uptake (Table 18). The plant yields of the tomato crop correlated with magnesium uptake except on Brookston loam.

4) Relationship between plant yields and the total uptake of potassium, calcium, and magnesium

In general, the relationship between plant yjelds and the uptake of potassium plus calcium and magnesium was similar to that obtained for potassium uptake and the yield of the various plants.

c. Relationships among the Plant Uptake of Potassium, Calcium, and Magnesium

1) Relationship between plant uptake of potassium and calcium

In general the simple correlation coefficients for potassium versus calcium uptake were negative except for the lst and 6th crops grown on all the soils and for the 2nd crop on Kalamazoo sandy loam and Landes-Abscota sandy loam (Table 19). An antagonistic relationship between the 2 elements was further demonstrated by Burkhart and Collins (15) and Oya (63). The factors which induced the positive correlation between potassium and calcium for the lst crop on all the soils, and the 2nd crop on Kalamazoo sandy loam and Landes-Abscota sandy loam must be studied in the future with more refined methods.

The relationship between potassium and calcium uptake was positive for the 6th crop on all the soils. The reason seemed to be that the soils had been depleted of potassium by the time of the 6th crop; consequently increased levels of potassium application remarkably affected plant growth (Table 7) which led to more absorption of calcium coupled with the high requirement of the tomato plant for calcium.

2) Relationship between plant uptake of potassium and magnesium

The relationship between the plant uptake of potassium and magnesium was generally negative (Table 19), which may indicate the apparent antagonistic relationships between the 2 elements in the plant absorption. However the positive relationship between the potassium and magnesium uptake for the lst crop grown on Brookston loam, for the 5th crop on Genesee loam, for the lst crop on Kalamazoo sandy loam, and for the 2nd crop on Landes-Abscota sandy loam must be studied further. The positive relationship between potassium and magnesium uptake of the 6th crop on all the soils demonstrates similar reasons to the relationship between potassium and calcium uptake in the same crop.

Table 19. Relationship between the potassium, calcium, and magnesium uptake of the plants

Comparison			Crop			
	1	2	3	4	5	6
			Simple correlation coefficient (r)			
			Brookston loam			
K vs. Ca	0.45*	−0.07	−0.52*	−0.85**	−0.33	0.69*
K vs. Mg	0.47*	−0.80**	−0.91**	−0.86**	−0.34	0.23
Ca vs. Mg	0.95**	0.28	0.71**	0.93**	0.49*	0.50
K vs. Ca+Mg	0.46*	−0.48*	−0.80**	−0.87**	−0.07	0.67*
K vs. $\sqrt{Ca+Mg}$	0.49*	−0.48*	−0.81**	−0.87**	−0.07	0.66*
			Genesee loam			
K vs. Ca	0.24	−0.35	−0.71**	−0.77**	−0.27	0.84**
K vs. Mg	−0.80**	−0.90**	−0.89**	−0.91**	0.72**	0.91**
Ca vs. Mg	0.28	0.64**	0.88**	0.65**	0.24	0.91**
K vs. Ca+Mg	−0.17	−0.75**	−0.82**	−0.92**	0.05	0.86**
K vs. $\sqrt{Ca+Mg}$	−0.16	−0.75**	−0.83**	−0.92**	0.06	0.83**
			Kalamazoo sandy loam			
K vs. Ca	0.73**	0.70**	−0.30	−0.28	−0.58**	0.83**
K vs. Mg	0.69**	−0.07	−0.94**	−0.89**	−0.44	0.76**
Ca vs. Mg	0.84**	0.55*	0.51*	0.48*	0.62**	0.97**
K vs. Ca+Mg	0.74**	0.58*	−0.67**	−0.81**	−0.58**	0.83**
K vs. $\sqrt{Ca+Mg}$	0.73**	0.57*	−0.65**	−0.82**	−0.58**	0.81**
			Landes-Abscota sandy loam			
K vs. Ca	0.17	0.07	−0.52*	−0.44	−0.68**	0.56
K vs. Mg	−0.87**	0.88**	−0.87**	−0.60**	−0.43	0.85**
Ca vs. Mg	0.15	0.0001	0.56**	0.56*	0.80**	0.63
K vs. Ca+Mg	−0.30	0.09	−0.78**	−0.59**	−0.64**	0.62
K vs. $\sqrt{Ca+Mg}$	−0.30	0.10	−0.79**	−0.58**	−0.65**	0.61

3) Relationship between plant uptake of calcium and magnesium

The relationship between the plant uptake of calcium and magnesium was positive for all the crops without any exception (Table 19). Calcium and magnesium may be considered to be absorbed in somewhat similar order by the plants.

4) Relationship between plant uptake of potassium and calcium plus magnesium

The relationship between the plant uptake of potassium and calcium plus magnesium appeared to be similar to that of the plant uptake of potassium and calcium on Brookston loam and Kalamazoo sandy loam, or of potassium and magnesium on Genesee loam and Landes-Abscota sandy loam (Table 19).

5) Relationship between plant uptake of potassium and the square root of calcium and magnesium

The relationship between the plant uptake of potassium and the square root of calcium plus magnesium was almost the same as that of the plant uptake of potassium versus calcium plus magnesium.

4. Quantity of Potassium Released from Nonexchangeble Forms

a. Potassium Released from Nonexchangeable Forms

In order to find the amounts of potassium released to the plants from the original nonexchangeable forms in the soils, the amount of potassium (mg) taken up from the 0 potassium treatment by the respective crops per pot were converted to pounds of plant potassium per acre from which the exchangeabale soil potassium, analyzed before the start of the experiment, was subtracted (Table 20). The weights of soil per pot were 2.70 kg, 2.65 kg, 2.60 kg, 2.55 kg, 2.50 kg, and 2.45 kg for the lst, 2nd, 3rd, 4th, 5th, and 6th crops, respectively. The negative values for the "release from nonexchangeable K" in Table 20 show that the potassium uptake of that crop was less than the potassium originally in exchangeable form. The potassium release from the nonexchangeable forms in the experimental soils were in the order of Brookston loam > Kalamazoo sandy loam > Landes-Abscota sandy loam > Genesee loam for the sequence of 6 croppings. The original exchangeable potassium, 151, 93, and 275 lbs per acre for Brokston loam, Genesee loam, and Kaloamazoo sandy loam respectively, appeared to be a sufficient source of potassium for the lst crop grown on these three soils since the crop did not show any response to applied potassium under the conditions of the experiment. In general, nonexchangeable potassium was released only in small quantities after the 3rd crop in all soils (Table 20 and Figures 9 to 12).

Table 20. **Potassium released to the plants from nonexchangeable forms in Brookston, Genesee, Kalamazoo, and Landes-Abscota soils**

K in plant and from nonexchangeable forms[a]	Crop						
	1	2	3	4	5	6	Total
	K uptake						
			Brookston loam				
			(mg/pot)				
Plant K	241.5	581.0	89.5	56.0	37.0	61.9	1,066.9
			(lbs/A)				
Plant K	178.9	438.4	68.8	43.9	29.6	50.5	810.1
K from non-exchangeable froms	27.9	438.4	68.8	43.9	29.6	50.5	659.1
			Genesee loam				
			(mg/pot)				
Plant K	114.0	175.3	40.4	33.1	26.9	15.0	404.6
			(lbs/A)				
Plant K	84.4	132.3	31.1	26.0	21.5	12.2	307.5
K from non-exchangeable forms	−8.6	123.7	31.1	26.0	21.5	12.2	214.5
			Kalamazoo sandy loam				
			(mg/pot)				
Plant K	272.0	574.5	70.0	37.5	25.4	20.5	999.9
			(lbs/A)				
Plant K	201.5	433.6	53.8	29.4	20.3	16.7	755.3
K from non-exchangeable forms	−73.5	360.1	53.8	29.4	20.3	16.7	480.3
			Landes-Abscota sandy loam				
			(mg/pot)				
Plant K	122.8	253.0	59.5	40.8	24.9	23.7	524.7
			(lbs/A)				
Plant K	91.0	190.9	45.8	32.0	19.9	19.3	398.9
K from non-exchangeable forms	16.0	190.9	45.8	32.0	19.9	19.3	323.9

[a] K release from nonexchageable forms= (plant uptake of K from K=0 plots) − (exchangeable K before cropping)[b]

[b] Exchangeable K before cropping was 151, 93, 275, and 75 lbs/A for Brookston loam, Genesee loam, Kalamazoo sandy loam, and Landes-Abscota sandy loam, respectively (Table 1).

b. Potassium Release as Affected by Potassium Treatment

The amounts of potassium taken up by the plants from the nonexchangeable forms were calculated at the respective levels of the potassium treatment in the same way for Table 20 and presented in Figures 9 to 12.

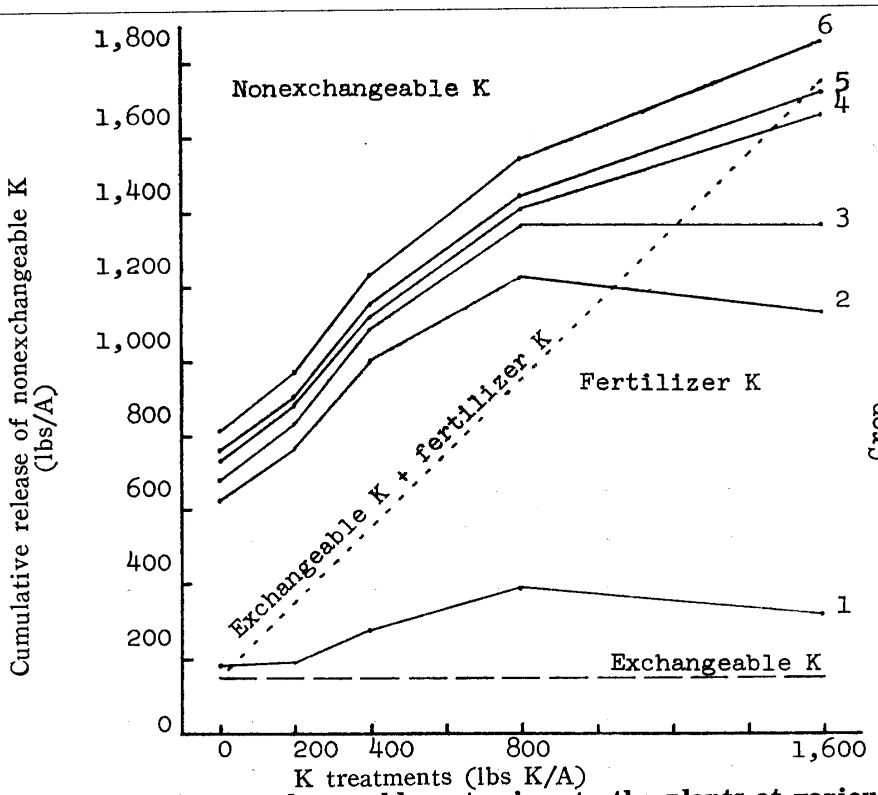

Fig. 9. Release of nonexchangeable potassium to the plants at various levels of potassium treatment for Brookston loam[a]

[a]The broken line indicates the original level of exchangeble K. The dotted line indicates exchageable K plus fertilizer K.

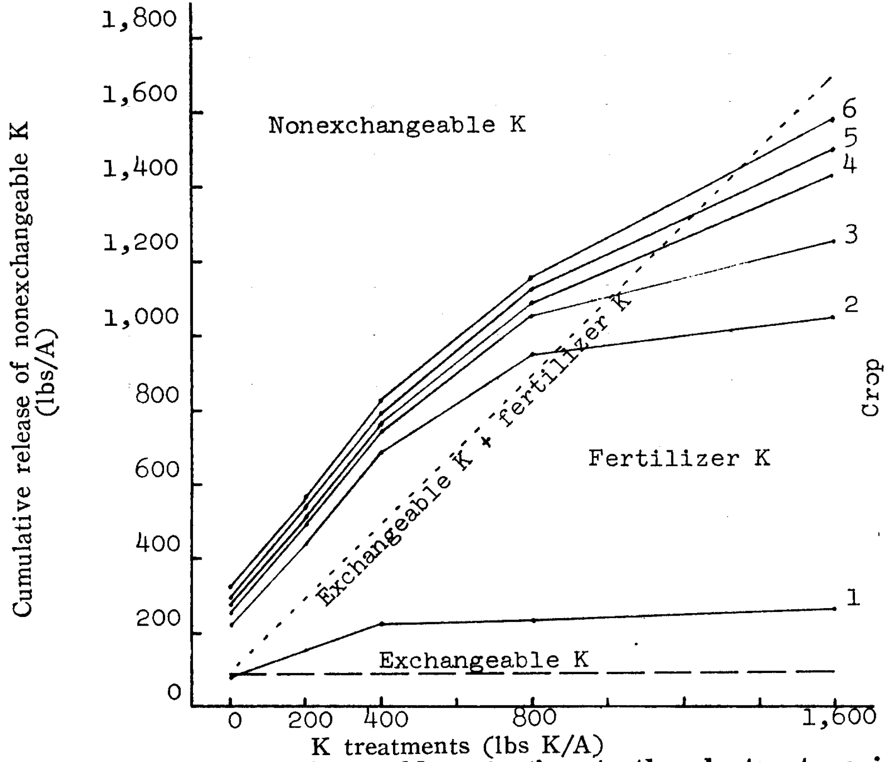

Fig. 10. Release of nonexchangeable potassium to the plants at various levels of potassium treatment for Genesee loam[a]

[a]The broken line indicates the original level of exchangeable K. The dotted line indicates exchangeable K plus fertilizer K.

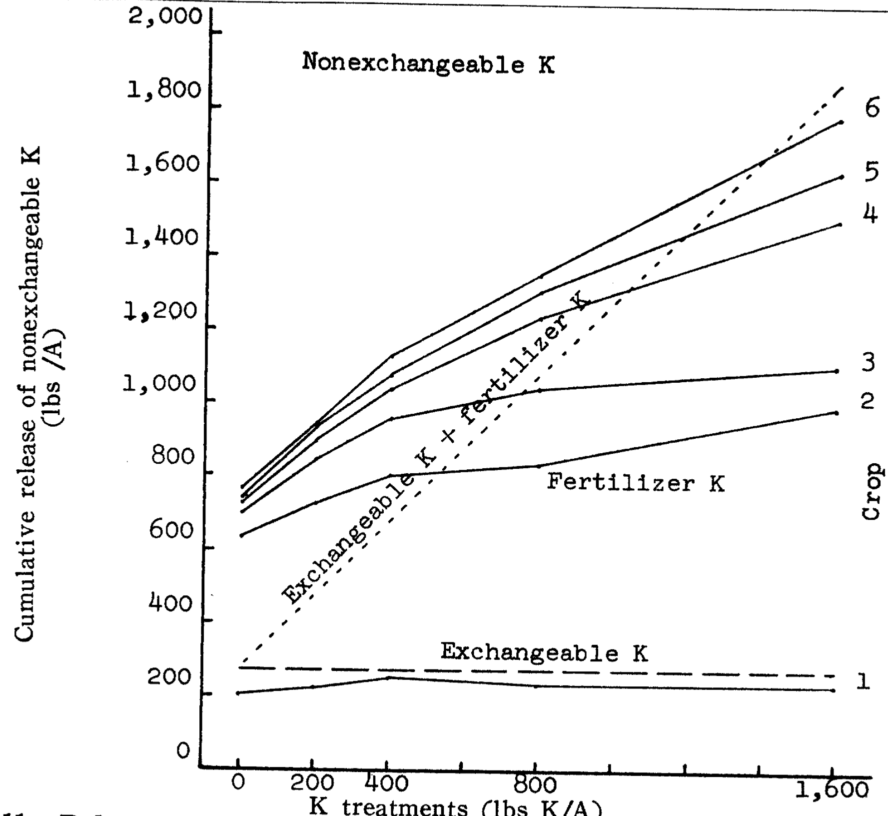

Fig. 11. Release of nonexchangeable potassium to the plants at various levels of potassium treatment for Kalamazoo sandy loam[a]

[a]The broken line indicates the orginal level of exchangeable K. The dotted line indicates exchangeable K plus fertilizer K.

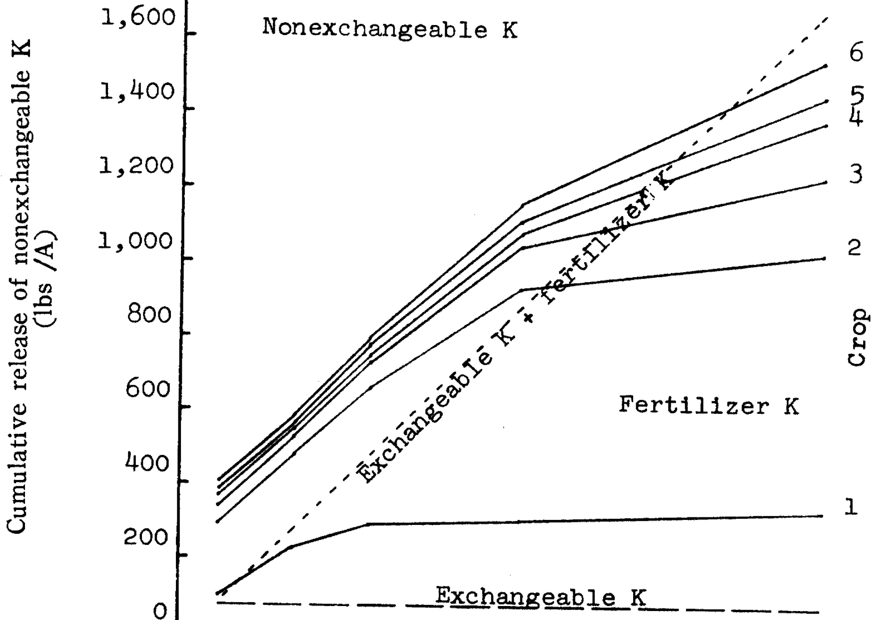

Fig. 12. Release of nonexchangeble potassium to the plants at various levels of potassium treatment for Landes-Abscota sandy loam[a]

[a]The broken line indicates the original level of exchangeable K. The dotted line indicates exchangeble K plus fertilzer K.

In Brookston loam, the amounts of nonexchangeable soil potassium released to the plant were 659, 614, 664, 588 and 106 lbs per acre from the 0, 200, 400, 800, and 1,600 potassium treatments, respectively (Figure 9). From Figure 9, it will be understood that nonexchangeable soil potassium was utilized intensively by earlier crops grown on plots with low potassium applications. The release of nonexchangeable soil potassium gradually decreased when the cropping advanced. During the period of 6 croppings, the release of nonexchangeable soil potassium from the 0, 200, 400 and 800 potassium treatments reached similar amounts. The lower release from the 1,600 potassium treatment than from the other treatment may mean that the initial large application of potassium reduced the necessity of plant absorption of nonexchangeable soil potassium or caused potassium fixation which induced difficulty in the release of nonexchangeable soil potassium. From the release pattern in Figure 9, it may be expected that nonexchangeable soil potassium will be released from the 1,600 potassium treatment for further cropping, if the cropping continues, to attain nearly the same amounts released from the lower potassium treatment-plots at a slow rate.

In Genesee loam, more nonexchangeable soil potassium was released to the plants in the 200, 400 and 800 potassium treatment than in the 0 potassium treatment (Figure 10). The clay minerals such as vermiculite-chlorite-montmorillonite interstratified minerals and mica (or illite) present in Genesee loam (Table 31) seemed to promote the release of nonexchangeable soil potassium by stimulated root growth, which may have intensified plant weathering of the mica or illite as reported (17, 58), by the application of potassium. Genesee loam containing 10% vermiculite and 18% mica in its clay fraction (Table 31) also appeared to fix the applied potassium at the 1,600 potassium treatment where the original amount of nonexchangeable soil potassium was not released at all during 6 croppings (Figure 10).

The release of nonexchangeable soil potassium from Kalamazoo sandy loam was much lower in the 800 and 1,600 potassium treatments than in the 0, 200 and 400 potassium treatments (Figure 11) which released 437 to 480 lbs of nonexchangeable potassium per acre. The plants on this soil seemed to be sufficiently furnished with the fertilizer and original exchangeable soil potassium without absorbing too much nonexchangeable soil potassium at the 800 and 1,600 potassium treatments. The exchangeable soil potassium was initially as high as 275 lbs per acre and potassium fixing clay was low (1.7%) in the clay fraction of 13.5% (Tables 29 and 31).

In Landes-Abscota sandy loam, as shown in Figure 12, neary the same amounts of nonexchangeable soil potassium were released in the 0 through 800 potassium treatments where the potassium release ranged from 319 to 275 lbs per acre. At the 1,600 potassium treatment, no release was indicated from the nonexchangeable soil potassium. The initial application of such a large quantity of potassium seemed to have caused potassium fixation, since the soil clay was predominated by vermiculite-chlorite interstratified minerals (Table 31). Fixed potassium by vermiculite is released at a slower rate than native potassium in biotite (26). The potassium release from Landes-Abscota sandy loam seemed to be slower than from Brookston loam.

Sufficient potassium must be supplied to plants grown on a soil to fix potassium and release it very slowly. Miller (54), who investigated response of tomatoes to potassium on a Sodus Experimental Farm soil classified as Genesee sandy clay loam (18.6% vermiculite) suggested that 1,126 and 150 lbs of potassium per acre be applied broadcast and sidedressed respectively to obtain 44,000 lbs per acre fresh market yield for transplanted C1327 tomatoes.

IV CHEMICAL PROPERTIES OF THE SOILS

A. METHODS AND MATERIALS

1. Exchangeable and Nonexchangeable Potassium

Exchangeable and nonexchangeable potassium was determined on the original soil samples, the samples collected after the 5th crop, and the incubated samples.

All the samples were air-dried, thoroughly mixed and passed through a sieve with 2 mm openings. Soil incubation was carried out in one gallon containers for a period of 5 croppings (13 months) with fertilizer treatment administered as for growing plants in the greenhouse. Water was added to maintain the soil at field capacity.

Exchangeable potassium was extracted by shaking a 2.5 g sample of the soil with 20 ml of neutral 1 N ammonium acetate solution for 1 minute and by centrifuging the suspension to collect the clear supernatant. The soil was washed 3 more times with ammonium acetate solution. The collected supernatant was determined for potassium on a Coleman Model 21 Flame Photometer.

Nonexchangeable potassium was obtained by subtracting the exchangeable potassium value from the value of total potassium extracted with boiling 1 N nitric acid solution.

A 2.5 g sample of the soil was boiled with 1 N nitric acid in a 100 ml beaker on the hot plate for 25 minutes in a way similar to that of Pratt and Morse (68). The soil was then filtered and washed with 0.1 N nitric acid solution. The combined leachate and washing was determined for potassium.

2. Potassium Release and Fixation by Wetting and Drying Treatments

Potassium release and fixation of the original soils were studied by alternate wetting and drying procedures. The method employed was essentially the same as that of Volk (92).

A 2.5 g sample of the soil was placed in a 125 ml Erlenmyer flask to which 2.5 ml of 0.1 N potassium chloride solution was added. The mixture was allowed to stand for 1 hour to obtain a thorough wetting of the soil and then it was placed on a hot plate at 70° C to attain dryness. To the dried soil sample, 2.5 ml of water was added for each experiment after the second one. Such wetting and drying procedures were repeated 10 times. The soil was then shaken for 1 minute with neutral 1 N ammonium acetate solution and transferred to a centrifuge tube for centrifugal separation of the clear supernatant. The soil was washed 4 more times with ammonium acetate solution. Exchangeable potassium was determined on the collected solution flame photometrically. Released or fixed potassium, using the wetting and drying technique, was calculated by subtracting the recovered potassium after the treatment from the originally exchangeable potassium plus the added potassium in 2.5 ml of 0.1 N potassium chloride solution. The control was kept moist with 2.5 ml of 0.1 N potassium chloride solution added for two days during the period of the wetting-drying treatment.

3. Potassium Release and Fixation by Freezing and Thawing Treatments

Potassium release or fixation by freezing-thawing treatments were studied on the original soils with the similar method to Fine *et al.*, (2).

A 2.5 g sample of the soil was placed in a centrifuge tube to which distilled water was added to attain near saturation. The amount of water was twice the moisture content held by the soil when kept at 1/3 atmospheric pressure (4.9 $\mathrm{lbs/in^2}$) for 24 hours. The moisture contents of the experimental soils at 1/3 atmospheric pressure were 20.5% for Brookston loam, 17.0% for Genesee loam, 12.6% for Kalamazoo sandy loam and 14.2% for Landes-Abscota sandy loam.

The centrifuge tube containing the soil was placed in a deep freezer for 30 minutes to become frozen. The temperature of the freezer was kept at −23° C (−9.4° F). The soil was then thawed at room temperature of 25.6° C (78° F) for 1 hour. Subsequent to 10 freezing-thawing treatments, the soil was washed 5 times with neutral 1 N ammonium acetate solution by shaking with a mini-shaker and by centrifuging the suspension. The supernatant collected from each washing was brought up to 100 ml with distilled water and exchangeable potassium determined with a flame photometer. The control was kept at saturation for 3 days, the same period required for the freezing-thawing treatment.

4. Studies of Potassium Potential and Quantity-Intensity Relationships of Potassium in the Original, Cropped and Incubated Soils

The quantity-intensity relationships of soil potassium were determined on the experimental soils before cropping and following the 2nd and 5th crops. The method employed was essentially the same as that of Matthew and Beckett (50).

Five gram samples of the soil were placed into five 125 ml Erlenmeyer flasks and shaken for 1 hour with 0.002 M calcium chloride solution in various concentrations of potassium chloride: 0, 0.25, 0.50, 1.0 and 2.0 mM. The suspensions were filtered after a shaking (1 hr) and equilibrating (1 hr) period at a constant temperature of 25° C. Potassium, calcium and magnesium were determined in the filtrate. The activity of each element was calculated from the concentration of potassium, calcium and magnesium in the filtrate according to the formula;

$$A = rC_M$$

where: A is the activity of a given ion,

r is the activity coefficient and

C_M is the molar concentration of the given ion.

For calculation of the activity coefficient (r), the following Deby-Huckel equation was employed,

$$-\log r = (AZ_+ Z_- \sqrt{\mu}) / (1 + \mathrm{Bai}\sqrt{\mu})$$

where: A is a constant for a given solvent water, 0.5080 at 25° C,

Z_+ is the charge of positive ion,

Z_- is the charge of negative ion,

B is a constant, 0.3281×10^8 at 25° C,

ai is a constant which varies for different ions,

3×10^{-8} for K^+, 6×10^{-8} for Ca^{++}, 8×10^{-8} for Mg^{++}, and 3×10^{-8} for Cl^- (42), and

μ is ionic strength.

The ionic strength was calculated by the formula,

$$\mu = \tfrac{1}{2}\Sigma C_M Z_M{}^2$$

where: C_M is the concentration of ion M, and Z_M is valance of ion M.

Further, activity ratio (AR^K) such as $^aK/\sqrt{^a(Ca+Mg)}$ was calculated after the equilibration. The gain or loss of potassium by the soil was also calculated by subtracting the potassium concentration of the equilibrated solution from the initial potassium concentration and was defined as $\triangle Ke$. The relationship between the AR^K and $\triangle Ke$ are presented graphically in Figures A17 to A20. The AR^K values are on the abscissa and $\triangle Ke$ values on the ordinate. The activity ratio of the equilibrating solution at $\triangle Ke = 0$, which is the point where the soil shows no gains or losses of potassium, was obtained by interpolating the curve to cross the $\triangle Ke = 0$ line and was defined as AR_e^K. The AR_e^K value is regarded as an intensity measurement for labile soil potassium.

A quantity of easily exchangeable soil potassium was obtained by extrapolating the linear portion of the asymptotic curve of the $\triangle K_e$-AR^K relation ship to cross the $AR^K = 0$ line and was defined as $-\triangle K^0$,

The potential buffering capacity (PBC^K) for soil potassium was calculated by dividing the $-\triangle K^0$ value by the AR_e^K value as a measure of the capacity of the soil to maintain the potassium availability according to Beckett (9).

The potassium potential as proposed by Zanstra and Mackenzie (99) was obtained by multiplying the $-\triangle K^0$ value by the PBC^K value.

B. RESULTS AND DISCUSSION

1. Exchangeable and Nonexchangeable Potassium

a. Exchangeable and Nonexchangeable Potassium in the Soil as Affected by Cropping

As shown in Table 21, the exchangeable potassium decreased by cropping except for Landes-Abscota sandy loam of the 1,600 potassium treatment. The magnitude of the decrease was greater in the soils with lower potassium treatments. The soils with higher potassium treatments retained exchangeable potassium near the levels in the original soils. This seems to indicate that the exchangeable potassium was hardly depleted from these soils with higher potassium treatments by cropping because of the equilibrium movement from nonexchangeable forms which were enriched by the potassium applications. With Landes-Abscota sandy loam the enrichment of nonexchangeable potassium by the applied potassium seemed to be great enough to release it when the plants had absorbed all previously exchangeable potassium.

Table 21. Exchangeable and nonexchageable potassium in original, cropped and, incubated soils[a]

K treatment	Exchangeable K	Nonexchangeable K	Exchangeable K	Nonexchangeable K
(lbs/A)	(mg/100 g)			
	Brookston loam			
	Original sample			
	10.6	31.9		
	After 5 crops		*After incubation*	
0	7.1	31.7	10.4	34.0
200	7.4	31.9	12.6	37.1
400	7.1	35.0	14.6	40.7
800	7.9	35.0	21.7	45.6
1,600	8.8	36.1	33.6	53.1
	Genesee loam			
	Original sample			
	5.7	24.3		
	After 5 crops		*After incubation*	
0	4.6	23.7	5.4	27.0
200	4.6	23.7	7.2	30.2
400	4.4	25.4	8.6	32.3
800	4.7	27.6	11.9	39.6
1,600	5.4	33.0	25.2	49.6
	Kalamazoo sandy loam			
	Original sample			
	15.0	26.7		
	After 5 crops		*After incubation*	
0	3.3	17.4	14.5	27.9
200	3.3	17.5	21.6	28.1
400	4.0	18.7	29.5	26.0
800	5.0	22.8	46.5	25.2
1,600	11.5	28.0	83.3	19.7
	Landes-Abscota sandy loam			
	Original sample			
	4.4	20.8		
	Afer 5 crops		*After incubation*	
0	3.6	18.6	4.1	22.6
200	3.7	20.5	5.3	27.8
400	3.6	21.2	6.5	30.4
800	4.3	21.0	9.3	34.1
1,600	5.2	25.7	20.6	42.0

[a] All values are averges of 2 determinations.

Application of more than 200 lbs of potassium per acre on all soils increased nonexchangeable potassium over the respective original soils except for Kalamazoo sandy loam where only the 1,600 potassium treatment resulted in an increase of nonexchangeable potassium. The nonexchangeable potassium of Kalamazoo sandy loam seems to be very easily released in nature being different from other three soils. The rate of decrease at the 0 potassium treatment from the level of the original Kalamazoo sandy loam was the greatest among the soils.

b. Exchangeable and Nonexchangeable Potassium in the Soils as Affected by Incubation

By soil incubation both exchangeable and nonexchangeable potassium increased with the potassium additions except for Kalamazoo sandy loam where nonexchangeable potassium decreased with the 800 and 1,600 potassium treatments (Table 21).

Nonexchangeable potassium in the incubated soil at the 1,600 potassium treatment for Brookston, Genesee and Landes-Abscota soils, and the 200 potassium treatment for Kalamazoo soil were 156%, 184%, 186%, and 101%, respectively, when compared with that of the 0 potassium treatment in each soil. The rate of the increase in nonexchangeable potassium seemed to be related to the original potassium level, clay content, and clay mineralogy of the soils.

Brookston loam contained 18.5% clay which was higher than Genesee loam and Landes-Abscota sandy loam, and 8.3% vermiculite in the clay fraction (Tables 29 and 31). Its original nonexchangeable potassium was 31.9 mg per 100 g soil (Table 21). The clay contents of Genesee loam and Landes-Abscota sandy loam were 11.5% and 14.8%, respectively, and the vermiculite contents of the clay fraction were 10.0% and 8.9%, respectively. However, the original nonexchangeable potassium of the two soils was much lower than Brookston loam. The rate of nonexchangeable potassium increase by higher levels of potassium application was, therefore, greater with Genesee loam and Landes-Abscota sandy loam than with Brookston loam.

In Kalamazoo sandy loam, the soil incubation with more than the 200 potassium treatment resulted in a decrease of nonexchangeable potassium. The reason is not clear and should be studied in the future.

Potassium which was nonextractable with 1 N nitric acid before the incubation became extractable and significant as nonexchangeable potassium during the incubation period since nonexchangeable potassium at the 0 potassium treatment with incubation treatment was higher than the original soil in all cases. Nitric acid nonextractable potassium may include more tightly fixed and mineral constituent potassium.

c. *Ratio of Exchangeable Potassium to Nonexchangeable Potassium*

The percentage ratios of exchangeable potassium to nonexchangeable potassium were calculated from Table 21 and presented in Table 22. The percentage ratio obtained for the soils receiving no potassium ranges from 19 to 22. The ratio appears constant in all the soils which were depleted of potassium by the plants as shown at the 0 potassium treatment of the cropped soils independent of the soil's clay content and mineralogy. Therefore, it might be possible to predict that only the soils with a percentage ratio of exchangeable potassium to nonexchangeable potassium the same or lower than this range respond to potassium application in plant production if the analyzed sample is not collected immediately after cropping. Further study is necessary on this matter. In fact, the lst crop responded little to the applied potassium in all the soil (Tables 3 to 6) where the percentage ratio was higher than 23 except for Landes-abscota sandy loam where the percentage ratio was 21. The tomato plants grown on the newly treated soils did not respond to the applied potassium (Table 8) indicating stronger power to utilize nonexchangeable potassium than wheat.

Some potassium treated soils show a lower percentage ratio than at the 0 potassium treatment in Brookston loam, Genesee loam, and Landes-Abscota sandy loam. However, the percentage ratios at higher potassium treatment are expected to increase, for it takes a certain period of time to attain the equilibrium between exchangeable and nonexchangeable potassium. This increase will be expected from the phenomenon shown in the percentage ratio with the incubated soils.

Nonexchangeable potassium is present about 5 times much as exchangeable potassium in the potassium depleted soils.

The percentage ratio of exchangeable potassium to nonexchangeable potassium in the incubated soils increased with the increase in nonexchangeable potassium except for Kalamazoo sandy loam. This tendency demonstrates that the soil released more potassium when its capacity to hold nonexchangeable potassium approached the limit or that more external potassium was required to satisfy the nonexchangeable potassium holding capacity of the soils approaching the limit.

Table 22. Ratio of exchangeable to nonexchangeable potassium in orginal, cropped and incubated soils

K treatment	Ratio of exchangeable to nonexchangeable K		
	Original sample	After 5 crops	After incubation
(lbs/A)		(%)	
Brookston loam			
	33		
0		22	31
200		23	34
400		20	36
800		23	48
1,600		24	63
Genesee loam			
	23		
0		19	20
200		19	24
400		17	27
800		17	30
1,600		16	51
Kalamazoo sandy loam			
	56		
0		19	52
200		19	77
400		21	113
800		22	185
1,600		41	423
Landes-Abscota sandy loam			
	21		
0		19	18
200		18	19
400		17	21
600		20	27
1,600		20	49

2. Potassium Release and Fixation by Wetting and Drying Treatments

The effects of the wetting-drying treatment on potassium release and fixation of the soils are presented in Table 23. A comparison of the control samples indicates that all the soil except Kalamazoo sandy loam fixed potassium when kept moist as control with 0.1 N potassium chloride solution. The potassium fixation was in the order of Landes-Abscota sandy loam>

Genesee loam> Brookston loam. The reversed order of percentage of potassium saturation for the cation exchange capacity of the respective soils could be expected (Table 24). The release of potassium was observed only with Kalamazoo sandy loam. The percentage of potassium saturation for this soil was exceptionally higher than for the other soils. The results obtained appear to be a good indication of potassium equilibration in the soil; that is, equilibration moved toward fixing of potassium when a quantity of potassium in the solution was added to the already equilibrated state at comparatively low levels of exchangeable and nonexchangeable potassium for the soil's capacity as observed with Brookston loam, Genesee loam, and Landes-Abscota loam. In Kalamazoo sandy loam the equilibrium moved toward releasing potassium from the equilibrated state at a comparatively high level of exchangeable and nonexchangeable potassium for the soil's capacity even when potassium was given to the solution equivalent to 10 me of K per 100g soil higher than the 0.39 me exchangeable potassium of the soil (Table 24).

Table 23. Potassium release and fixation of the soils as affected by wetting and drying

Treatment (3,900 ppm K added)	Soil	Release (−) or fixation (+) of K	Change
		mg/100 g[a]	%[b]
Control (kept moist)	Brookston loam	21.3 (+)	5.3
	Genesee loam	34.3 (+)	8.7
	Kalamazoo sandy loam	2.2 (−)	0.6
	Landes-Abscota sandy loam	41.8 (+)	10.6
10 wetting and drying cycles	Brookston loam	127.9 (+)	31.9
	Genesee loam	100.4 (+)	25.4
	Kalamazoo sandy loam	33.5 (+)	8.3
	Landes-Abscota sandy loam	112.5 (+)	28.8

[a] All values are averages of 2 determinations.

[b] Percentage of change= (released or fixed K/orginal K+added K) x 100.

Table 24. Percentage of potassium saturation for the soils' cation exchange capacity

Soil	CEC[a]	Exchangeable K[b]	K saturation
	——— me/100 g	———	%
Brookston loam	20.7	0.27	1.3
Genesee loam	15.8	0.14	0.9
Kalamazoo sandy loam	7.0	0.39	5.6
Landes-Abscota sandy loam	13.2	0.11	0.8

[a] The cation exchange capacity (CEC) of the soils was taken from Table 1.

[b] The exchangable K (mg/100 g) was taken from Table 21 and converted to me/100 g basis.

Potassium fixation was observed with all four soils when undergoing wetting-drying treatments, indicating some effects of clay content, clay mineralogy and degree of potassium saturation. Brookston loam, with the highest clay content (montmorillonite and vermiculite predominated) among the soils (Tables 29 and 31), fixed the highest amount of potassium. Landes-Abscota sandy loam with vermiculite-chlorite interstratified minerals and mica (or illite) as dominant clay minerals, and Genesee loam with kaolinite and vermiculite-chlorite-montmorillonite interstratified minerals also fixed large amounts of potassium. The mechanisms of potassium fixation have already been discussed in the section, "Mechanisms of Potassium Release and Fixation in Soils".

Kalamazoo sandy loam also fixed potassium but only in small amounts. The mineralogy of the soil is mainly vermiculite-chlorite interstratified minerals and kaolinite. Potassium fixing sites of vermiculite-chlorite interstratified minerals were already highly saturated (5.6%) in Kalamazoo sandy loam before the treatment since the soil was originally high in exchangeable potassium unlike Landes-Abscota sandy loam.

3. Potassium Release and Fixation by Freezing and Thawing Treatments

All four soil, Brookston loam, Genesee loam, Kalamazoo sandy loam, and Landes-Abscota sandy loam, tended to release potassium when kept moist as the control (Table 25). Since potassium was not added to the solution, the increase in exchangeable potassium resulted from a release of potassium from nonexchangeable forms.

Table 25. Potassium release and fixation of the soils as affected by freezing and thawing

Treatment	Soil	Exchangeable K Before treatment[a]	Exchangeable K After treatment	Release (−) or fixation (+)	Change[b]
		mg K/100 g[c]			%
Control (kept moist)	Brookston loam	10.61	10.71	0.10 (−)	0.9
	Genesee loam	5.66	5.86	0.20 (−)	3.5
	Kalamazoo sandy loam	14.95	16.56	1.61 (−)	10.8
	Landes-Abscota sandy loam	4.44	4.85	0.41 (−)	9.2
10 freezing and thawing cycles	Brookston loam	10.61	10.51	0.10 (+)	0.9
	Genesee loam	5.66	5.46	0.20 (+)	3.5
	Kalamazoo sandy loam	14.95	16.36	1.41 (−)	9.4
	Landes-Abscota sandy loam	4.44	4.55	0.11 (−)	2.5

[a] Exchangeable K before treatment was determined on air-dry samples.

[b] Percentage of change = (released or fixed K/originally exchangeable K) x 100.

[c] All values are averages of 2 determinations.

Freezing and thawing treatments had only a slight effect on the soils to fix or release potassium. Montomorillonite rich soil, Brookston loam, and vermiculite-chlorite-montmorillonite interstratified mineral-rich soil, Genesee loam tended to fix potassium. Kalamazoo sandy loam, rich in exchangeable potassium, and Landes-Abscota sandy loam, rich in vermiculite-chlorite interstratified minerals, still tended to release potassium. The release of potassium from Kalamazoo and Landes-Abscota soils, however, was to a lesser degree with the freezing and thawing treatment than with the control. Therefore, it may be presumed that the freezing and thawing treatment of the tested soils without addition of potassium effected the release or the lessening of fixation of potassium.

4. Quantity-Intensity Relationships of Soil Potassium in Original, Cropped, and Incubated Soils

The quantity-intensity relationship of soil potassium was plotted with the determined activity ratio (AR^K) on the abscissa and the changes of potassium concentration ($\triangle K_e$) in the equilibrating solution on the ordinate (Figures A17 to A20). The linear portion of the asymptotic curve was extrapolated to cross the points of $AR^K = 0$ and $\triangle K_e = 0$. The cross points of the curve and $AR^K = 0$, and the curve and $\triangle K_e = 0$ were determined as $-\triangle K^0$ and AR_e^K, respectively. The $-\triangle K^0$ represents the change of potassium concentration in the equilibrating solution when the activity ratio, $AR^K = {}^aK/\sqrt{{}^a(Ca + Mg)}$, of the solution is 0 by the release of potassium from the soil to the solution. It was regarded as the amount of easily exchangeable potassium for quantity measurement by Matthews and Beckett (50). The AR_e^K is the activity ratio of the equilibrating solution when no potassium is gained or lost, and taken as an intensity measurement of labile soil potassium.

Curves for the quantity-intensity relationships of potassium in original Brookston, Genesee, Kalamazoo, and Landes-Abscota soils are presented in Figures A17 to A20. The values of $-\triangle K^0$, AR_e^K, PBC^K and K potential were obtained for the cropped and incubated soils as well as for the original soils and presented in Tables 26 and 27.

Both $-\triangle K^0$ and AR_e^k values increased with the potassium treatment but decreased with the advance of the cropping since the crops depleted soil potassium. The PBC^K values did not generally seem to show a tendency to increase upon the addition of potassium as initially proposed by Beckett (9), since the changes of potassium activity in the soil solution and of the amounts of exchangeable (or labile) potassium on the soil particles were taking place in diverse magnitude in different soils when potassium depletions occured. For example, since Brookston loam and Kalamazoo sandy loam were relatively higher than Genesee loam and Landes-Abscota sandy loam in the percentage ratio of exchangeable to nonexchangeable potassium (Table 22), a more rapid release of exchangeable potassium into the soil solution would be anticipated upon depletion of solution potassium in the former soils rather than in the latter soils.

In the incubated soils, both the $-\triangle K^0$ and AR_e^K values rose with the increasing potassium treatment but the PBC^K values generally decreased. This seems to be the result of a greater increase of solution potassium than exchangeable potassium.

The effect of time on the increase of $-\triangle K^0$ and AR_e^K values was not clear. This suggests that adequate equilibrium between nonexchangeable and exchangeable potassium ($-\triangle K^0$) and potassium in the soil solution could be attained at least within 6 months.

Table 26. Quantity-intensity relationships for original and cropped soils

Smple	K treatment	$-\Delta K^0$	AR_e^k	PBC^k	K potential
	lbs/A	me/100g	$(M/l)^{1/2}$	$-\Delta K^0/AR_e^k$	$-\Delta K^0 \times PBC^k$
			Brookston loam		
Original soil		0.220	0.0026	84.6	18.6
After 2 crops	0	0.115	0.0012	95.8	11.0
	200	0.110	0.0014	78.6	8.6
	400	0.115	0.0018	63.9	7.3
	800	0.170	0.0025	65.4	11.1
	1,600	0.330	0.0070	47.1	15.5
After 5 crops	0	0.050	0.0006	83.3	4.2
	200	0.060	0.0007	85.7	5.1
	400	0.070	0.0009	77.8	5.4
	800	0.090	0.0012	75.0	6.8
	1,600	0.100	0.0015	66.7	6.7
			Genesee loam		
Original soil		0.120	0.0015	80.0	9.6
After 2 crops	0	0.060	0.0012	50.0	3.0
	200	0.070	0.0012	58.3	4.1
	400	0.090	0.0014	64.3	5.8
	800	0.100	0.0020	50.0	5.0
	1,600	0.320	0.0060	53.3	17.1
After 5 crops	0	0.060	0.0008	75.0	4.5
	200	0.045	0.0006	75.0	3.4
	400	0.050	1.0008	62.5	3.1
	800	0.050	0.0008	62.5	3.1
	1,600	0.070	0.0012	58.3	4.1
			Kalamazoo sandy loam		
Original soil		0.315	0.0168	18.9	6.0
After 2 crops	0	0.080	0.0021	38.1	3.1
	200	0.130	0.0042	31.0	4.0
	400	0.260	0.0102	25.5	6.0
	800	0.485	0.0292	16.6	8.1
	1,600	0.935	0.0658	14.2	13.3
After 5 crops	0	0.030	0.0009	33.3	1.0
	200	0.030	0.0009	33.3	1.0
	400	0.045	0.0012	37.5	1.7
	800	0.055	0.0020	27.5	1.5
	1,600	0.160	0.0076	21.1	3.4
			Landes-Abscota sandy loam		
Original soil		0.090	0.0012	75.0	6.8
After 2 crops	0	0.025	0.0004	62.5	1.6
	200	0.025	0.0004	62.5	1.6
	400	0.080	0.0010	80.0	6.4
	800	0.100	0.0013	76.9	7.7
	1,600	0.220	0.0042	52.4	11.5
After 5 crops	0	0.030	0.0003	100.0	3.0
	200	0.050	0.0005	100.0	5.0
	400	0.075	0.0007	107.1	8.0
	800	0.085	0.0009	94.5	8.0
	1,600	0.120	0.0013	92.3	11.1

Table 27. Quantity-intensity relationships for incubated soils

Period of incubation	K treatment	$-\Delta K^0$	AR_e^k	PBC^k	K potential
	lbs/A	me/100g	$(M/l)^{1/2}$	$-\Delta K^0/AR_e^k$	$-\Delta K^0 \times PBC^k$
			Brookston loam		
6 months	0	0.125	0.0024	52.1	6.5
	200	0.225	0.0039	57.7	13.0
	400	0.270	0.0044	61.4	16.6
	800	0.410	0.0077	53.4	21.9
	1,600	0.740	0.0172	43.0	31.8
13 months	0	0.130	0.0025	52.0	6.8
	200	0.140	0.0028	50.0	7.0
	400	0.265	0.0037	71.6	19.0
	800	0.395	0.0070	56.4	22.3
	1,600	0.580	0.0141	41.1	23.8
			Genesee loam		
6 months	0	0.080	0.0016	50.0	4.0
	200	0.130	0.0028	46.4	6.0
	400	0.155	0.0036	43.1	6.7
	800	0.240	0.0051	47.1	11.3
	1,600	0.475	0.0169	29.9	14.2
13 months	0	0.085	0.0014	60.7	5.2
	200	0.150	0.0027	55.6	8.3
	400	0.170	0.0036	47.2	8.0
	800	0.225	0.0062	36.3	8.2
	1,600	0.610	0.0169	36.1	22.0
			Kalamazoo sandy loam		
6 months	0	0.280	0.0096	29.2	8.2
	200	0.420	0.0154	27.6	11.6
	400	0.600	0.0294	20.4	12.2
	800	0.925	0.0556	16.6	15.4
	1,600	1.305	0.0866	15.1	19.7
13 months	0	0.280	0.0104	26.9	7.5
	200	0.350	0.0195	17.9	6.3
	400	0.500	0.0350	14.3	7.2
	800	0.790	0.0650	12.2	9.6
	1,600	1.500	0.1320	11.4	17.1
			Landes-Abscota sandy loam		
6 months	0	0.080	0.1012	66.7	5.3
	200	0.120	0.0116	75.0	9.0
	400	0.140	0.1122	63.6	8.9
	800	0.220	0.0037	59.5	13.1
	1,600	0.410	0.0098	41.8	17.1
13 months	0	0.095	0.0010	95.0	9.0
	200	0.130	0.0026	50.0	6.5
	400	0.140	0.0024	59.3	8.3
	800	0.210	0.0040	52.5	11.0
	1,600	0.560	0.0124	45.2	25.3

Table 28. Relatioships between plant uptake of potassium and various measurements of soil potassium determined after the 2nd and 5th crops

Plant uptake of K and K measurement	Crop					
	1	2	3	4	5	6
	Wheat			Sorghum		Tomato
	Simple correlation coeffcient $(r)^a$					
	Brookston loam					
After the 2nd crop						
$-\Delta K^0$	0.28	0.62	0.98**	0.97**	0.99**	0.98**
AR_e^k	0.26	0.62	0.97**	0.98**	0.99**	0.97**
PBC^k	0.56	−0.91*	−0.84	−0.69	−0.81	−0.86
K potential	0.14	0.34	0.86	0.87	0.86	0.84
After the 5th crop						
$-\Delta K^0$	0.79*	0.94*	0.93*	0.70	0.85	0.93*
AR_e^k	0.70	0.89*	0.97**	0.78	0.90*	0.96**
PBC^k	0.58	−0.82	−0.96**	−0.82	−0.88*	−0.93*
K potential	0.87*	0.97**	0.82	0.53	0.73	0.83
Exchangeable K	0.62	0.68	0.97**	0.89*	0.90**	0.98**
Nonexchangeable K	0.85	0.94*	0.81	0.59	0.70	0.78
Total K	0.85	0.93*	0.91*	0.71	0.83	0.90*
	Genesee loam					
After the 2nd crop						
$-\Delta K^0$	0.65	0.73	0.95*	0.99**	0.97**	0.98**
AR_e^k	0.62	0.72	0.95*	0.99**	0.97**	0.98**
PBC^k	0.11	−0.25	−0.44	−0.44	−0.40	−0.40
K potential	0.69	0.73	0.93*	0.98**	0.96**	0.97**
After the 5th crop						
$-\Delta K^0$	0.13	0.35	0.67	0.84	0.72	0.74
AR_e^k	0.52	0.86	0.88*	0.92*	0.92*	0.92*
PBC^k	−0.90*	−0.93*	−0.81	−0.60	−0.81	−0.79
K potential	−0.53	−0.32	0.09	0.39	0.14	0.17
Exchangeale K	0.49	0.64	0.92*	0.98**	0.92*	0.93*
Nonexchangeable K	0.76	0.88*	0.99**	0.92*	1.00**	0.99**
Total K	0.75	0.87	1.00**	0.94*	1.00**	1.00**

Table 28 (cont'd.)

Plant uptake of K and K measurement	Crop					
	1	2	3	4	5	6
	Wheat			Sorghum		Tomato
	Simple correlation coefficients (r)[a]					
	Kalamazoo sandy loam					
After the 2nd crop						
$-\Delta K^0$	0.43	0.93*	0.85	1.00**	1.00**	1.00**
AR_e^k	0.36	0.90*	0.81	1.00**	1.00**	1.00**
PBC^k	−0.66	−0.98**	−1.00**	−0.87	−0.86	−0.87
K potential	0.54	0.95*	0.89*	0.98**	0.99**	0.99**
After the 5te crop						
$-\Delta K^0$	0.31	0.83	0.70	0.96**	0.97**	0.97**
AR_e^k	0.25	0.80	0.67	0.96**	0.97**	0.96**
PBC^k	−0.01	−8.75	−0.65	−0.93**	−0.90*	−0.89*
K potential	0.46	0.85	0.74	0.94*	0.96**	0.96**
Exchangeable K	0.29	0.83	0.70	0.97*	0.98**	0.97**
Nonexchangeable K	0.37	0.91*	0.84	1.00**	0.99**	0.99**
Total K	0.34	0.88*	0.79	1.00**	1.00**	1.00**
	Landes-Abscota sandy loam					
After the 2nd crop						
$-\Delta K^0$	0.74	0.89*	0.97**	0.93*	1.00**	0.97**
AR_e^k	0.65	0.82	0.96**	0.98**	0.99**	0.99**
PBC^k	0.16	−0.08	−0.43	−0.68	−0.45	−0.52
K potential	0.84	0.95*	0.92*	0.79	0.94*	0.89*
After the 5th crop						
$-\Delta K^0$	0.91*	0.94*	0.92*	0.80	0.95*	0.89*
AR_e^k	0.87	0.95*	0.96**	0.83	0.97**	0.92*
PBC^k	−0.27	−0.69	−0.77	−0.68	−0.66	−0.75
K potential	0.95*	0.90*	0.87	0.74	0.91*	0.83
Exchangeable K	0.63	0.89*	0.99**	0.94*	0.96**	0.98**
Nonexchangeable K	0.79	0.81	0.91*	0.91*	0.97**	0.92**
Toal K	0.77	0.14	0.95*	0.93*	0.98**	0.95*

[a] * and ** indicate significance at 5% and 1% probability levels respectively.

The potassium potential which was obtained by multiplying the $-\triangle K^0$ value by the PBC^K value to mangify the presence of the exchangeable potassium showed a general tendency to increase with the potassium treatment in both cropped and incubated soils.

5. Relationships between Plant Uptake of Potassium and Various Measurements of Soil Potassium

In order to examine which meaurements are the best indicators of soil potassium availability, simple correlation coefficients were calculated for potassium uptake of the respective crops and the various measurments of soil potassium, and presented in Table 28. The values shown in Tables 9 to 12 were used for the plant uptake of potassium; $-\triangle K^0$, AR_e^k, PBC^K and K potential were obtained from Table 26; exchangeable and nonexchangeable potassium values were from Table 21. The total potassium was taken as the sum of the exchangeable and nonexchangeable forms.

a. Plant Uptake of Potassium and Soil Potassium Measured as $-\triangle K^0$ *and* AR_e^K

In general, both $-\triangle K^0$ and AR_e^K values correlated to a similar extent with plant uptake of potassium except for those obtained on Genesee loam in which the $-\triangle K^0$ values measured after the 5th crop were less well correlated with potassium uptake than were the AR_e^K values. The relationship between plant uptake of potasium and the $-\triangle K^0$ and AR_e^K values, measured after the 2nd crop, improved for all soils with the depletion of soil potassium resulting from successive cropping.

b. Plant Uptake of Potassium and PBC^K

There was a tendency for the PBC^K values to corrleate negatively with plant uptake of potassium on all the soils. However, the negative relationship appeared somewhat lower for Genesee loam and Landes-Abscota sandy loam than for Brookston loam and Kalamazoo sandy loam.

c. Plant Uptake of Potassium and K Potential

The K potential values, obtained by multiplying $-\triangle K^0$ by PBC^K values, appeared to be correlated with plant uptake of potassium. The K potential values, however, were generally inferior to $-\triangle K^0$ and AR_e^K on all soils except on Kalamazoo sandy loam, where the K potential was better correlated with potassium uptake when measured after the 2nd crop.

d. Plant Uptake of Potassium, and Exchangeable, Nonexchangeable and Total Soil Potassium

The exchangeable and nonexchangeable forms of soil potassium, measured on the soils subsequent to harvesting the 5th crop, were found to be in significant correlation with plant uptake of potassium on all soils, except for that of Brookston loam, as the potassium depletion advanced. The nonexchangeable potassium correlated poorly with the plant uptake of potassium on Brookston loam.

The total soil potassium measured after the 5th crop correlated with plant uptake of potassium similar to that of exchangeable potassium on Genesse loam, and to a similar extent to that for nonexchangeable potassium on Kalamazoo and Landes-Abscota sandy loam soils. The total soil potassium of Brookston loam was not as well correlated as the exchangeable potassium with plant uptake of potassium but better correlated than the nonexchangeable potassium.

V PHYSICAL AND MINERALOGICAL PROPERTIES OF SOILS

A. METHODS AND MATERIALS

1. Mechanical Analysis

In order to examine the physical properties of the soils used for the experiment, a mechanical analysis was carried out with the hydrometer method as described by Day (20).

A 40 g sample of the soil was placed in a dispersing cup, to which 100 ml of dispersing reagent (5% Calgon solution) and 400 ml of distilled water were added. After the sample was soaked, it was mixed for 5 minutes with a motor mixer and transferred to a sedimentation cylinder. The suspension was brought to 1,000 ml with distilled water and allowed to stand in a constant temperature room, and thoroughly mixed when the temperature of the suspension became constant (20.5° C). Hydrometer measurements were performed at predetermined time intervals.

The summation percentage was calculated after corrections for the Calgon concentration and temperature were made. The particle sizes were calcultaed with sedimentation time and sedimentation paramerters suggested by Day (20).

The percentages of the separates were interpolated from a curve that was obtained by plotting the summation percentage against the particle size on the log scale of semilogarithmic paper. The sand fraction was obtained by subtracting the percentage of silt and clay from 100.

2. X-Ray Diffraction Studies

From each soil, 4 different samples were used for the X-ray diffraction studies. They included the original soils, samples collected after the 5th crop on the 0 and 1,600 potassium treatment, and samples collected from the 1,600 potassium treatment after incubating the soils for 13 months without cropping.

The soils were screened through a sieve with 2 mm openings and pretreated to remove organic matter, carbonates, soluble salts and free iron oxides by the methods described by Kunze (43). Clay films for the X-ray diffraction studies were prepared according to the method designed by Mortland (57).

a. Dissolution of Carbonate and Soluble Salts

A given amount of soil, 30 g for Brookston loam, and 40 g for Genesee loam, Kalamazoo sandy loam, and Landes-Abscota sandy loam, was placed in a 400 ml beaker to which 75 ml of buffer solution (1 N sodium acetate solution adjusted to pH 5 with asetic acid) was added, and the soil was suspended by stirring. The soil suspension was digested on a hot plate at low temperature (about 70° C) for 30 minutes with intermittent stirring. The suspension was then centrifuged and the supernatant discarded.

b. Removal of Organic Matter

The soil in the centrifuge tubes was wetted with sodium acetate buffer solution and transferred to a 400 ml beaker with a small increment of water. To the beaker 5 ml of 30% hydrogen peroxide was added and the mixture was carefully stirred. A second 5 ml increment of hydrogen peroxide was added to the beaker containing the soil after the reaction had subsided and the mixture was digested on a hot plate. In order to insure completion of the reaction, 2 more 10 ml increments of hydrogen peroxide were added after the reaction subsided and the suspension was digested for 4 hours. The suspension, as it manifested the loss of dark color due to organic matter, was evaporated to a thin paste, which was stirred well with a solution of sodium acetate and centrifuged. The recovered mineral matter was washed once with distilled water.

c. Removal of Free Iron Oxides

To the soil in the centrifuge tube, were added 40 ml of 0.3 M sodium acetate solution to chelate ferrous and ferric forms of iron and 5 ml of 1 M sodium bicarbonate to buffer the soltion. The suspension was warmed on the hot plate for a total of 15 minutes with occasional stirring. A 10 ml solution of saturated sodium chloride was added to promote flocculation, and the suspension was centrifuged.

d. Collection of the Clay Fraction

The clay fraction was collected by repeated siphoning of the dispersed soil. The soil in the centrifuge tube, treated for the removal of free iron oxides, was transferred to a sedimentation cylinder (1,000 ml), which was filled with distilled water and kept in the constant temperature room. The suspension was stirred vigorously with a plunger after it had attained a constant temperature (21° C), and stood for 23 hours to allow the coarser fractions ($>2\mu$) to settle below 30 cm from the surface of the suspension, according to Stokes law. Then the suspension was siphoned from the depth of 30 cm. The volume of the siphoned suspension which contained only the clay fraction was reduced by centrifuging with addition of a saturated sodium chloride solution. The clay was washed several times with distilled water to remove excess salt and transferred to an appropriate jar for storage.

e. Preparation of the Clay Film

About 10 ml of the clay suspension kept in the storage jar was placed in a test tube and allowed to stand overnight after the addition of several drops of glycerol. Onto a porous ceramic plate in the plate holder on a vacuum flask, 5 to 10 drops of the glycerol-solvated clay suspension were added with distilled water and vacuum was applied.

The clay film deposited on the porous ceramic plate was leached with three increments of 1 N magnesium chloride solution containing 10% glycerol to saturate the clay with magesium. The clay film was then washed with 5 increments of water containing 10% glycerol to remove excess magnesium chloride and air-dried in a desiccator over calcium chloride.

f. X-Ray Diffraction Patterns

The clay film prepared was used for the first X-raying as a manesium-saturated, glycerol-solvated, oriented aggregate. A Phillips-Norelco X-ray unit was used with a copper source and nickel filter for X-ray diffraction patterns. After the first X-raying, the clay film was leached with 1 N potassium chloride solution to saturate the clay with potassium, and washed with water to remove excess salt. The potassium saturated clay film was air-dried and used for the 2nd X-raying, then heated at 300° C, cooled and X-rayed for the 3rd time. The clay film was heated at 550° C, cooled and X-rayed for the 4th time. Heating lasted for 2 hours each time.

3. Cation Exchange Capacities and Total potassium of the Clay Fractions

The cation exchange capacity (CEC) and total potassium of the clay fractions were determined according to the method designed by Mortland (57).

The clay fraction ($<2\mu$) which had been stored after the pretreatment for the X-ray diffraction studies were used for both the determinations of cation exchange capacity and total potassium. First the cation exchange capacity (by Ca/Mg) was determined by saturating the clay with calcium ion and then replacing it with magnesium ion. Secondly, the cation exchange capacity (by K/NH_4) was determined by saturating the clay with potassium ion and then replacing it with ammonium ion. The difference in the cation exchange capacity (me/100 g), determined by the two methods was used for the calculation of vermiculite content in the clay fraction employing the following equation; percentage of vermiculite = ((CEC by Ca/Mg) − (CEC by K/NH_4)/153.9) x 100.

For the determination of total potassium, the clay was digested with hydrofluoric acid in a platinum crucible and taken up with 0.1 N hydrochloric acid, then the solution was used for the determination of potassium. The total potassium was employed to estimate mica content in the clay fraction by multiplying the percentage of total potassium by a factor of 12.

B. RESULTS AND DISCUSSION

1. Textural Designation of the Soils

The results of the mechanical analysis are shown in Table 29. Also listed in the table are the textural designations for each soil after referring to the textural triangle (83).

2. Active Fractions of the Soils

The clay fraction is the most active portion of the mineral fraction of the soil. The clay content of the various soils (Table 29) is shown in the following order: Brookston loam> Landes-Abscota sandy loam > Kalamazoo sandy loam > Genesee loam. However, the order in cation exchange capacity (by Ca/Mg) of the whole soil (Table 1) is: Brookston loam> Genesee loam > Landes-Abscosa sandy loam> Kalamazoo sandy loam. The fact that the clay content of the soils and their cation exchange capacities are not directly related suggests that the clay content is not the only factor involved in the activity of the soil in the economy of the plant nutrients, but the kinds of clay as well as the organic matter content must be considered; the coarser fractions such as silt may also be involved.

If the CEC (cation exchange capacity) is taken as a measure of physical and chemical activity of the soil, the contribution of the silt fraction to the CEC of the soils is shown in Table 30.

Table 29. Mechanical analysis of the soils and their textural designation

Separate	Size (diameter)	Soil Brookston	 Genesee	 Kalamazoo	 Landes-Abscota
	mm	% of separate[a]			
Sand	2.0 – 0.05	32.0	51.0	60.2	63.5
Silt	0.05 – 0.002	49.5	37.5	26.3	21.7
Coarse silt	0.05 – 0.02	15.0	15.2	7.8	4.2
Fine silt	0.02 – 0.002	34.5	22.3	18.5	17.5
Clay	< 0.002	18.5	11.5	13.5	14.8
Textural designation		Loam	Loam	Sandy loam	Sandy loam

[a] All values are averages of 2 determinations.

Table 30. Cation exchange capacity of the organic matter, clay and silt fractions of Brookston, Genesee, Kalamazoo and Landes-Abscota soils

Soil	Whole soil	Organic matter	Clay	Silt
	CEC me/100 g			
Brookston loam	20.7 (100.0)[a]	7.2 (34.8)	8.4 (40.6)	5.1 (24.6)
Genesee loam	15.8 (100.0)	6.6 (41.8)	5.0 (31.6)	4.2 (26.6)
Kalamazoo sandy loam	7.0 (100.0)	2.7 (38.6)	3.8 (54.3)	0.5 (7.1)
Landes-Abscota sandy loam	13.2 (100.0)	4.6 (34.8)	6.3 (47.7)	2.3 (17.4)

[a] The values in the parentheses show the percentage of CEC derived from the respective fractions

The CEC of the organic matter and clay fractions was obtained by multiplying the percentage of organic matter of the soils (Table 1) by 200, and by multiplying the percentage of clay (Table 29) by the CEC (by Ca/Mg) of the clay fraction (Table 31), respectively.

The CEC derived from the silt fraction was obtained by subtracting the CEC of the organic matter plus that of the clay fraction from the CEC of the whole soil.

A large portion of the CEC of Brookston loam is derived from the organic matter and silt fractions as well as from the clay fraction. Brookston loam had the highest clay content and consequently the highest CEC among the experimental soils. Genesee loam on the other hand contained the least clay, and among the soils it had the highest contribution to the CEC (nearly 70%) from the organic matter and silt fractions.

Kalamazoo sandy loam and Landes-Abscota sandy loam received the major portion of the CEC from the clay and organic matter. The silt fraction contributed less CEC to these two soils than to the Brookston and Genesee soils.

3. Cation Exchange Capacities, and Kinds and Relative Amounts of Minerals Present in the Clay Fractions of Original Soils

The cation exchange capacity values (CECs) determined by Ca/Mg and K/NH_4 methods, the percentage of vermiculite, the total amount of potassium and the percentage of mica in the clay fractions of the original soils are summarized in Table 31. The kinds and relative amounts of minerals found in the clay fractions are also indicated in Table 31. The more important X-ray diffraction patterns, which were used as a basis for identifying the clay minerals present in the soils, are presented in Figures A21 to A36.

It was found when the CECs are higher, the amount of montmorillonite and vermiculite were higher. The reported CECs are: 80—100 for montmorillonite, 100—150 for vermiculite, 10—40 for illite, 3—15 for kaolinite, and 10—40 for chlorite when expressed as me per 100 g of the respective clays (34).

Table 31. **Mineralogical properties of the clay fractions of the original, cropped, and incubated Brookston, Genesee, Kalamazoo, and Landes-Abscota soils**

K treatment and cropping	CEC		Vermiculite	Total K	Mica	Kinds[a] and relative amounts[b] of minerals present in clay fraction
	Ca/Mg	K/NH_4				
	me/100g		%	%	%	
			Brookston	*loam*		
Original soil	45.1	32.4	8.3	2.3	27.6	$\overset{++++}{\mathrm{Mo}}>\overset{++}{\mathrm{V}}>\overset{++}{\mathrm{Mi}}>\overset{++}{\mathrm{Q}}>\overset{++}{\mathrm{Ka}}>\overset{+}{\mathrm{Ch}}$
5 crops with 0 lbs K/A	48.1	33.3	9.6	1.9	22.8	$\overset{++++}{\mathrm{Mo}}>\overset{++}{\mathrm{V}}>\overset{++}{\mathrm{Mi}}>\overset{++}{\mathrm{Ka}}>\overset{++}{\mathrm{Q}}>\overset{+}{\mathrm{Ch}}$
5 crops with 1,600 lbs K/A	43.2	31.2	7.8	1.9	22.8	$\overset{++++}{\mathrm{Mo}}>\overset{++}{\mathrm{V}}>\overset{++}{\mathrm{Mi}}>\overset{++}{\mathrm{Q}}>\overset{++}{\mathrm{Ka}}>\overset{+}{\mathrm{Ch}}$
Incubated with 1,600 lbs K/A	41.5	32.6	5.9	2.3	27.6	$\overset{++++}{\mathrm{Mo}}>\overset{++}{\mathrm{V}}>\overset{++}{\mathrm{Mi}}>\overset{++}{\mathrm{Q}}>\overset{++}{\mathrm{Ka}}>\overset{+}{\mathrm{Ch}}$
			Genesee	*loam*		
Original soil	43.1	27.7	10.0	1.5	18.0	$\overset{+++}{\mathrm{Ka}}>\overset{+++}{\mathrm{V\text{-}ch\text{-}mo}}>\overset{+}{\mathrm{Mi}}>\overset{+}{\mathrm{Q}}$
5 crops with 0 lbs K/A	44.5	28.6	10.3	1.5	18.0	$\overset{+++}{\mathrm{Ka}}>\overset{+++}{\mathrm{V\text{-}ch\text{-}mo}}>\overset{+}{\mathrm{Mi}}>\overset{+}{\mathrm{Q}}$
5 crops with 1,600 lbs K/A	45.3	32.8	8.2	1.7	20.4	$\overset{+++}{\mathrm{Ka}}>\overset{+++}{\mathrm{V\text{-}ch\text{-}mo}}>\overset{+}{\mathrm{Mi}}>\overset{+}{\mathrm{Q}}$
Incubated with 1,600 lbs K/A	43.2	33.1	6.6	1.7	20.4	$\overset{+++}{\mathrm{Ka}}>\overset{+++}{\mathrm{V\text{-}ch\text{-}mo}}>\overset{+}{\mathrm{Mi}}>\overset{+}{\mathrm{Q}}$

Table 31 (cont'd.)

K treatment and cropping	CEC		Vermiculite	Total K	Mica	Kinds[a] and relative amounts[b] of minerals present in clay fraction
	Ca/Mg	K/NH$_4$				
	me/100g		%	%	%	
			Kalamazoo sandy loam			
Original soil	28.2	25.5	1.7	1.5	18.0	$\overset{+++}{\text{V-ch}} > \overset{+++}{\text{Ka}} > \overset{++}{\text{Q}} > \overset{+}{\text{Mi}} > \overset{+}{\text{Ch}}$
5 crops with 0 lbs K/A	25.2	22.4	1.8	1.4	16.8	$\overset{+++}{\text{V-ch}} > \overset{+++}{\text{Ka}} > \overset{++}{\text{Q}} > \overset{+}{\text{Mi}} > \overset{+}{\text{Ch}}$
5 crops with 1,600 lbs K/A	26.0	23.9	1.4	1.5	18.0	$\overset{+++}{\text{V-ch}} > \overset{++}{\text{Ka}} > \overset{++}{\text{Q}} > \overset{+}{\text{Mi}} > \overset{+}{\text{Ch}}$
Incubated with 1,600 lbs K/A	30.0	27.3	1.8	1.5	18.0	$\overset{++++}{\text{V-ch}} > \overset{++}{\text{Ka}} > \overset{++}{\text{Q}} > \overset{+}{\text{Mi}} > \overset{+}{\text{Ch}}$
			Landes-Abscota sandy loam			
Original soil	42.7	29.0	8.9	2.4	28.8	$\overset{+++}{\text{V-ch}} > \overset{++}{\text{Mi}} > \overset{++}{\text{Ka}} > \overset{+}{\text{Q}}$
5 crops with 0 lbs K/A	46.6	27.9	12.2	2.0	24.0	$\overset{+++}{\text{V}} > \overset{++}{\text{Mi}} > \overset{++}{\text{Ka}} > \overset{++}{\text{V-ch-mo}} > \overset{+}{\text{Q}}$
5 crops with 1,600 lbs K/A	41.7	28.5	8.6	2.4	28.8	$\overset{+++}{\text{V}} > \overset{++}{\text{Mi}} > \overset{++}{\text{Ka}} > \overset{+}{\text{Mo-ch}} > \overset{+}{\text{Q}}$
Incubated with 1,600 lbs K/A	37.6	28.5	5.9	2.7	32.4	$\overset{+++}{\text{Mi}} > \overset{++}{\text{V-ch}} > \overset{++}{\text{Ka}} > \overset{+}{\text{Mo-ch}} > \overset{+}{\text{Q}}$

[a] Ch=chlorite; Ka= kaolinite; Mi= Mica (or illite) ; Mo= montmorillonite; Mo−ch= montmorillonite−chlorite interstratified minerals; Q= quartz; V= vermiculite; V−ch= vermiculite−chlorite interstratified minerals; and V−ch−mo= vermicnlite-chlorite-montmorillonite interstratified minerals.

[b] Number of + indicates relative qnantity of the minerals; ++++= very high, +++= high, ++= medium and +=low.

Since the clay fraction of Brookston loam contained a large quantity of montmorillonite plus vermiculite, it shows a higher CEC (by Ca/Mg) than that of other three soils. In Genesee loam, the randomly interstratified minerals of vermiculite-chlorite-montmorillonite seemed to be quite active resulting in a high CEC (by Ca/Mg). The clay fraction of Kalamazoo sandy loam showed lower activity in the CEC (by Ca/Mg) and in the fixation of potassium, which was indicated by the difference between the CECs by Ca/Mg and dy K/NH_4, when compared with the other soils. Vermiculite-chlorite interstratified minerals were dominant in clay fraction of both Kalamazoo sandy loam and Landes-Abscota sandy loam. However, the CEC and potassium fixation were higher for the clay fraction of Landes Abscota sandy loam than for Kalamazoo sandy loam. The difference of the clay fraction of the two soils in the CEC and potassium fixation, although it must be studied in the future, was probably that: (a) the minor minerals in Kalamazoo sandy loam were kaolinite, quartz, mica (or illite), and chlorite in decreasing order, whereas mica (or illite), kaolinite, and quartz in Landes-Abscota sandy loam, (b) gibbsite-like layers may have been formed in vermiculite-chlorite interstratified menerals of Kalamazoo sandy loam but brucite-like layers in that of Landes-Abscota sandy loam, and (c) the vermiculite-chlorite interstratified minerals of Kalamazoo sandy loam may have been larger in size and higher in crystallinity than those of Landes-Abscota sandy loam.

4. Effects of Potassium Exhaustion and Incubation on Clay Mineralogy of the Soils

Changes in clay mineralogy which were caused by cropping and incubation were presented in Table 31. The assumptions are that: (a) the potassium fixation (the difference between the cation exchange capacity by Ca/Mg and K/NH_4) was caused only by vermiculite; and (b) the total potassium was derived only from mica. The parts of the X-ray diffraction patterns used for identifying the kinds and relative amounts of clay minerals are presented in Appendices G to J.

In Bookston loam the percentage of vermiculite increased slightly and the percentage of mica decreased when soil potassium was exhausted by 5 croppings without the addition of potassium. If the assumptions were appropriate, the results would be an indication of the change of mica, after releasing its potassium, to vermiculite. When the soil was cropped 5 times with enough potassium applied (K=1,600 lbs), the percentage of vermiculite did not increase but stayed near the level of the original soil. The decrease of mica in this case may be an indication of plant weathering of mica (17, 58), by which mica released its potassium directly to the plant roots and may have changed to montmorillonite through vermiculite. This process would take place more intensively in Brookston loam than in the other three soils because the plant growth was most vigorous in Brookston loam (Table 3 and 6). The percentage of vermiculite markedly decreased when the soil was incubated for 13 months with the 1,600 potassium treatment. An increase in the percentage of mica was not indicated by potassium analysis when compared with the original soil, but a slight increase in 10 Å peak was recognized in the X-ray diffraction pattern (Figure A23) indicating the change of vermiculite to mica (or illite). The alteration of minerals appears more sensitively reflected in the clay X-ray diffraction pattern than in the potassium content of the clay minerals (58). Mineralogical changes in Genesee loam were not detected from potassium exhaustion by crooping. This is likely to mean that the soil potassium had already been depleted before the experiment was initiated. The decrease in the percentage of vermiculite and the increase in the percentage of mica (or illite) took place when the soil was cropped with enough potassium (K=1,600 lbs) and also when incubated with this rate of potassium, indicating the changes of vermiculite to mica (or illite) after fixing applied potassium as obseved by Rich and Lutz (75).

Only minor changes in the clay mineralogy upon the cropping of Kalamazoo sandy loam were evidenced with and without the addition of potassium. The vermiculite-chlorite interstratified minerals increased when incubated with the 1,600 potassium treatment as identified from the X-ray diffraction patterns.

The percentage of vermiculite in Landes-Abscota sandy loam increased markedly due to potassium exhaustion by 5 croppings without the addition of potassium. The decrease in the percentage of mica suggests the change of mica to vermiculite. The X-ray diffraction patterns show that discrete vermiculite was formed from vermiculite-chlorite interstratified minerals upon the depletion of potassium. Also identified was the formation of vermiculite-chlorite-montmorillonite interstratified minerals. The decrease of vermiculite and increase of mica in the soils with applied potassium indicated the change of vermiculite to mica by fixing potassium.

The results obtained may imply some important relationships between clay mineralogy of the soils and fertilization practices. If soils such as Brookston loam, Genesee loam, and Landes-Abscota sandy loam were cropped with only small applications of potassium, the soils would eventually become potassium depleted and become rich in vermiculite, resulting in the fixation of applied potassium and the decrease of its availability for immediate use to plants. If a large amount of potassium were applied to these soils, it would be bound in clay minerals such as mica and illite, and released later to meet the plant requirements. In contrast, applied potassium would be exposed to the hazard of leaching in Kalamazoo sandy loam which has a clay mineralogy capable of fixing little potassium. The bound potassium by fixation in Brookston, Genesee, and Landes-Abscota soils may be released at different rate (Figures 9, 10 and 12). If the rate of release is too slow, it may become a barrier for potassium supply of the soils to plants (Figures 10 and 12), as suggested by Mortland (55).

SUMMARY

The objectives of this thesis were to study and compare the ability of Brookston loam, Genesee loam, Kalamazoo sandy loam, and Landes-Abscota sandy loam to release and/or fix soil potassium under different cropping programs, and to relate these phenomena to their physical, chemical, and mineralogical properties.

Five levels of potassium, 0, 200, 400, 800 and 1,600 lbs per acre were applied initially to all soils and the soils were planted to 6 crops in the following sequence: 3 crops of wheat, 2 crops of sorghum, and 1 crop of tomatoes. Plant response to the applied potassium, the interrelationships among potassium, calcium, and magnesium uptake of the plants were investigated and the potassium supplying power of the soils were evaluated.

The 3rd crop (wheat) and the 6th crop (tomatoes) grown on Brookston loam were the only crops to show a yield response to the potassium treatments. In the case of Genesee loam the 3rd crop (wheat) and the succeeding crops, 2 crops of sorghum and 1 crop of tomatoes, responded to the potassium treatments. The plant response obtained from applied potassium on Kalamazoo sandy loam was the same as that obtained for Genesee loam, but the yields of the 2nd crop (wheat) was negatively affected by the potassium treatments. All crops except the 2nd (wheat) grown on Landes-Abscota sandy loam responded to applied potassium.

Potassium concentration of the plants rose with increasing levels of applied potassium while the concentrations of plant calcium and magnesium generally decreased.

Potassium concentration in the plants declined as the cropping advanced whereas that of calcium and magnesium increased.

Potassium uptake of the plants grown on all the soils was significantly

affected by potassium treatments. However, plant uptake of calcium and magnesium varied with the crop and soils.

Plant yields were generally positively correlated with potassium uptake and with the uptake of potassium plus calcium and mangesium, but negatively correlated with uptake of calcium and magnesium except for the 6th crop (tomatoes) in which the yields were positively correlated with all uptake measurements.

The overall potassium supplying power, as measured by potassium uptake of the plants at the 0 potassium treatment, was in the following order: Brookston loam > Kalamazoo sandy loam > Landes-Abscota sandy loam > Genesee loam.

The stem tissue of wheat (2nd crop) was analyzed by the elecron microprobe X-ray technique. A higher concentration of potassium but a lower concentration of calcium and magnesium was obtained for the sample from the 400 potassium treatment on Brookston loam; on the other hand, a lower concentration of potassium but a higher concentration of calcium and magnesium was obtained from the 0 potassium treatment on Genesee loam.

Chemical properties of the soils were studied in relation to potassium availability by determining exchangeable and nonexchangeable forms of potassium, the release and fixation of potassium upon wetting-drying, and freezing-thawing treatments, and quantity-intensity relationships of soil potassium.

After 5 croppings the levels of exchangeable soil potassium for all soils were found to be considerably less than that of the original soil levels.

Nonexchangeable potassium was retained at levels higher than the original levels, even after 5 croppings, when potassium was initially applied to the rate of 400 or more pounds of K per acre on Brookston loam, Genesee loam, and Landes-Abscota sandy loam, and at the rate of 1,600 lbs of K per acre on Kalamazoo sandy loam.

The applied potassium seems to have been converted to nonexchangeable forms and then released gradually upon the depletion of exchangeable potassium by the plants. The rate of potassium release was considered to be more rapid for Kalamazoo sandy loam, which had the lowest potassium fixing and cation exchange capacities among the soils.

When the soil was incubated for 13 months with the various levels of applied potassium both the exchangeable and nonexchangeable potassium increased except in the case of Kalamazoo sandy loam in which the nonexchangeable potassium decreased with levels of applied potassium exceeding 400 lbs per acre.

The degree of increase in exchangeable and nonexchangeable potassium appeared greater when the initial levels of potassium in the 2 forms were lower and the contents of potassium fixing clay were higher in the soils.

The alternate wetting and drying treatments resulted in the fixation of potassium by all soils. Potassium fixation was in the following order: Brookston loam > Landes-Abscota sandy loam > Genesee loam > Kalamazoo sandy loam.

Only small quantities of potassium were released by Kalamazoo sandy loam and Landes-Abscota sandy loam, and conversely small amounts of potassium were fixed by Brookston loam and Genesee loam when the soils were alternately frozen and thawed.

Soil potassium as defined in terms of $-\triangle K^0$ and AR_e^K decreased by cropping but increased with the levels of applied potassium in both cropped and incubated soils. PBC^K decreased with the levels of applied potassium in the cropped soil but showed various tendencies by different soils when incubated. Effects of cropping on the PBC^K were varied among the soils. The K potential obtained by multiplying $-\triangle K^0$ by PBC^K values tended to increase with the levels of applied potassium in both cropped and incubated soils but decreased by cropping.

When $-\triangle K^0$, AR_e^K, PBC^K, K potential, and exchangeable, nonexchangeable, and total potassium (the sum of exchangeable and nonexchangeable potassium) were correlated with the plant uptake of potassium, $-\triangle K^0$, AR_e^K and exchangeable potassium offered better measurement to evaluate availability of soil potassium for Brookston loam; AR_e^K and exchangeable, nonexchangeable, and total potassium for Genesee loam; nonexchangeable and total potassium for Kalamazoo sandy loam; and $-\triangle K^0$, AR_e^K and exchangeable, nonexchangeable, and total potassium for Landes-Abscota sandy loam.

Physical properties of the soils were evaluated by mechanical analysis; and the mineralogical properties by cation exchange capacity determination, total potassium contents of the clay fractions, and X-ray diffraction patterns.

The clay contents of the soils were: 18.5%, 11.5%, 13.5% and 14.8% for Brookston loam, Genesee loam, Kalamazoo sandy loam, and Landes-Abscota sandy loam, respectively.

The cation exchange capacities of the soils were: 20.7, 15.8 7.0 and 13.2 milliequivalents per 100 g for Brookston loam, Genesee loam, Kalamazoo sandy loam, and Landes-Abscota sandy loam, respectively. The organic matter, silt, and clay fractions contributed to the cation exchange capacity values of Brookston and Genesee loam soils. The silt fraction, however, was of minor significance in the cation exchange capacity values obtained for Kalamazoo and Landes-Abscota sandy loam soils.

The percentage of vermiculite in the clay fractions of the original soils was determined as 8.3, 10.0, 1.7 and 8.9 for Brookston loam, Genesee loam, Kalamazoo sandy loam, and Landes-Abscota sandy loam, respectivery.

The percentage of mica in the clay fractions of the original soils was; 27.6, 18.0, 18.0 and 28.8 for Brookston loam, Genesee loam, Kalamazoo sandy loam, and Landes-Abscota sandy loam soils, respectively.

Montmorillonite was the predominant clay mineral in Brookston loam; kaolinite and vermiculite-chlorite-montmorillonite interstratified minerals predominated in Genesee loam; vermiculite-chlorite interstratified minerals and kaolinite were dominant in Kalamazoo sandy loam; and vermiculite-chlorite interstratified minerals were predominant in Landes-Abscota sandy loam.

The cation exchange capacities of the clay fractions tended to increase when the soil potassium was depleted by cropping, the only exception was Kalamazoo sandy loam. When Brookston loam and Landes-Abscota sandy loam were incubated with 1,600 lbs of potassium per acre, their cation exchange capacities tended to decrease.

The vermiculite contents of the clay fractions tended to increase as soil potassium was depleted by the croping, most remarkably in Landes-Abscota sandy loam.

The percentage of mica in the clay fractions tended to increase in Genesee and Landes-Abscota soils when the soils were incubated with 1,600 lbs of patassium per acre. The alteration of the vermiculite-chlorite interstratified minerals to mica was remarkable especially in Landes-Abscota sandy loam.

The changes in cation exchange capacity and mineralogy were almost nil when the soils were planted to 5 crops with the 1,600 potassium treatment.

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米国ミシガン州の四土壌のカリ有効度に関する研究

大屋一弘*

要約

米国ミシガン州の四つの土壌一Brookston loam, Genesee loam, Kalamazoo sandy loam, Landes-Abscota sandy loam 一を用い，作物栽培下においてこれらの土壌が示すカリ供給力あるいは固定力を比較し，またこれら供試土壌のカリ供給・固定力と関係のある物理・化学・鉱物学的性質を調べる目的で研究を行なった。

先ず各土壌に5段階のカリ分（エーカー当り0，200，400，800，1,600ポンド）を施用し，後にカリの施用を行うことなく作物を6回（小麦2回，ソルガム2回，トマト1回の順で）ポットに栽培した。そして施用カリに対する作物の応答，作物のカリ・カルシウム・マグネシウム吸収，各土壌のカリ供給力などを調べた。結果は次の通りであった。

(1) Brookston loam においては第3作の小麦と第6作のトマトのみが施用カリに対して収量の応答を示し，Genesee loam では第3作以後の作物総てが施用カリに対して応答した。Kalamazoo sandy loam では Genesee loam におけると同様な結果が得られたが，第2作の小麦は施用カリに対してむしろ負の応答を示した。Landes-Abscota sandy loam では第2作以外は総て施用カリに対し応答した。

(2) 作物のカリ含量（%）は施用カリ量が増加するに従って増大したが，カルシウムとマグネシウムの含量（%）は逆に減少した。一方作物の栽培回数が進むと作物のカリ含量（%）は低下し，逆にカルシウムおよびマグネシウムの含量が増加する傾向を示した。

(3) 作物のカリ吸収量におよぼすカリ施用の効果は有為的であったが，カルシウムおよびマグネシウム吸収量におよぼす効果については作物間および土壌間で相違がみられた。

(4) 作物収量は一般に作物のカリ吸収量，およびカリ＋カルシウム＋マグネシウム吸収量と正の相関を示した。第6作以外は多くの場合収量とカルシウム吸収量およびマグネシウム吸収量との間に負の相関を示した。第6作（トマト）では殆んどの場合に，収量とカリ吸収量・カルシウム吸収量・マグネシウム吸収量・カリ＋カルシウム＋マグネシウム吸収量などとの間に正の相関がみられた。

(5) 無カリ区における作物のカリ吸収量を土壌のカリ供給力とみなした場合，供試土壌のカリ供給力は Brookston loam ＞ Kalamazoo sandy loam ＞ Landes-Abscota sandy loam ＞ Genesee loam の順であった。

小麦（第2作）の茎組織をX・線マイクロアナライザーを使用して調べたところ次の様な結果が得られた。

(1) エーカー当たり400ポンドのカリを施用した Brookston loam に栽培した小麦の茎にはカリの濃度が高く，カルシウムおよびマグネシウムの濃度は低い。

(2) Genesee loam の無カリ区に栽培した小麦の茎にはカルシウムおよびマグネシウムの濃度

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が高く，カリの濃度は低い。

供試土壌の化学的性質について，置換性および非置換性カリ・湿潤―乾燥反復処理によるカリの放出と固定・凍結―融解反復処理によるカリの放出と固定・カリの quantitity―intensity 関係などを調べた。結果は次の通りであった。

(1) 置換性カリは第5作後には著しく減少していた。

(2) 非置換性カリは Brookston loam, Genesee loam, Landes-Abscota sandy loam などの三土壌においてはエーカー当り400ポンド以上のカリを施用した場合，また Kalamazoo sandy loam では1,600ポンドのカリを施用した場合は何れも第5作後においても初期の含量よりも高い値を示した。

(3) 施用されたカリは最初は非置換態に変わり，その後作物が置換態のカリを消費するに従って徐々に放出されるものと思われた。カリを置換態にして放出する速度は，供試土壌の中でカリ固定力・陽イオン置換容量などが小さい Kalamazoo sandy loam において最も早いと思われた。

(4) 供試土壌にカリを施用して，作物を栽培せずに13カ月間インキュベートした場合，Kalamazoo Sandy loam 以外の土壌では置換性および非置換性カリの含量が増加した。Kalamazoo sandy loam では施用カリ量がエーカー当り400ポンド以上になると非置換性カリが減少した。インキュベーションによる置換性および非置換性カリの増加の程度は，初期のカリ含量が低い程，またカリ固定粘土の含量が多い程大であった。

(5) 土壌の湿潤―乾燥処理を反復した結果，供試土壌総てにカリ固定の現象がみられた。この場合にみられたカリ固定の程度は Brookston loam > Landes-Abscota sandy loam > Genesee loam > Kalamazoo sandy loam の順であった。

(6) 供試土壌を反復して凍結―融解処理した場合，Kalamazoo sandy loam と Landes-Abscota sandy loam は少量のカリを放出した。一方 Brookston loam と Genesee loam は少量のカリを固定した。

(7) 土壌カリを $-\triangle K^0$ とAK_e^kで表示する時，両者とも作物の栽培が進むにつれて減少したが，施用カリ量の増加に伴って栽培区（ポット）・インキュベイション区（ポット）の両方において増大した。PBC^k は栽培区ではカリの施用量が増加するに従って減少し，インキュベイション区では土壌間でPBC^k の増減に相違がみられた。PBC^k におよぼす作物栽培の影響は土壌によって差異があった。Kポテンシャル（$-\triangle K^0 \times PBC^k$）は栽培区およびインキュベイション区の両方において施用カリ量が増加するに従って増大する傾向にあったが，栽培回数が進むと減少した。

$-\triangle K^0$ ・AR_e^k ・PBC^k ・Kポテンシャル・置換性カリ・非置換性カリ・全カリ（置換性カリ＋非置換性カリ）などの測定値と作物のカリ吸収量との相関々係を調べた結果は次の通りであった。

(1) Brookston loam においては $-\triangle K^0$ ・AR_e^k および置換性カリなどを測定するとカリの有効度評価に役立つ。

(2) Genesee loam においてはAR_e^k ・置換性カリ・非置換性リ・全カリなどを測定すると良い。

(3) Kalamazoo sandy loam では非置換性カリおよび全カリが有効度評価に役立つ。

(4)　Landes-Abscota sandy loam において土壌カリの有効度評価には $-\triangle K^0$ ・AR_e^k ・置換性カリ・非置換性カリ・全カリなどが測定に値する項目である。

供試土壌の物理的性質（土性）を器械的分析により，また鉱物学的性質を陽イオン置換容量・粘土フラクション中の全カリ・X・線回折などによって調べた結果は次の通りであった。

(1)　供試土壌の粘土含量はそれぞれ Brookston loam 18.5%，Geness loam 11.5%，Kalamazoo sandy loam 13.5%，Landes-Abscota sandy loam 14.8%であった。

(2)　各土壌の陽イオン置換容量（me/100g）は Brookston loam 20.7，Genesee loam 15.8，Kalamazoo sandy loam 7.0，Landes-Abscota sandy loam 13.2であった。

(3)　土壌の各フラクションが陽イオン置換容量に貢献する割合をみると，Brookston loam と Genesee loam では有機物と粘土の他にシルトの貢献が大きかったが，Kalamazoo sandy loamと Landes-Abscota sandy loam ではシルトの貢献度は小さかった。

(4)　供試土壌の粘土フラクション中のバミキュライト含量（%）は Brookston loam 8.3，Genesee loam 10.0，Kalamazoo sandy loam 1.7，Landes-Abscota sandy loam 8.9であった。

(5)　粘土フラクション中のマイカ含量（%）は Brookston loam 27.6，Genesee loam 18.0，Kalamazoo sandy loam 18.0，Landes-Abscota sandy loam 28.8であった。

(6)　Brookston loam 中の主な粘土鉱物はモンモリロナイト，Genesee loam ではカオリナイトおよびバミキュライト—クロライト—モンモリロナイト混層鉱物，Kalamazoo sandy loam ではバミキュライト—クロライト混層鉱物およびカオリナイト，Landes-Abscota sandy loam ではバミキュライト—クロライト混層鉱物であった。

(7)　Kalamazoo sandy loam 以外の供試土壌においては粘土フラクションの陽イオン置換容量は作物栽培によって土壌カリが減少する時に大きくなった。

(8)　エーカー当り1,600ポンドのカリを施用してインキュベイトする時，Brookston loamと Landes-Abscota sandy loam においては粘土フラクションの陽イオン置換容量が減少した。

(9)　作物栽培による土壌カリの減少が起る時，粘土フラクション中のバミキュライト含量が増加した。この傾向は Landes-Abscota sandy loam において最も顕著であった。

(10)　供試土壌にエーカー当り1,600ポンドのカリを施用してインキュベイトする時，Genesee loam とLandes-Abscota sandy loam においては粘土フラクションのマイカ含量（%）が増加した。Landes-Abscota sandy loam においてはバミキュライト—クロライト混層鉱物からマイカへの変化が顕著にみられた。

(11)　カリ施用量が多くても（1,600ポンド／A），作物を5回栽培した土壌では陽イオン置換容量と粘土鉱物の変化は殆んど認められなかった。

Appendix A. DESCRIPTIONS OF THE SOILS

1. Brookston Loam

The poorly drained Brookston series developed from loam or silt loam parent materials (95). The soil profile description of Brookston loam at the collection site follows:

Horizons	Depth	Description
Ap	0 – 9"	Loam; very dark grayish brown (10YR 3/2); weak, coarse, granular structure; friable; pH 7.0; abrupt smooth boundary.
B_{1g}	9 – 21"	Clay loam; gray (5Y 5/1); moderate; medium, subangular blocky structure; firm; pH 7.5; clear smooth boundary.
B_{2g}	21 – 34"	Silt loam; yellowish brown (10YR 5/6) to brown (7.5YR5/3) with dark brown (7.5YR 3/2) mottles; weak, coarse, subangular blocky structure; friable; pH 7.8; abrupt wavy boundary.
C_g	34" +	Silt; mottles of dark grayish brown (10YR 4/2) and strong brown (7.5YR 5/6); weak, thin, platy structure; friable; calcareous.

2. Genesee Loam

The well-drained Genesee series developed from loam to silt stratified alluvial material (78). These soils occur on level flood plains along creeks and rivers. The soil profile description of Genesee loam at the collection site follows:

Horizons	Depth	Description
Ap	0 – 8"	Loam; dark brown (7.5YR 3/2); weak, fine to medium granular structure; friable; pH 6.3; irregular clear boundary.
B_2	8 – 26"	Loam; dark reddish brown (5YR 3/4); moderate, medium subangular blocky structure; friable; pH 7.0; abrupt wavy boundary.
$\mathrm{II}C_1$	26 – 45"	Sandy loam; yellowish brown (10YR 5/6); weak, medium subangular blocky structure; friable; pH 7.5; clear wavy boundary.
$\mathrm{III}C_2$	45" +	Gravelly sand; yellowish brown (10YR 5/6); single grained; loose; calcareous.

3. Kalamazoo Sandy Loam

The well-drained Kalamazoo series developed on level to strongly sloping areas on valley trains, outwash plains, moraines, kames, and eskers (40). The soil profile description of Kalamazoo sandy loam at the collection site follows;

Horizons	Depth	Description
Ap	0 – 8"	Sandy loam; dark reddish brown (5YR 3/2); weak, fine granular structure; very friable; pH 7.1; abrupt smooth boundary.

B_{21t}	8 – 15"	Clay loam; dark reddish brown (5YR 3/4); weak, fine, subangular blocky structure; friable; pH 6.7; gradual wavy boundary.
B_{22t}	15 – 20"	Gravelly loam and clay loam; dark reddish brown (5YR 3/4); weak, fine subangular blocky structure; friable; pH 5.5; clear irregular boundary.
B_{23}	20 – 25"	Loamy sand; dark brown (7.5YR 4/4); weak, fine, subangular blocky structure; very friable; pH 5.4; clear wavy boundary.
B_3	25 – 50"	Loamy sand to sand; dark brown (7.5YR 4/4); single grain sturcture; loose. pH 5.8; gradual wavy boundary.
IIC	50" +	Sand; very pale brown (10YR 7/3); single grain structure; loose; calcareous.

4. Landes-Abscota Sandy Loam

The well-drained soil collected from the Sodus Experimental Farm, Berrien County had charateristics of both the Landes and Abscota series. These series developed on flood plains along creeks and rivers. The parent materials of the Landes soils are stratified loamy fine sand to fine sandy loams while the Abscota soils are stratified sand to loamy sand (40, 78). The soil profile description at the collection site follows:

Horizons	Depth	Description
Ap	0 – 8"	Sandy loam; very dark gray brown (10YR 3/2); weak, fine granular structure; very friable; pH 7.0; abrupt smooth boundary.
A_{12}	8 – 12"	Sandy loam; very dark gray brown to very dark brown (10YR 3/2 – 10YR 2/2); weak, fine granular structure; very friable; pH 7.5; clear wavy boundary.
A_3	12 – 14"	Loamy sand; dark reddish brown (5YR 3/3); weak, fine granular structure; very friable; pH 7.8; clear wavy boundary
B_{21}	14 – 20"	Loam sand; dark reddish brow (5YR 3/4); weak, very fine subangular blocky structure; very friable; pH 8.0; clear wavy boundary.
B_{22}	20 – 32"	Sand; strong brown (7.5YR 5/6); single grain structure; loose; pH 8.0; abrupt wavy boundary.
IIC	32 – 42"	Fine sand and silt; light brownish gray (10YR 6/2); stratified; friable; calcareous; abrupt wavy bounbary.
IIIC	42" +	Sand and gravel; splotches of strong brown (7.5YR 5/8) in light gray (10YR 7/2); single grain structure; loose; calcareous.

Appendix B. PHOTOGRAPHS OF THE GROWTH RESPONSE OF WHEAT, SORGHUM, AND TOMATOES TO POTASSIUM ON BROOKSTON LOAM

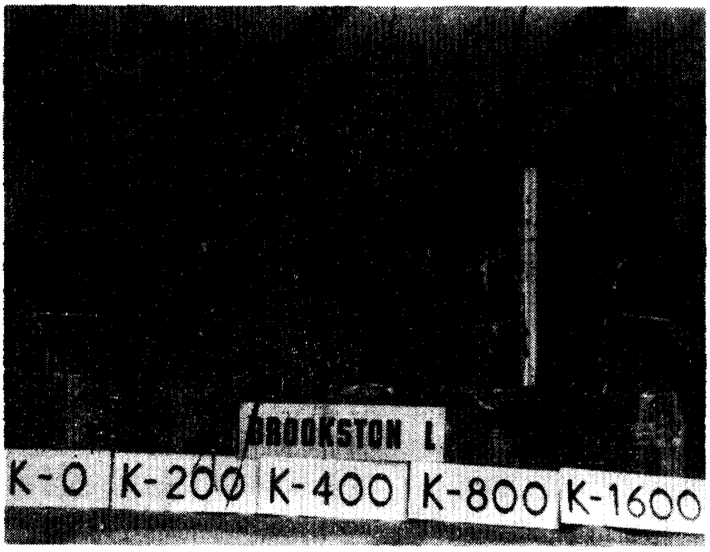

Fig. A1. The 2nd crop (wheat) at 40 days of growth on Brookston loam. Potassium treatments had no effect on plant yields (Tables 3 and 7)

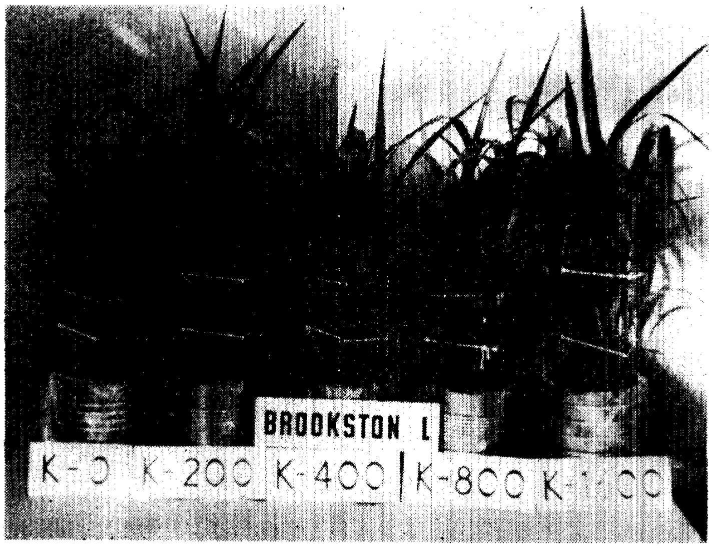

Fig. A2. The 5th crop (sorghum) at 70 days of growth on Brookston loam. Potassium treatments had no effect on plant yields (Tables 3 and 7).

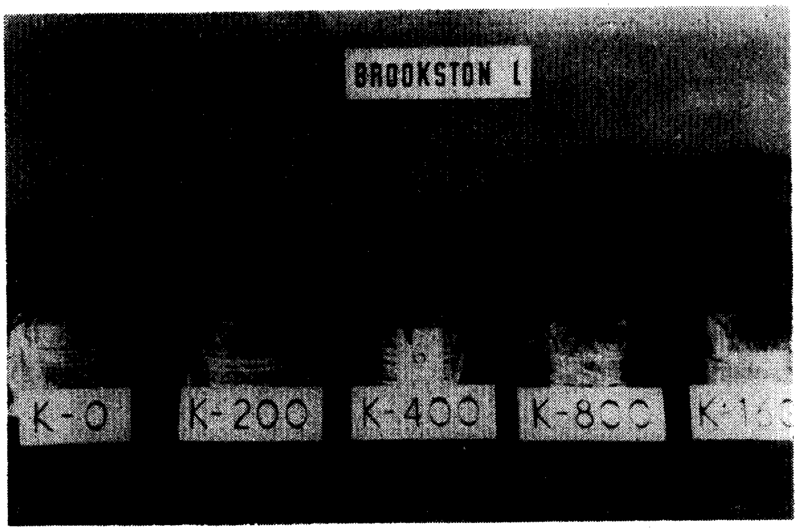

Fig. A3. The 6th crop (tomato) at 40 days of growth on Brookston loam. Potassium treatments significantly affected plant yields (Tables 3 and 7).

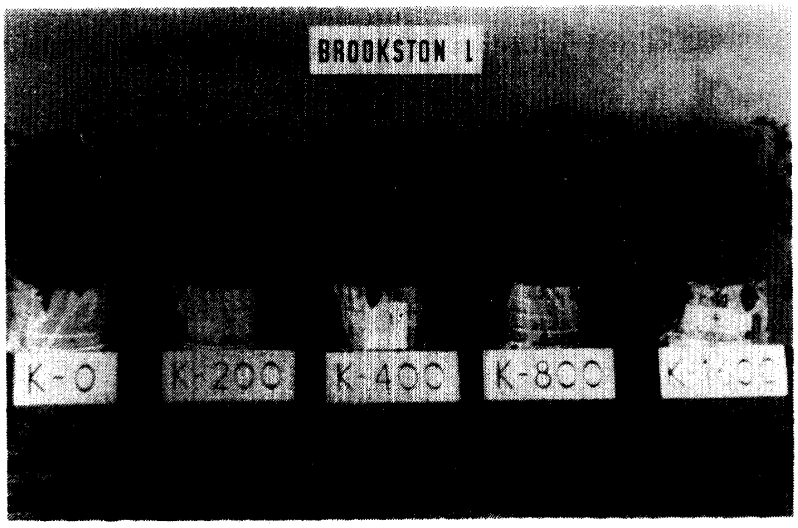

Fig. A4. Tomato plants at 40 days of growth on the unctopped soil of Brookston loam. Plant yields were not affected by potassium treatments (Table 8).

Appendix C. PHOTOGRAPHS OF THE GROWTH RESPONSE OF WHEAT, SORGHUM, AND TOMATOES TO POTASSIUM ON GENESEE LOAM

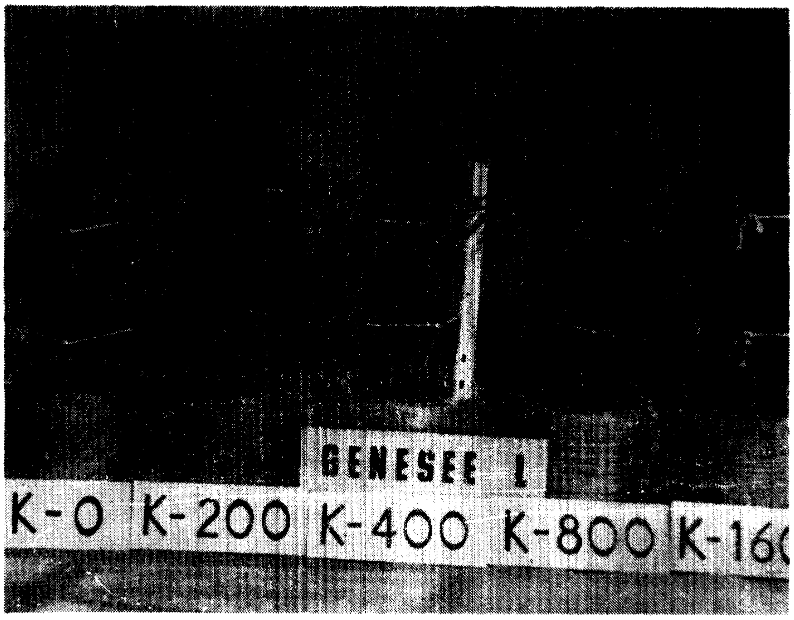

Fig. A5. The 2nd crop (wheat) at 40 days of growth on Genesee loam. Potassium treatments had no effect on plant yields (Tables 4 and 7).

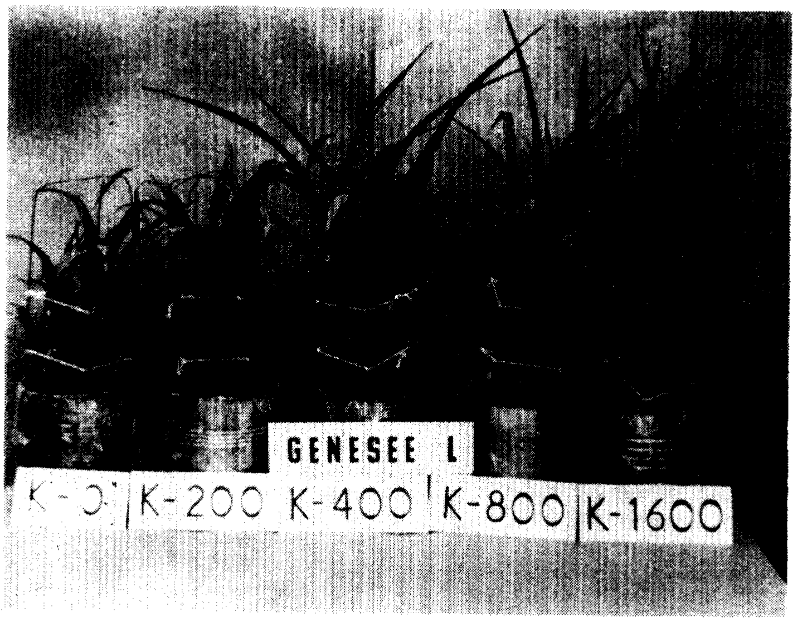

Fig. A6. The 5th crop (sorghum) at 70 days of growth on Genesee loam. Potassium treatments significatly affected plant yields (Tables 4 and 7).

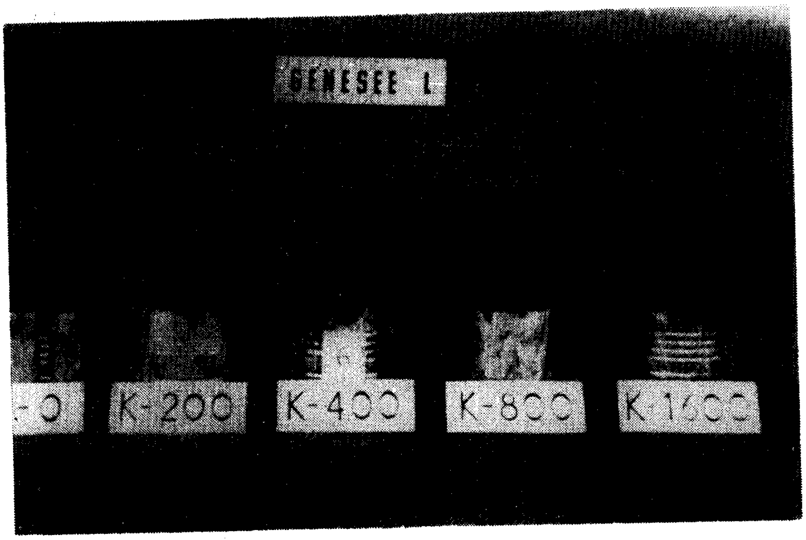

Fig. A7. The 6th crop (tomato) at 40 days of growth on Genesee loam. Potassium treatments significontly affected plant yields (Tafles 4 and 7).

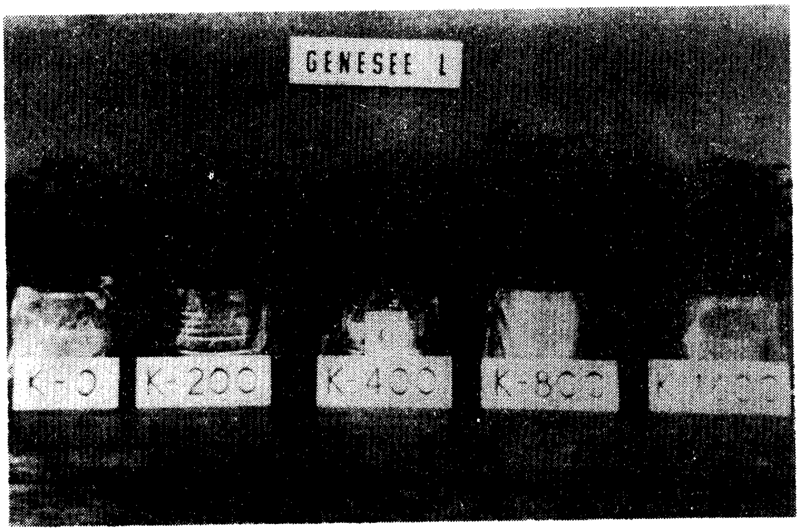

Fig. A8. Tomato plants at 40 days of growth on the uncropped soil of Genesee loam. Potassium treatments had no effect on plant yields (Table 8).

Appendix D. PHOTOGRAPHS OF THE GROWTH RESPONSE OF WHEAT, SORGHUM, AND TOMATOES TO POTASSIUM ON KALAMAZOO SANDY LOAM

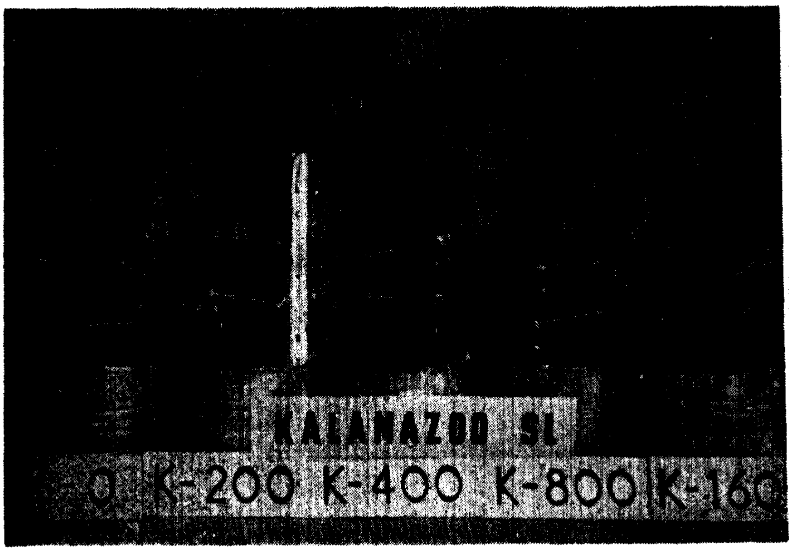

Fig. A9. The 2nd crop (wheat) at 40 days of growth on Kalamazoo sandy loam. The plants were unfavorably affected by the potassium treatments because soil potassium was originally high (Tables 1, 5 and 7).

Fig. A10. The 5th crop (sorghum) at 70 days of growth on Kalamazoo sandy loam. Potassium treatment significantly affected plant yields (Tables 5 and 7).

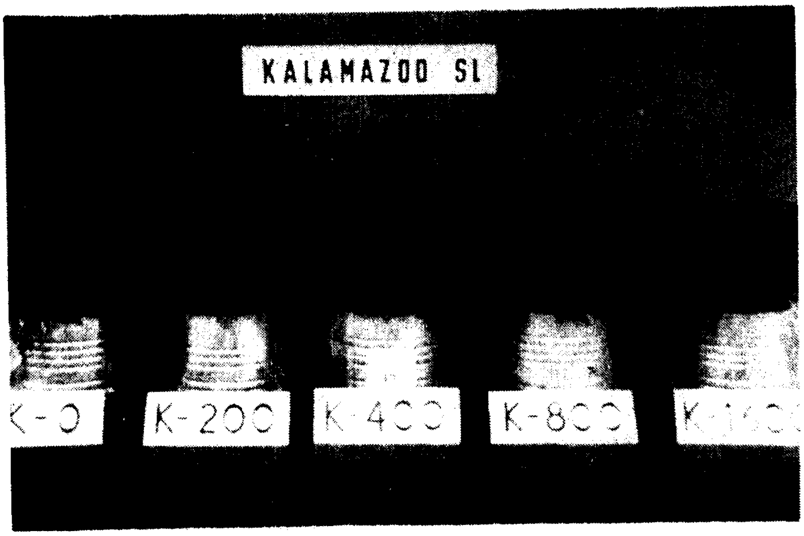

Fig. A11. The 6th crop (tomato) at 40 days of growth on Kalamazoo sandy loam. Potassium treatments significantly affected plant yields (Tables 5 and 7).

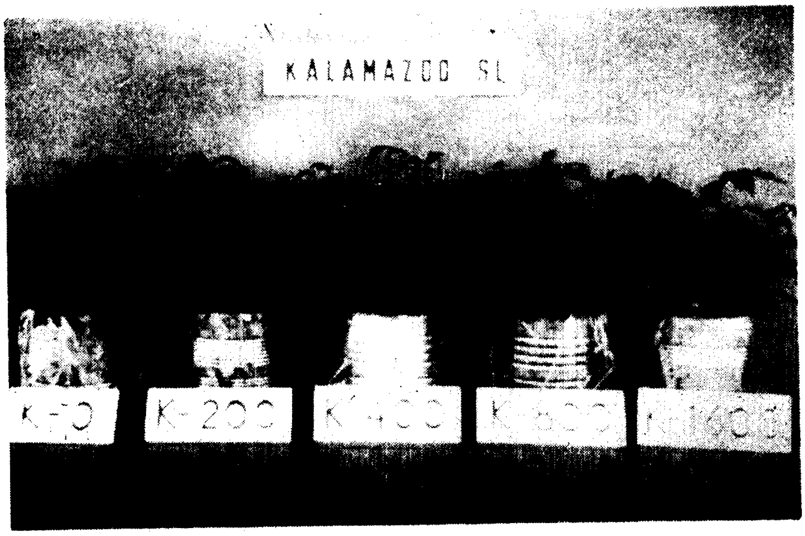

Fig. A12. Tomato plants at 40 days of growth on the uncropped soil of Kalamazoo sandy loam. Potassium treatment had no effect on plant yields (Table 8).

Appendix E. PHOTOGRAPHS OF THE GROWTH RESPONSE OF WHEAT, SORGHUM, AND TOMATOES TO POTASSIUM ON LANDES-ABSCOTA SANDY LOAM

Fig. A13. The 2nd crop (wheat) at 40 days of growth on Landes-Abscota sandy loam. Potassium treatments had no effect on plant yields (Tables 6 and 7).

Fig. A14. The 5th crop (sorghum) at 70 days of growth on Landes-Abscota sandy loam. Potassium treatments significantly affected plant yields (Tables 6 and 7).

Fig. A15. The 6th crop (tomato) at 40 days of growth on Landes-Abscota sandy loam. Potassium treatments significantly affected plant yields (Tables 6 and 7).

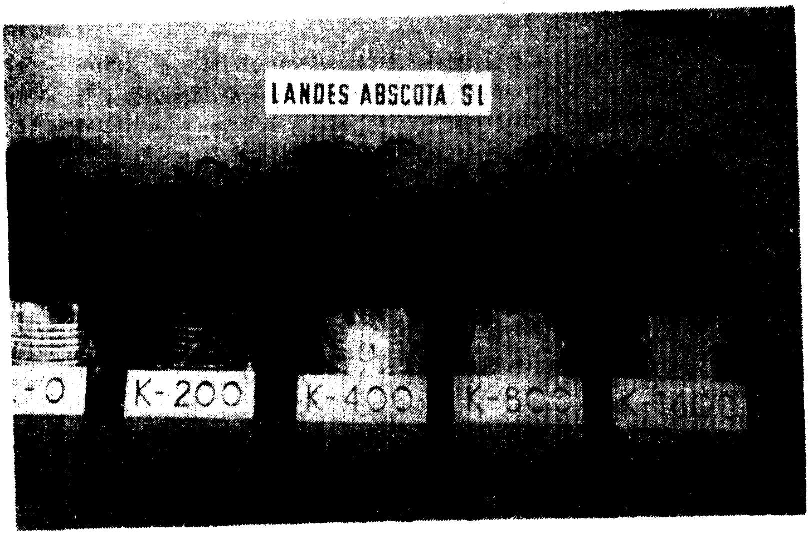

Fig. A16. Tomato plants at 40 days of growth on the uncropped soil of Landes-Abscota sandy loam. Potassium treatments had no effect on plant yields (Table 8).

Appendix F. RELATIONSHIPS OF POTASSIUM ACTIVITY RATIO (AR^K) TO POTASSIUM ABSORPTION OR RELEASE (ΔKe) ON THE UNCROPPED SOILS

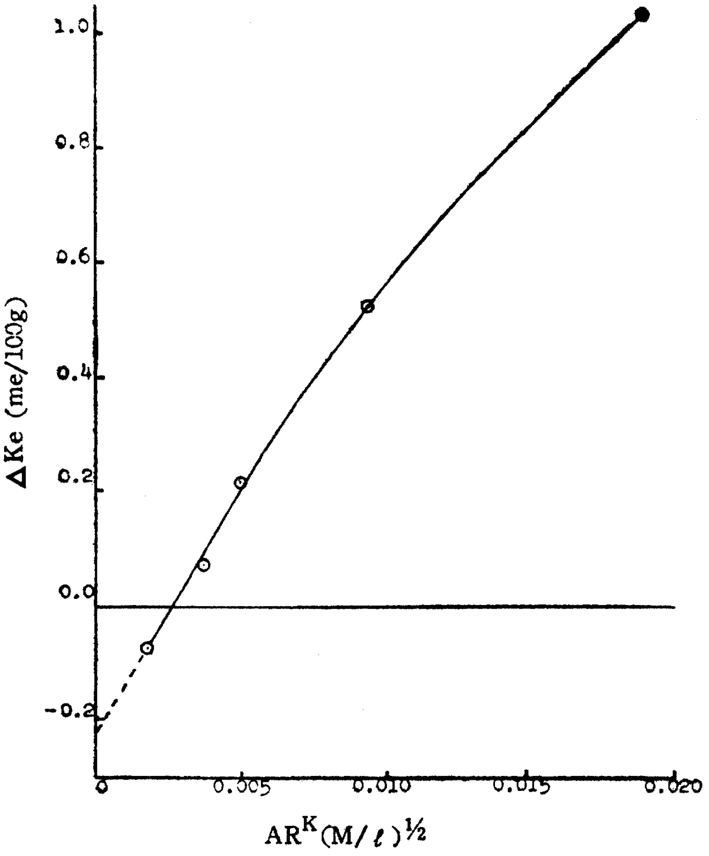

Fig. A17. **Relationship of potassium activity ratio (AR^k) to potassium adsorption or release (ΔKe) on Brookston loam**

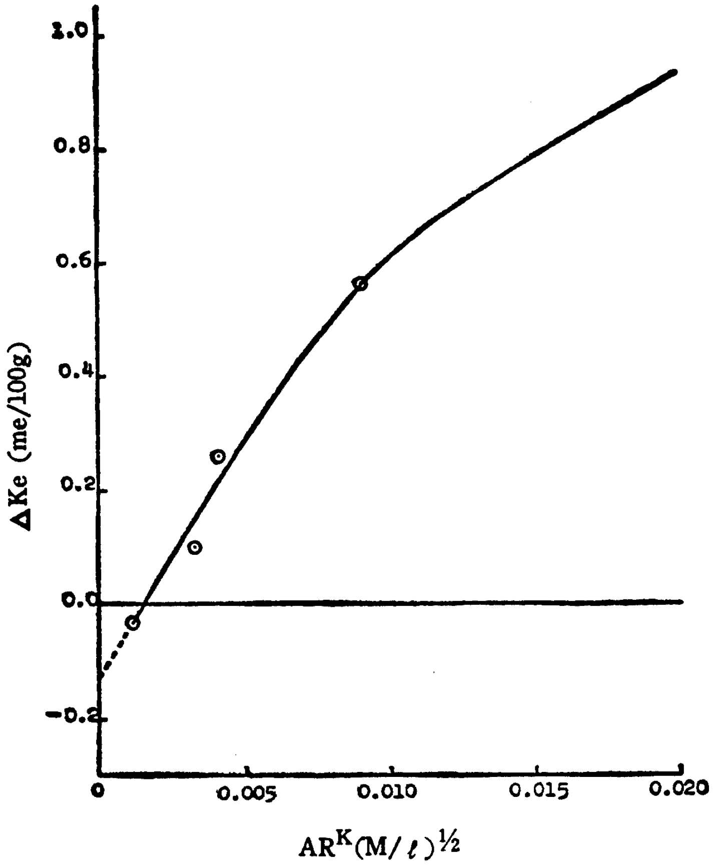

Fig. A18. Relationship of potassium activity ratio (AR^K) to potassium adsorption or release (ΔKe) on Genesee loam

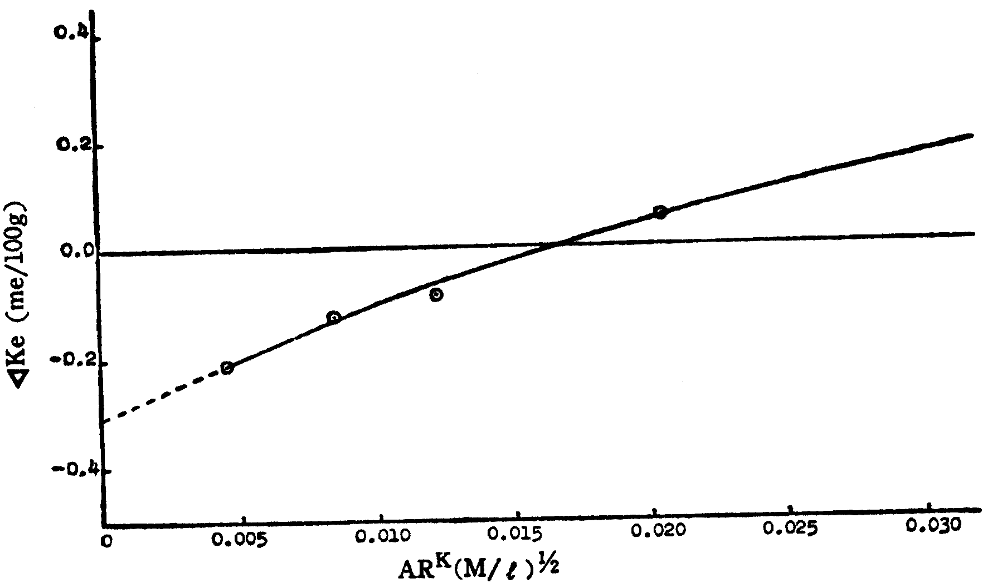

Fig. A19. Relationship of potassium activity ratio (AR^K) to potassium adsorption or release (ΔKe) on Kalamazoo sandy loam

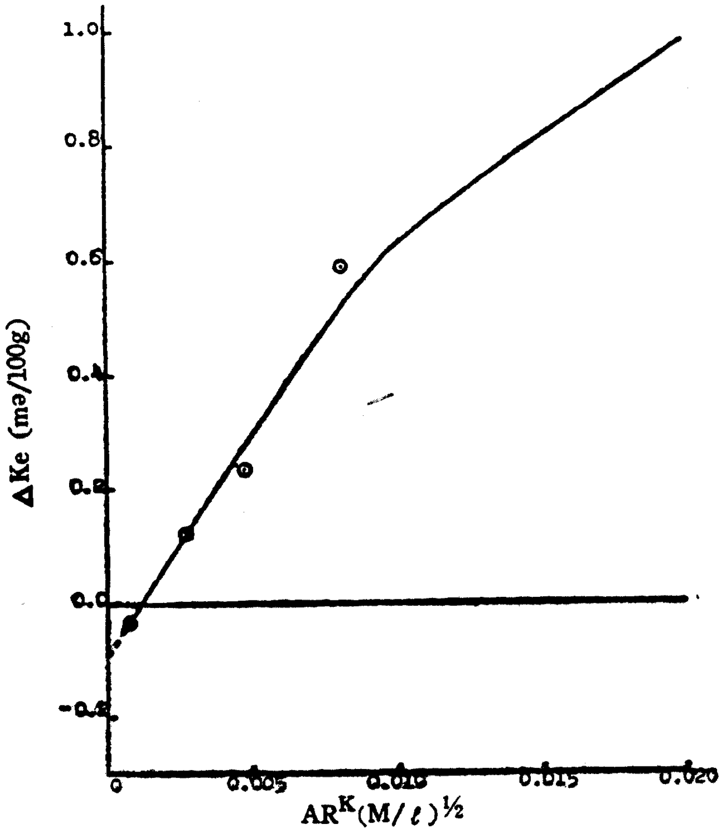

Fig. A20. Relationship of potassium activity ratio (AR^K) to potassium adsorption or release (ΔKe) on Landes-Abscota sandy loam

Appendix G. X-RAY DIFFRACTION PATTERNS OF THE CLAY FRACTION OF BROOKSTON LOAM

Legend:
A: Mg saturated, glycerol-solvated, air-dried sample.
B: K saturated, air-dried sample.
C: K saturated, heated (300° C) sample.
D: K saturated, heated (550° C) sample.

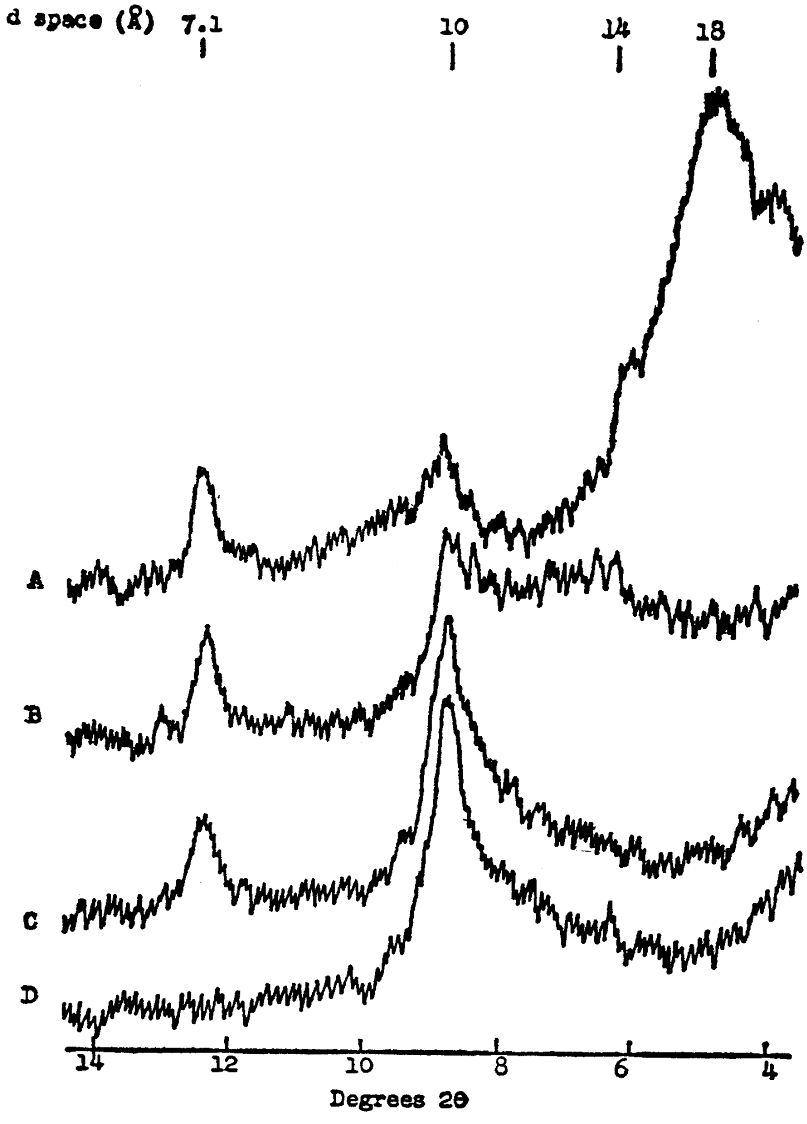

Fig. A21. X-ray diffraction pattern of the clay fraction of Brookston loam before cropping

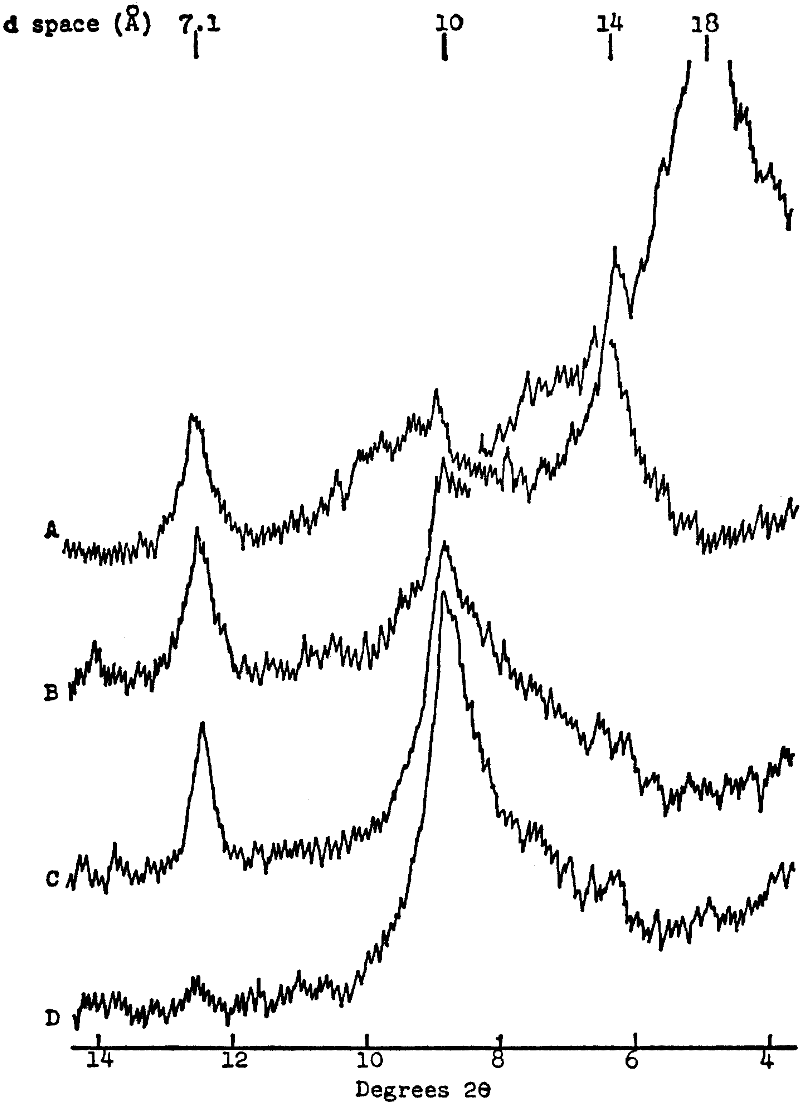

Fig. A22. X-ray diffraction pattern of the clay fraction of Brookston loam after the 5th crop on the 0 potassium treatment

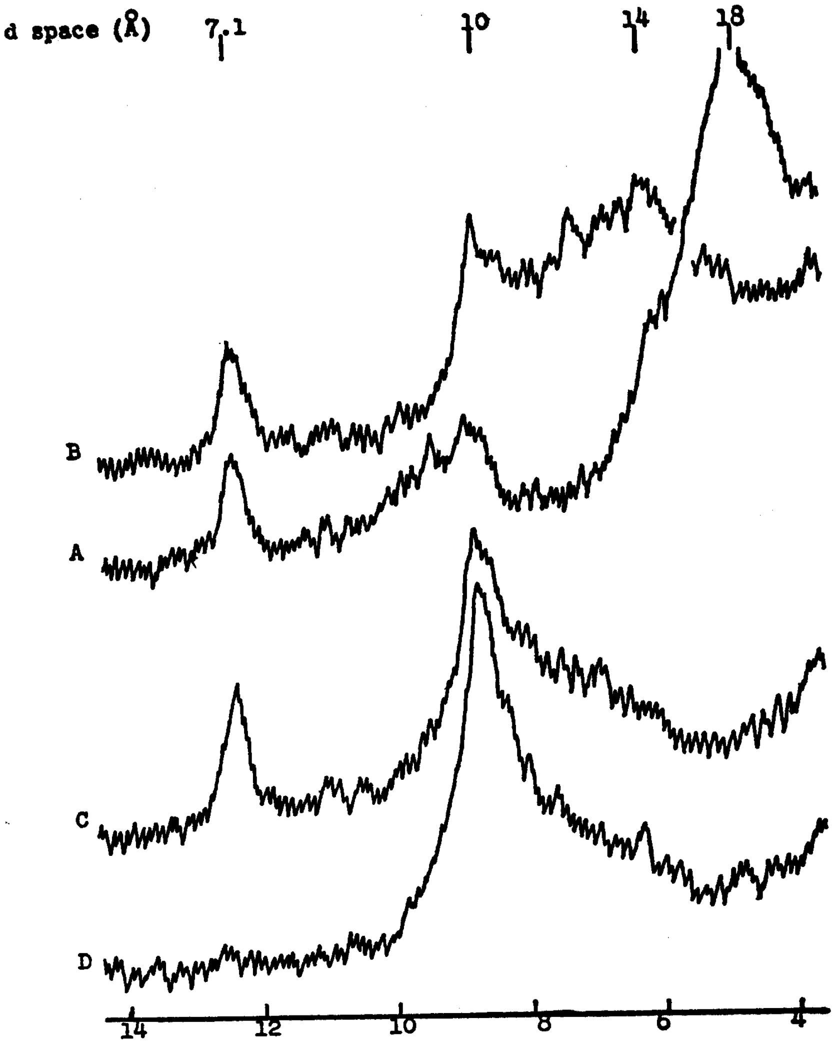

Fig. A23. X-ray diffraction pattern of the clay fraction of Brookston loam after the 5th crop on the 1,600 pound per acre potassium treatment

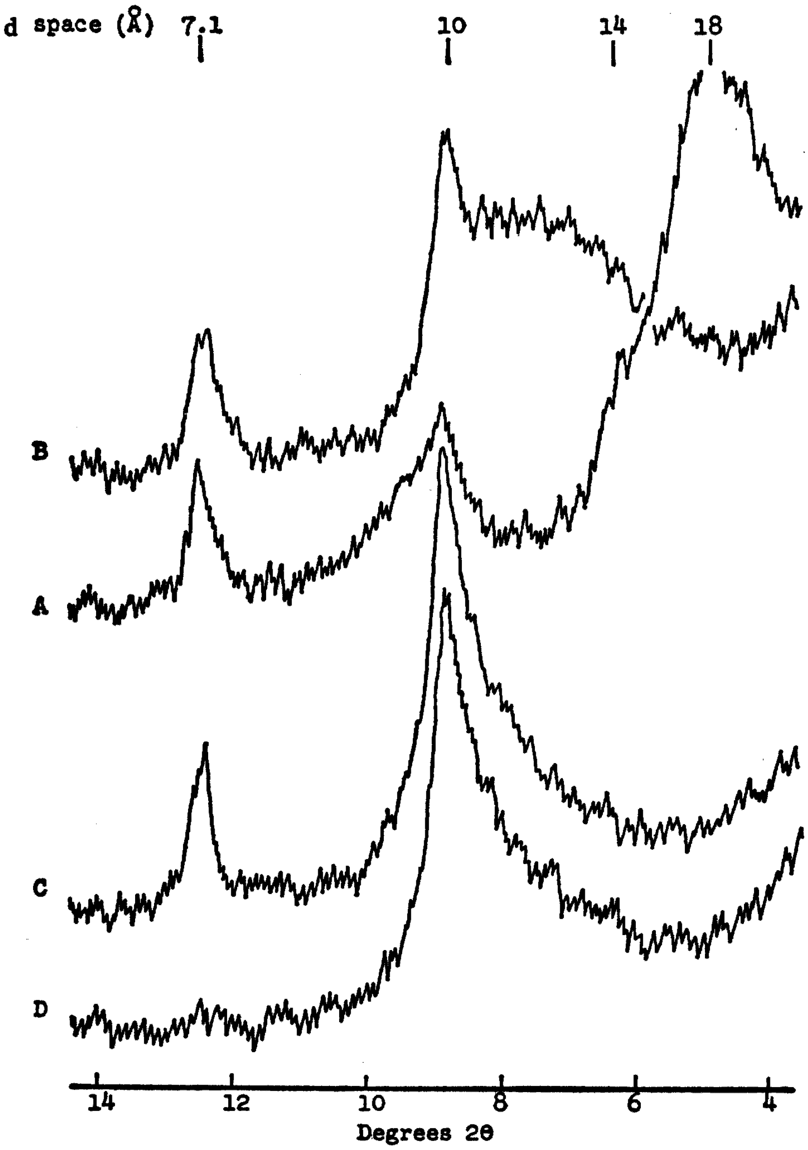

Fig. A24. X-ray diffraction pattern of the clay fraction of Brookston loam after a 18-month incubation period with 1,600 pounds of potassium per acre

Appendix H. X-RAY DIFFRACTION PATTERNS OF THE CLAY FRACTION OF GENESEE LOAM

Legend:

A: Mg saturated, glycerol-solvated, air-dried sample.

B: K saturated, air-dried sample.

C: K saturated, heated (300° C) sample.

D: K saturated, heated (550° C) sample.

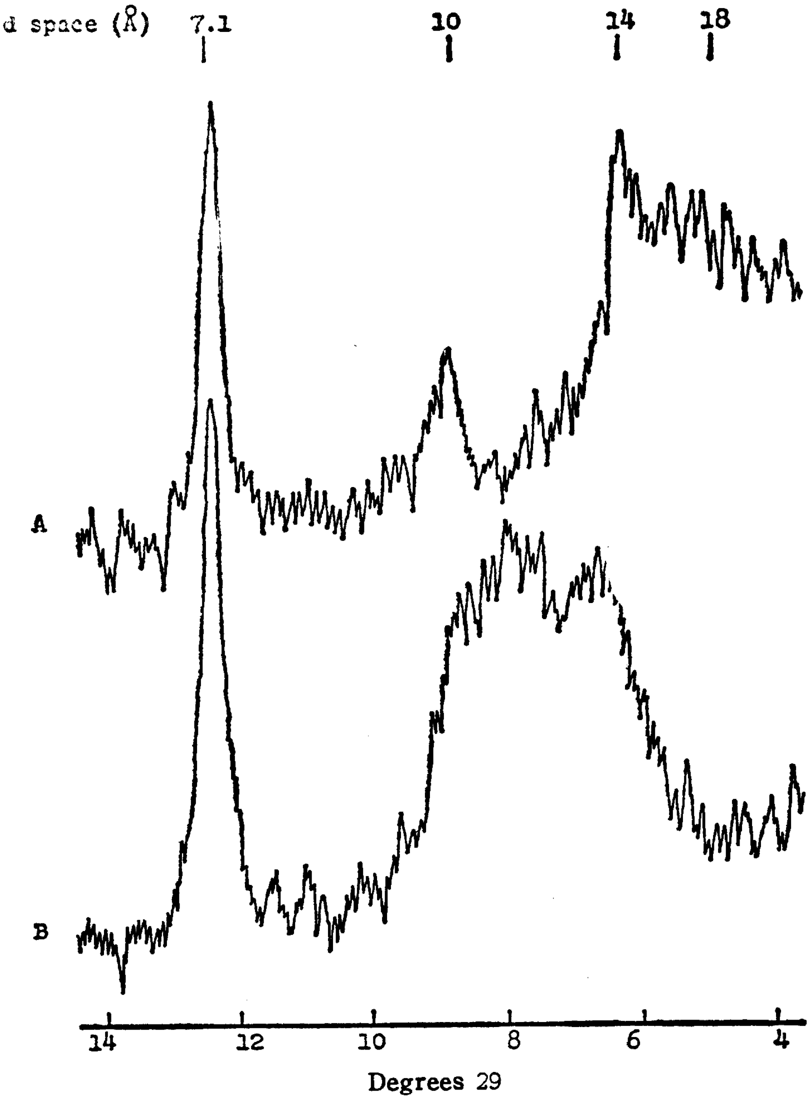

Fig. A25. **X-ray diffraction pattern of the clay fraction of Genesee loam before cropping**

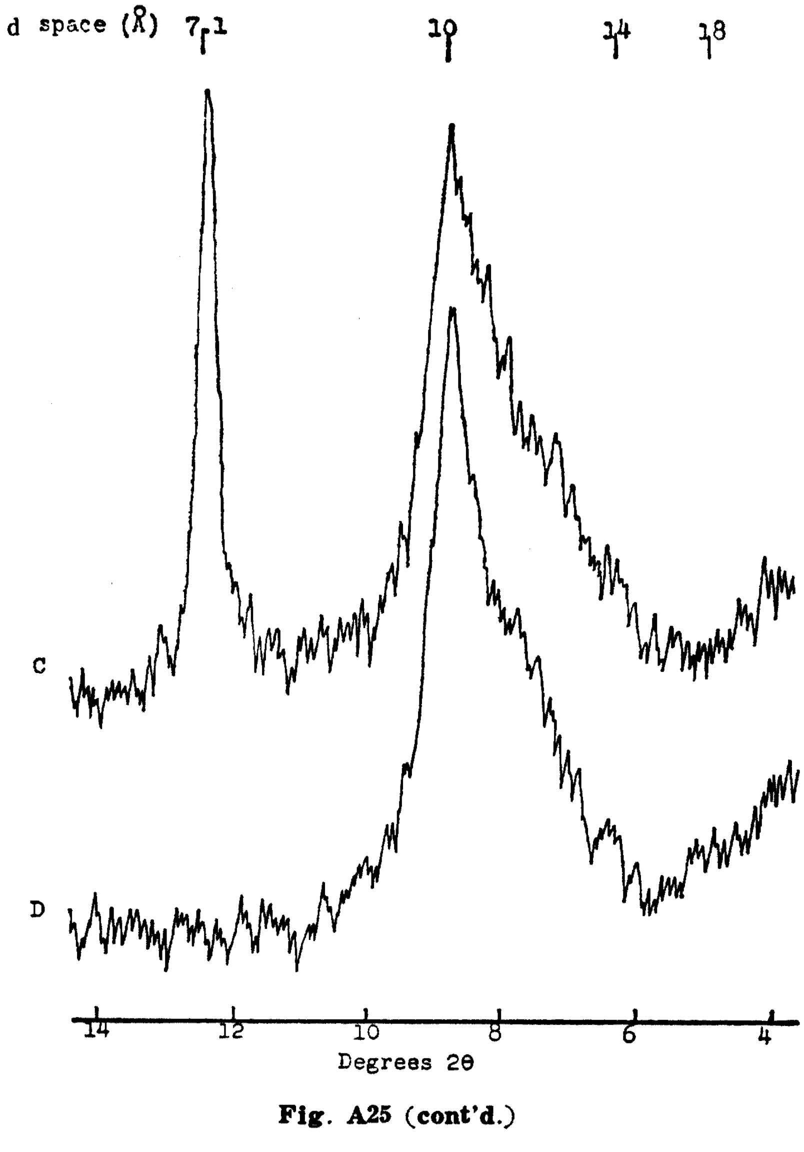

Fig. A25 (cont'd.)

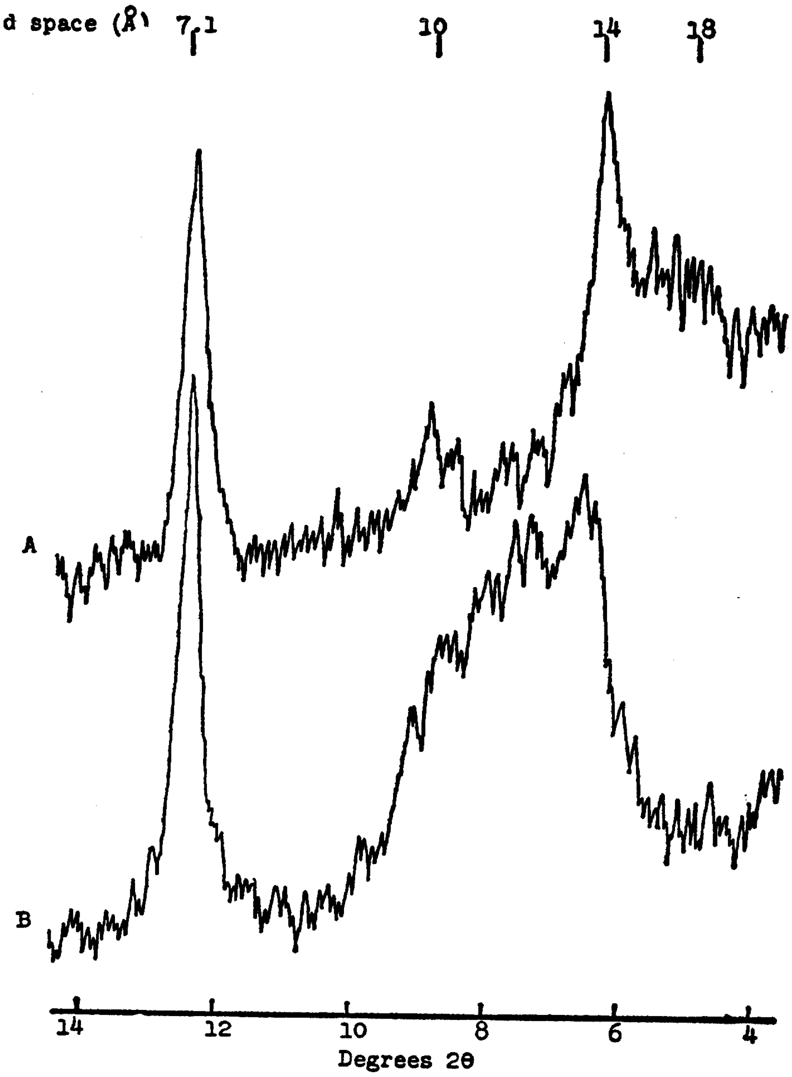

Fig. A26. X-ray diffraction pattern of the clay fraction of Genesee loam after the 5th crop on the 0 potassium treatment

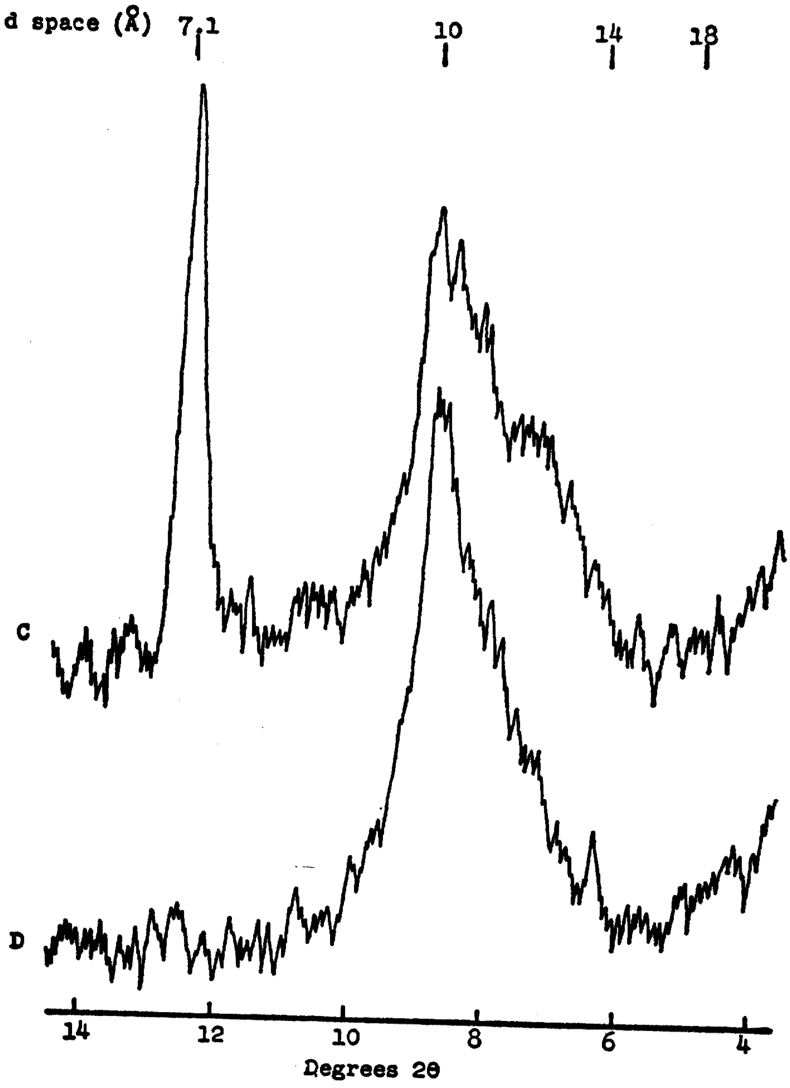

Fig. A26 (cont'd.)

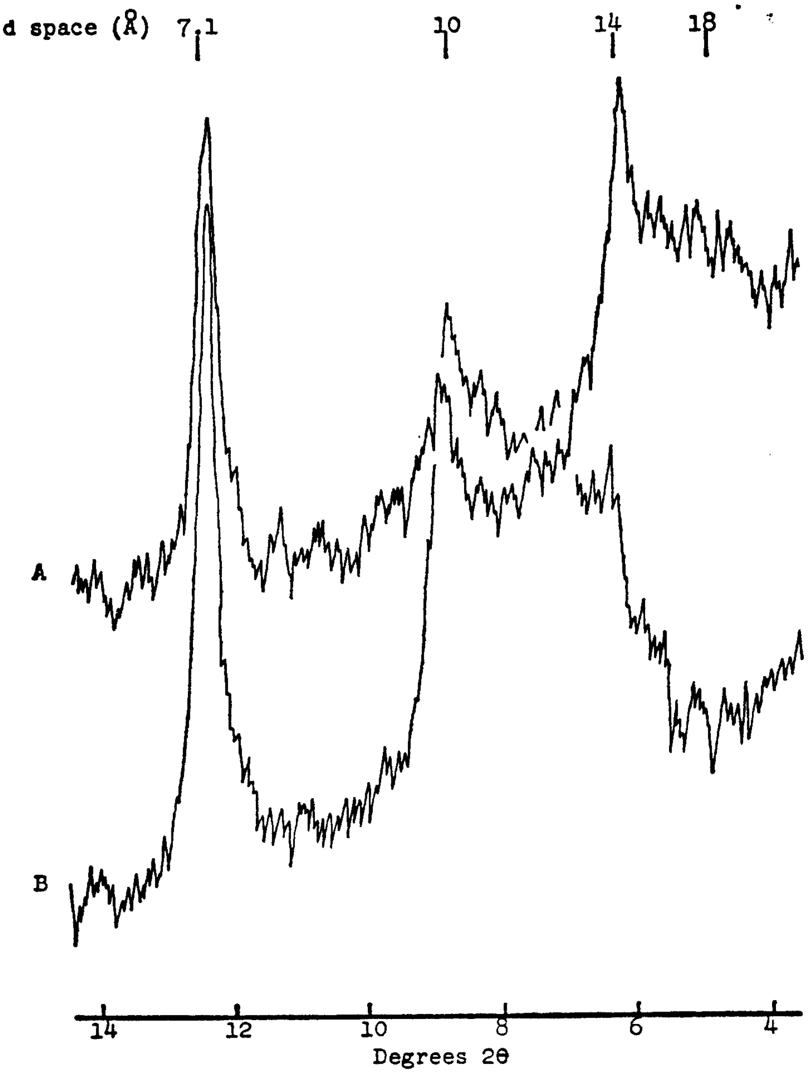

Fig. A27. X-ray diffraction pattern of the clay fraction of Genesee loam after the 5th crop on the 1,600 pound per acre potassium treatment

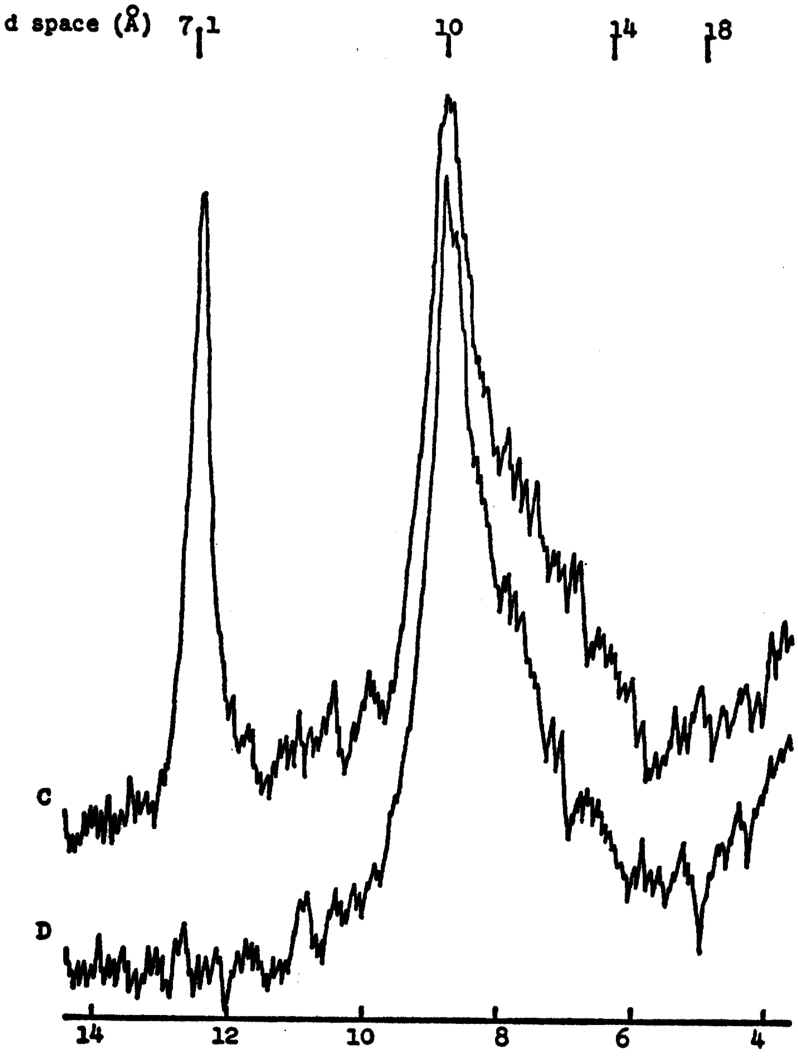

Fig. A27 (cont'd.)

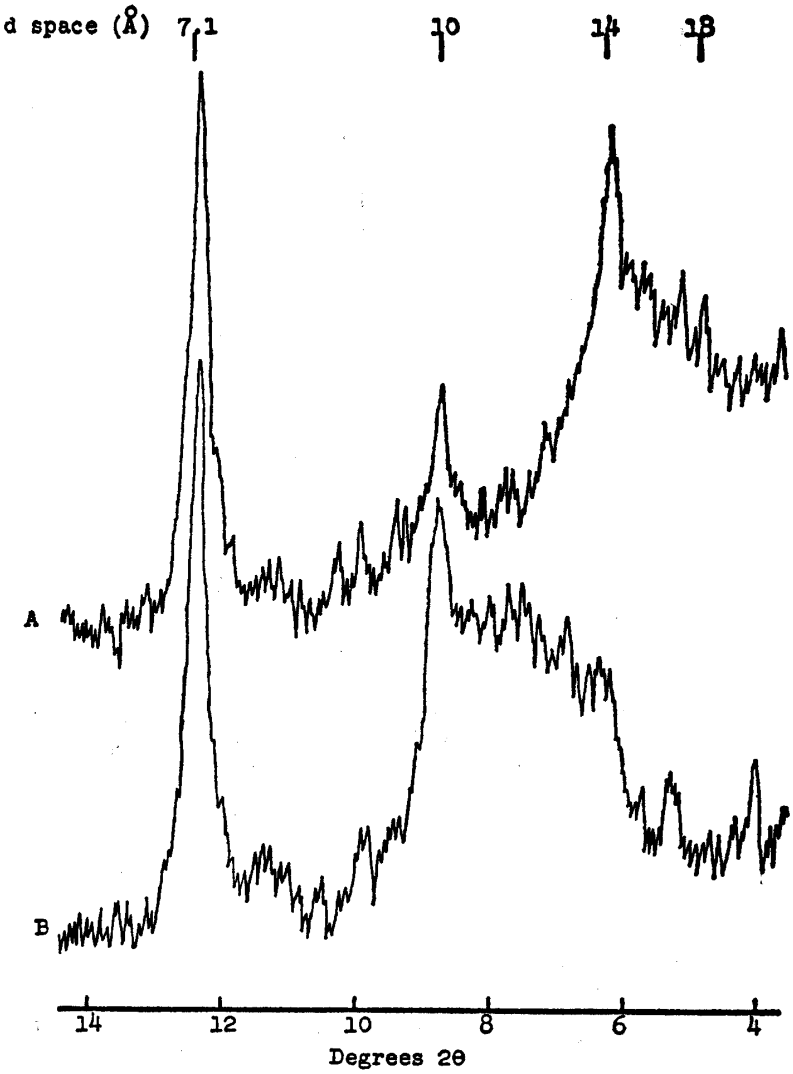

Fig. A28. X-ray diffraction pattern of the clay fraction of Genesee loam after a 13-month incubation period with 1,600 pounds of potassium per acre

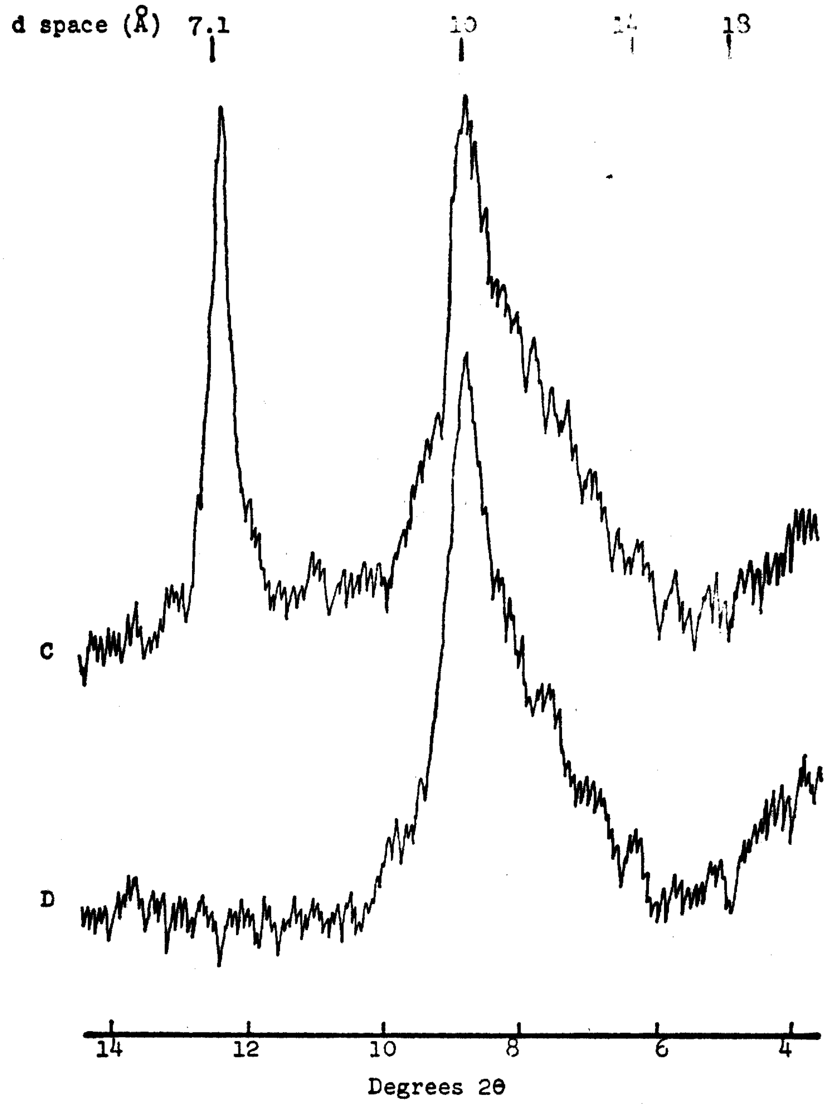

Fig. A28 (cont'd.)

Appendix I. X-RAY DIFFRACTION PATTERNS OF THE CLAY FRACTION OF KALAMAZOO SANDY LOAM

Legend:

A: Mg saturated, glycerol-solvated, air-dried sample.
B: K saturated, air-dried sample.
C: K saturated, heated, (300° C) sample.
D: K saturated, heated (550° C) sample

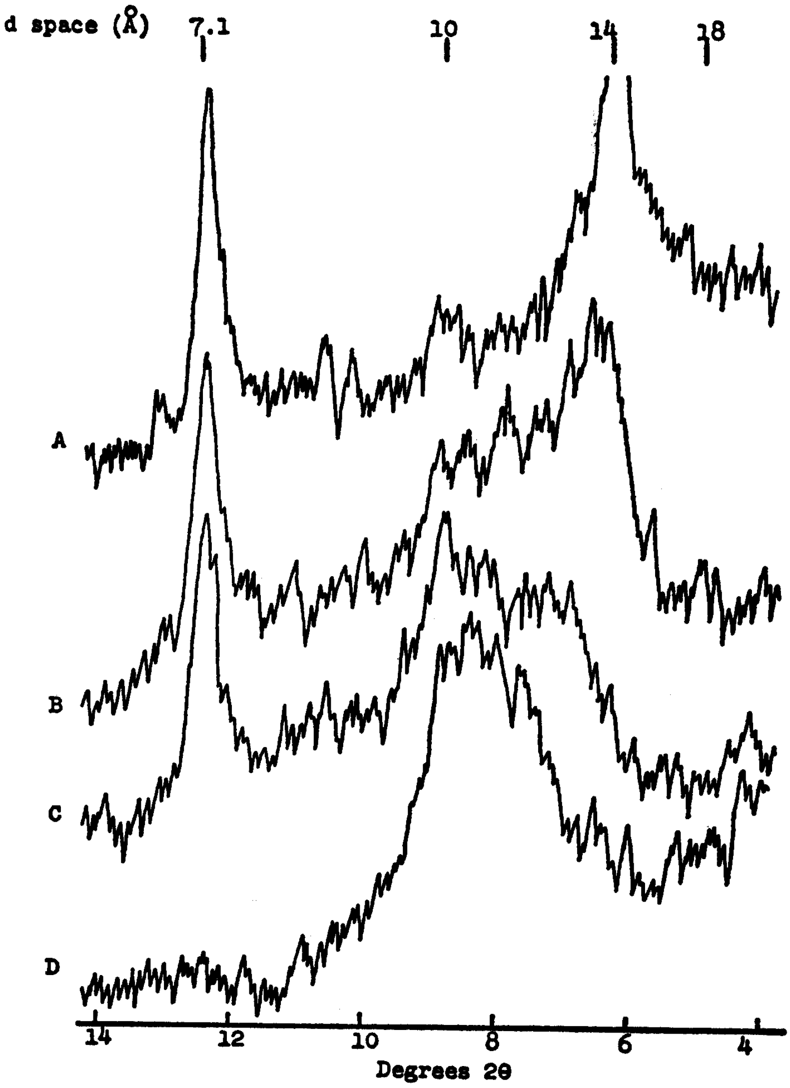

Fig. A29. X-ray diffraction pattern of the clay fraction of Kalamazoo sandy loam before cropping

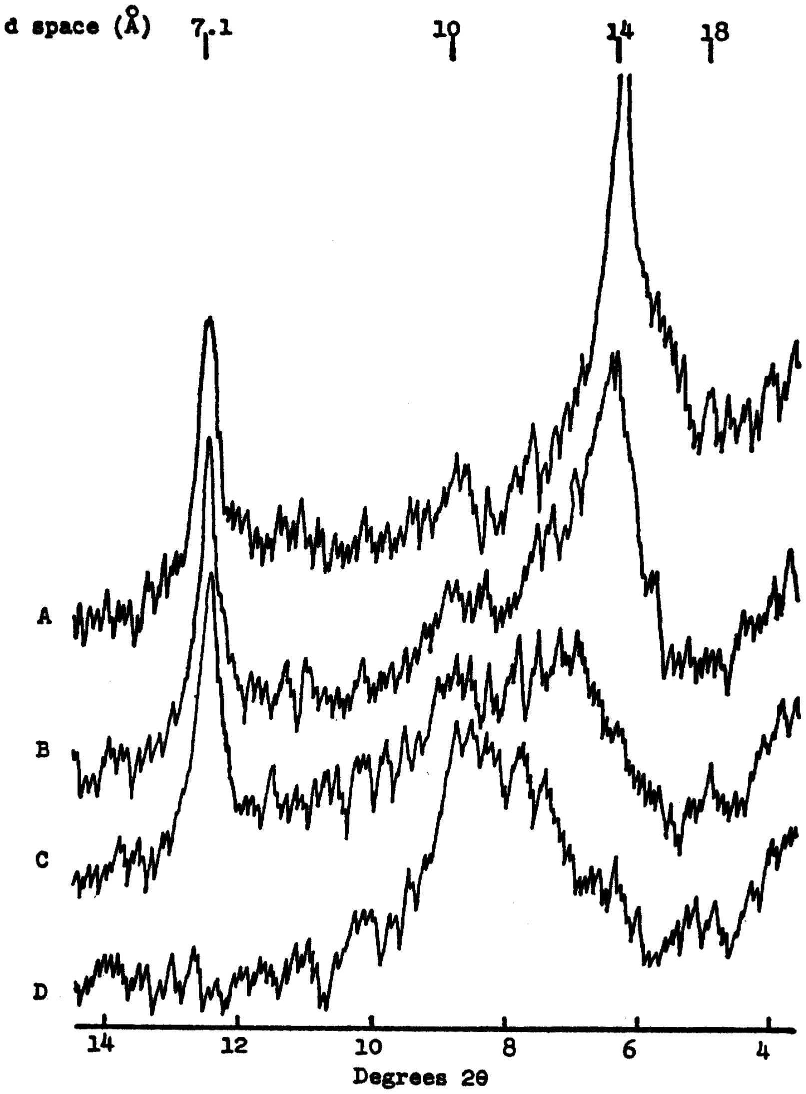

Fig. A30. X-ray diffraction pattern of the clay fraction of Kalamazoo sandy loam after the 5th crop on the 0 potassium treatment

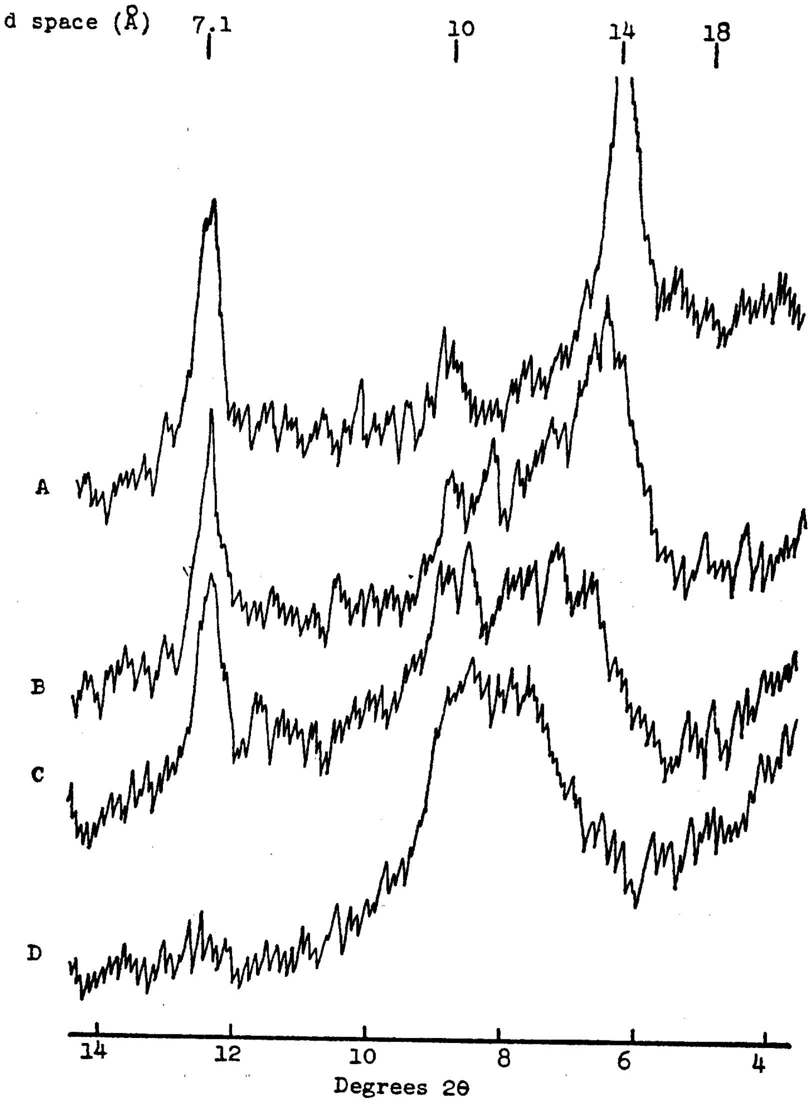

Fig. A31. X-ray diffracton pattern of the clay fraction of Kalamazoo sandy loam after the 5th crop on the 1,600 pound per acre potassium treatment

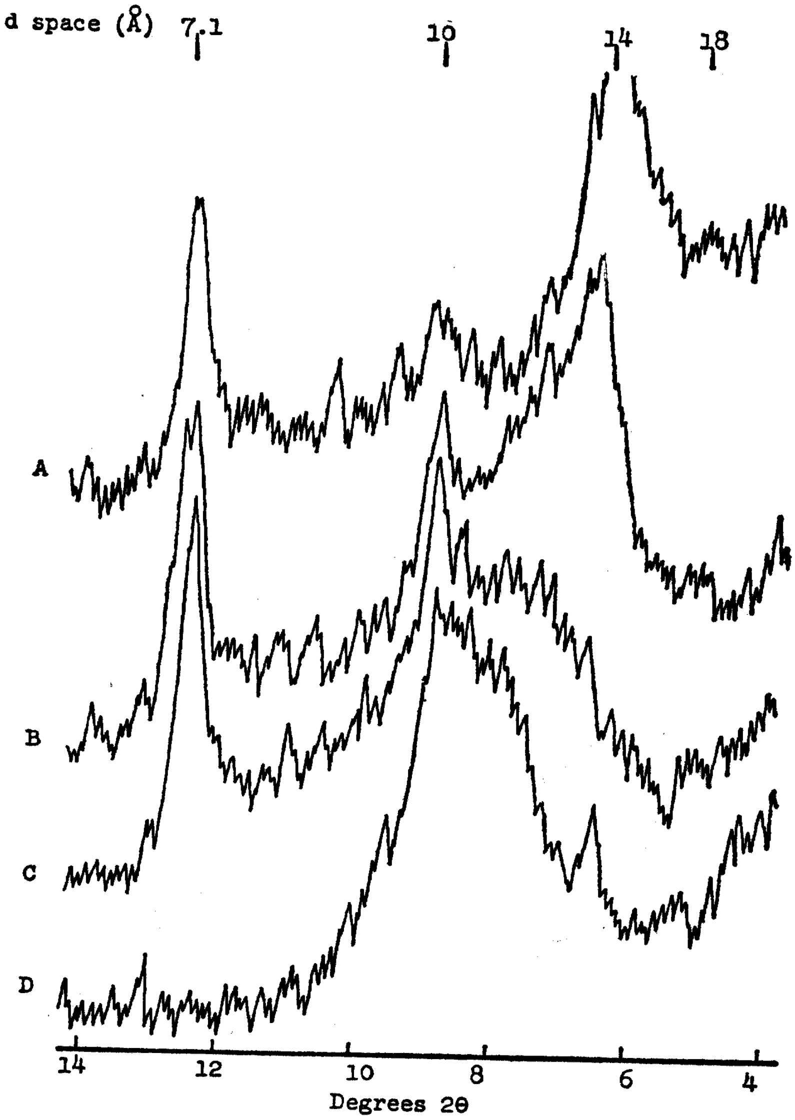

Fig. A32. X-ray diffraction pattern of the clay fraction of Kalamazoo sandy loam after a 13-month incudation period with 1,600 pounds of potassium per acre

Appendix J. X-RAY DIFFRATION PATTERNS OF THE CLAY FRACTION OF LANDES-ABSCOTA SANDY LOAM

Legend:

A: Mg saturated, glycerol-solvated, air-dried sample.
B: K saturated, air-dried sample.
C: K saturated, heated (300° C) sample.
D: K saturated, heated (550° C) sample.

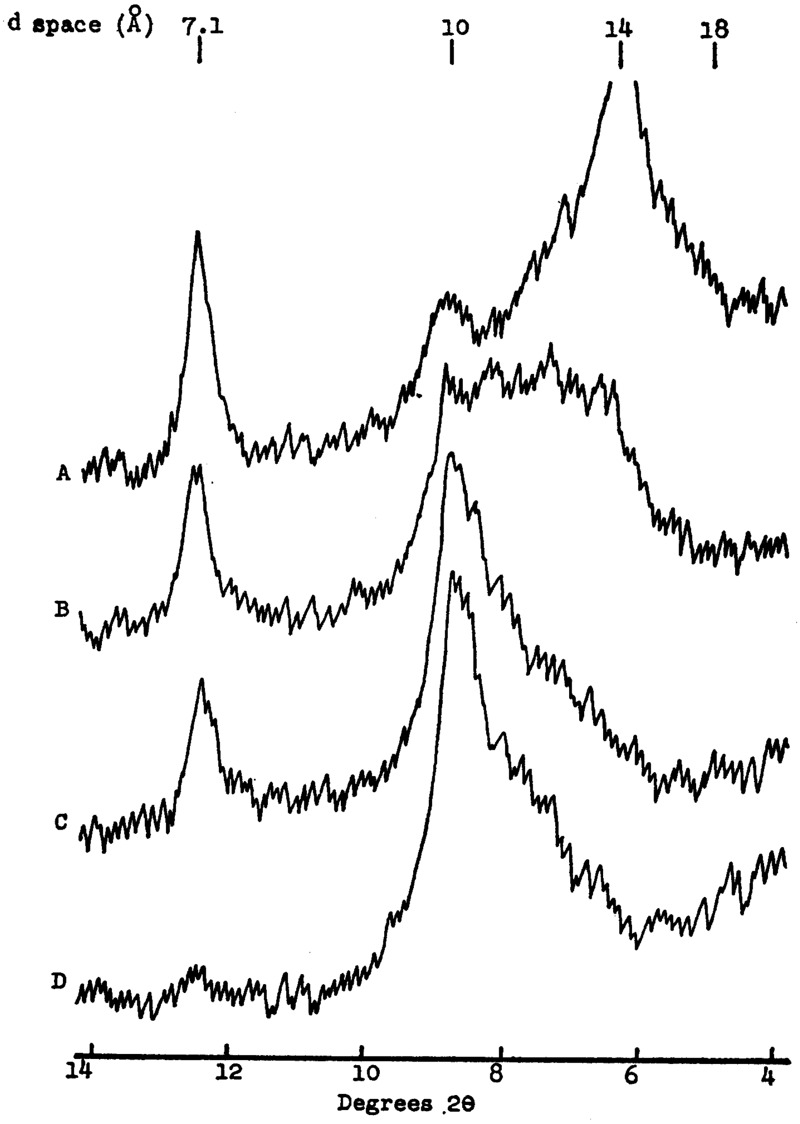

Fig. A33. X-ray diffraction pattern of the clay fraction of Landes-Abscota sandy loam before cropping

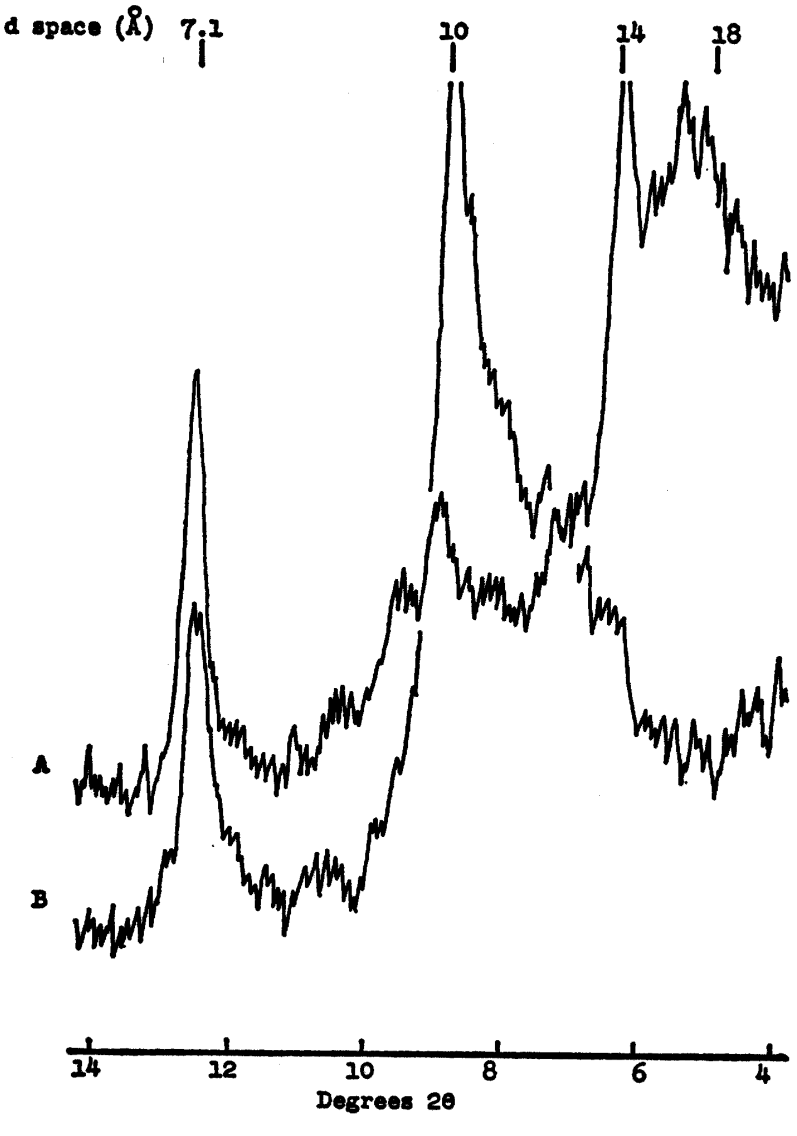

Fig. A34. X-ray diffraction pattern of the clay fraction of Landes-Adscota sandy loam after the 5th crop on the 0 potassium treatment

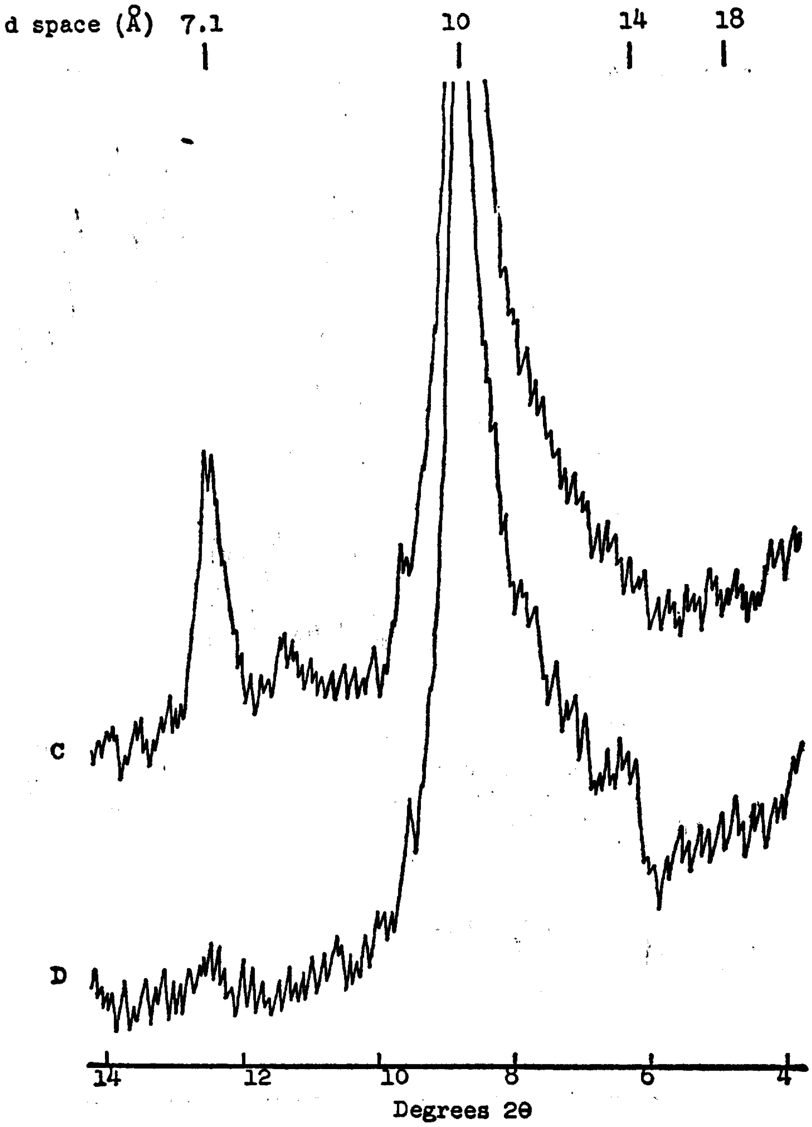

Fig. A34 (cont'd.)

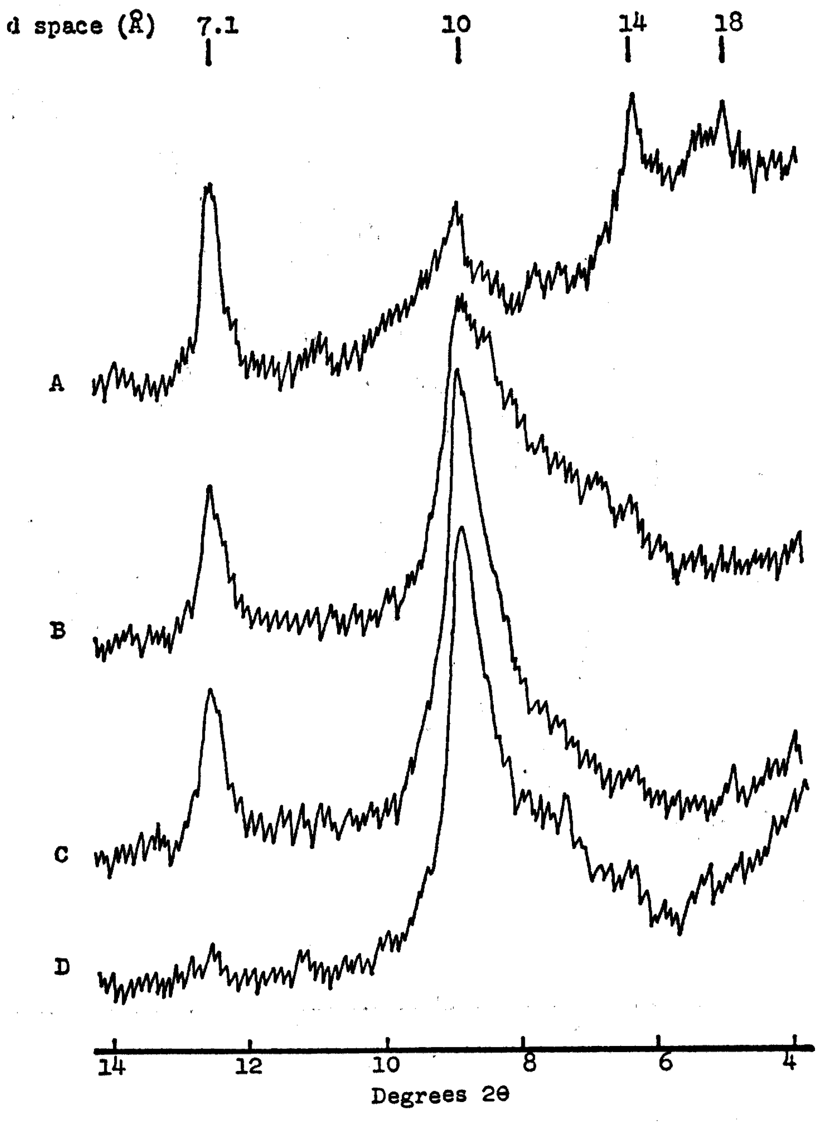

Fig. A35. **X-ray diffraction pattern of the clay fraction of Landes-Abscota sandy loam after the 5th crop on the 1,600 pound per acre potassium treatment**

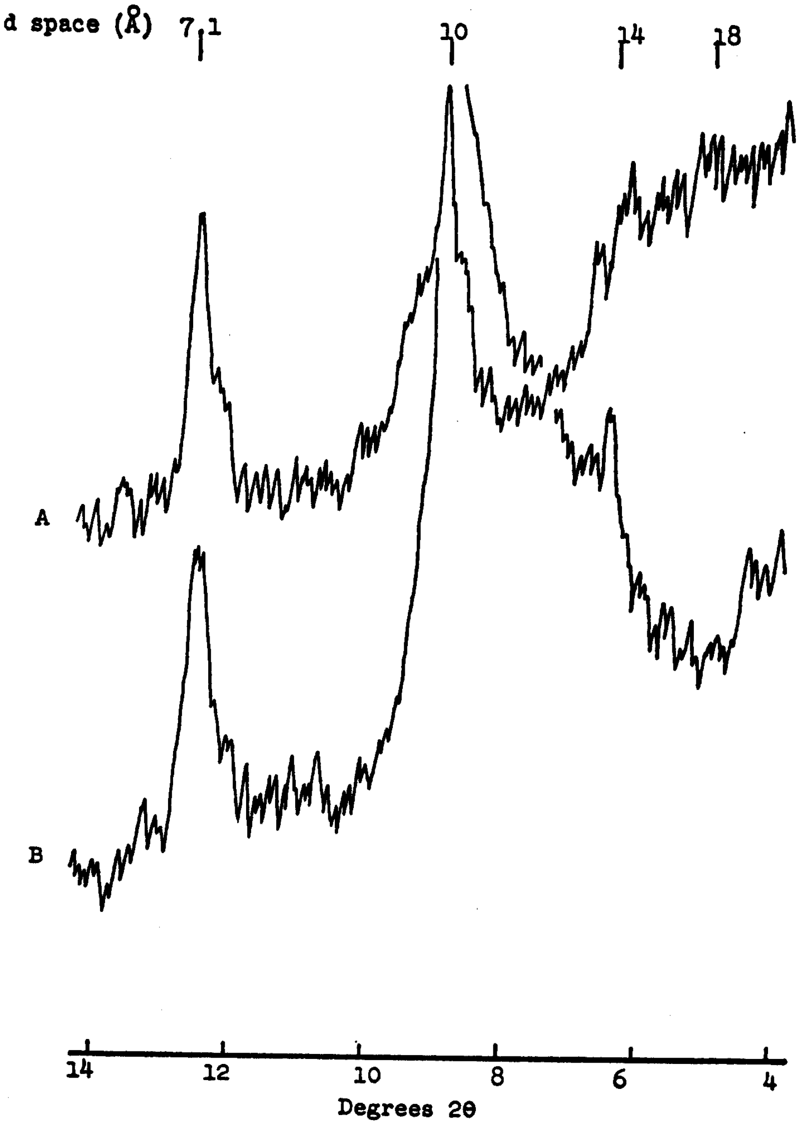

Fig. A36. X-ray diffraction pattern of the clay fraction of Landes-Abscota sandy loam after a 13-month incubation period with 1,600 pounds of potassium per acre

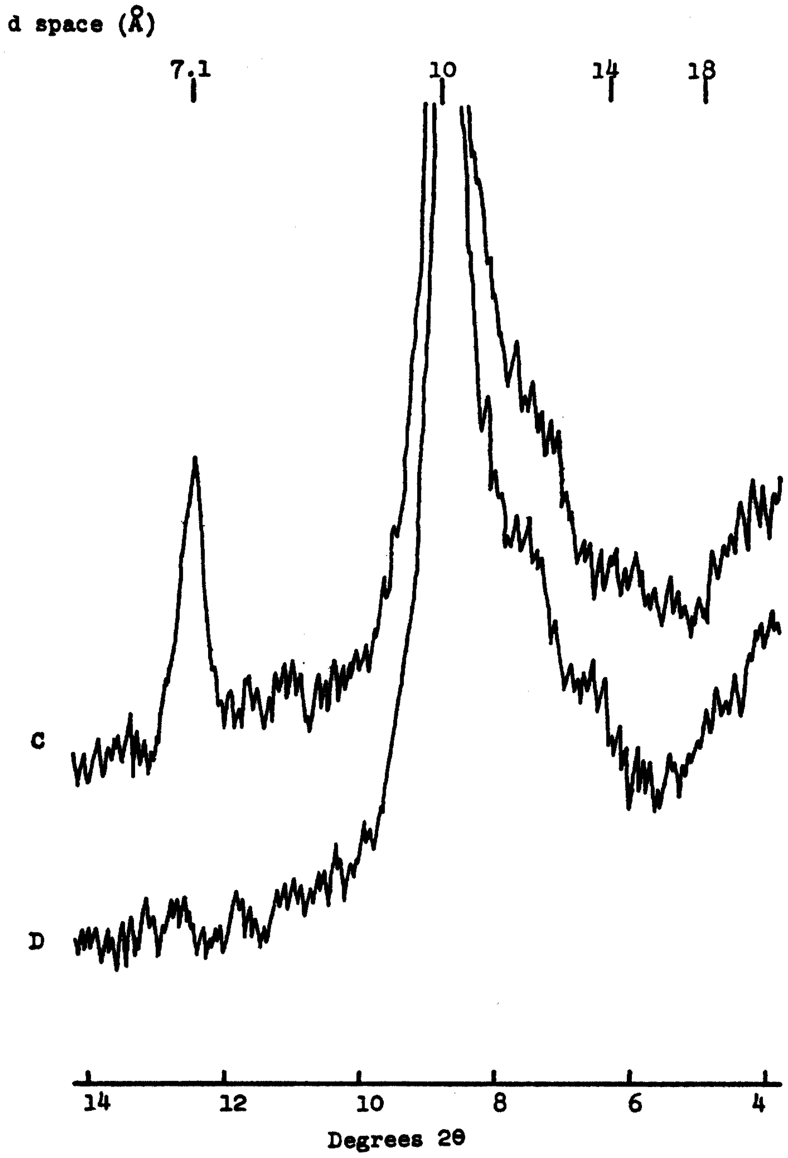

Fig. A36 (cont'd.)