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EVALUATION OF POTASSIUM AVAILABILITY  
OF FOUR MICHIGAN SOILS

By

Kazuhiko Oya

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## ABSTRACT

### EVALUATION OF POTASSIUM AVAILABILITY OF FOUR MICHIGAN SOILS

By

Kazuhiro Oya

Since the availability of soil potassium is affected by plant and soil factors, the supply of this element in four Michigan soils varying in chemical, physical and mineralogical properties was studied using wheat, sorghum and tomatoes as the indicator crops.

From December, 1968 to April, 1970 3 crops of wheat, 2 of sorghum, and 1 tomato crop were grown in sequence in the greenhouse on Brookston loam, Genesee loam, Kalamazoo sandy loam, and Landes-Abscota sandy loam. The following levels of potassium were applied on all soils: 0, 200, 400, 800, and 1,600 pounds per acre.

Applied potassium markedly affected plant yields obtained on Genesee loam, Kalamazoo sandy loam, and especially on Landes-Abscota sandy loam.

Potassium concentration in the plants increased with increasing levels of applied potassium while the concentration of plant calcium and magnesium generally decreased. These findings were verified by the application of the electron microprobe X-ray technique.

Potassium uptake by 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 the soil.

The potassium supplying power of the soils are in the following order: Brookston loam > Kalamazoo sandy loam > Landes-Abscota sandy loam > Genesee loam.

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

Subsequent to a 13-month incubation period of the soils with various levels of applied potassium, both the exchangeable and nonexchangeable potassium content of all soils increased except for that of Kalamazoo sandy loam.

The alternate wetting and drying treatments resulted in the fixation of potassium in the following order: Brookston loam > Landes-Abscota sandy loam > Genesee loam > Kalamazoo sandy loam. The fixation or release of potassium by the soils subjected to freezing and thawing was of minor importance.

Of the various criteria employed for evaluating potassium availability  $-\Delta K^0$ ,  $AR_e^k$ , exchangeable, nonexchangeable, and total potassium were generally most meaningful.

The percentage of vermiculite and mica in the clay fractions of the original soils were determined as: 8.3 and 27.6 for Brookston loam (18.5% clay); 10.0 and 18.0 for Genesee loam (11.5% clay); 1.7 and 18.0 for Kalamazoo sandy loam (13.5% clay); and 8.9 and 28.8 respectively for Landes-Abscota sandy loam (14.8% clay).

The following clay minerals were found to predominate in the four soils studied: montmorillonite in Brookston loam; kaolinite, and vermiculite-chlorite-montmorillonite interstratified minerals in Genesee loam; vermiculite-chlorite interstratified minerals and kaolinite in Kalamazoo sandy loam; and vermiculite-chlorite interstratified minerals in Landes-Abscota sandy loam.

The vermiculite content of the clay fractions tended to increase as soil potassium was depleted by cropping, whereas the mica content tended to increase when the soils were incubated with 1,600 pounds of potassium per acre. These tendencies were most pronounced with Landes-Abscota sandy loam.

This thesis is affectionately dedicated  
to my wife Sachiko

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## 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 (Kardos, 1964). Soils containing montmorillonite, illite and vermiculite are capable of fixing potassium applied to the soil as fertilizer (Bartlett and Simpson, 1967, Kardos, 1964, and Welch and Scott, 1961). 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 (Richards and McLean, 1961).

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  $\text{NH}_4\text{OAc}$  (Bray, 1948), 1 N  $\text{HNO}_3$  (Pratt and Morse, 1954), and sodium tetraphenylboron (Schulte and Corey, 1965). 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  $a_{\text{K}}/\sqrt{a_{\text{Ca}} + a_{\text{Mg}}}$  has been proposed as a good measure for potassium availability (Matthews and Beckett, 1962) for certain soils, and its usefulness has been tested to some extent (Acquaye and MacLean, 1965, and Beckett, 1964b). 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: (1) levels of potassium in the soil (DeMent et al., 1959); (2) absorptive power of plant species (Tisdale and Nelson, 1966); (3) soil temperature (Weber and Caldwell, 1964); (4) soil moisture or wetting-drying conditions (Bates and Scott, 1964); (5) soil pH (Page and Ganjie, 1964); (6) soil organic matter (Mortland, 1961); (7) concentrations of coexisting cations such as Ca, Mg, and  $\text{NH}_4$  (Oliver and Barber, 1966, Powell and Hutcheson, 1965, and Welch and Scott, 1961); (8) texture of the soil (Nuttall et al., 1967); and (9) types of clay mineral present in the soil (Rich and Lutz, Jr., 1965).

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 (Cummings, 1959, and Doll et al., 1965). 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 potassium 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.

## CHAPTER I

### 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 (Evans and Soger, 1966). 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 (Evans and Soger, 1966, and Lawton and Cook, 1954).

Plants with an inadequate supply of potassium may show poor fruit or seed formation, yellowing of the leaves, poor growth, and low resistance to coldness and drought (Tisdale and Nelson, 1966).

Explanations of the disturbance in carbohydrate and nitrogen metabolism relative to potassium nutrition are probably that: (1) 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 glycolic pathway (The insufficient energy reduces nitrogen assimilation which requires a large amount of energy from the outside.); (2) 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 (Fairley and Kilgour, 1966).

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 (Fujiwara, 1964).

### 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 potassium, 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 (1928), and Drake and Scarseth (1939).

Newton (1928) 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 (1939) 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  $K_2O$  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 of plants to absorb potassium. Lewis and Eisenmenger (1948) 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 monocotyledon plants such as oats and corn as studied by Beeson (1941). 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. (1959) 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 potassium (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 (1959) showed the relationship between potassium uptake of the plant and exchangeable soil potassium.

An experiment by Oya (1965) with kaolinitic Hawaiian latosols showed the potassium contents of peanut leaves increased with additions of potassium up to 800 pounds per acre at lower calcium treatments.

The process of nutrient uptake and transport of potassium in the plant against a concentration gradient requires energy (Fried and Broeshart, 1967). 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 (1954) 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 potassium 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. (1959).

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 ( $\text{NH}_4^+$ ) 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 (Welch and Scott, 1961, Macleod and Carson, 1966, and Bartlett and Simpson, 1967).

Macleod and Carson (1966) 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  $\text{NH}_4^+$  form. The potassium concentrations of timothy, orchardgrass, and brome grass were about 3.5% irrespective of the ammonium levels in the culture containing 50 ppm. of potassium.

Bartlett and Simpson (1967) 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 (Welch and Scott, 1961).

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

#### b. Phosphorus

Readily available soil phosphorus exists in the forms of such anions as  $\text{H}_2\text{PO}_4^-$ ,  $\text{HPO}_4^{2-}$  and less abundantly as  $\text{PO}_4^{3-}$  (Kardos, 1964). 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 (1954).

Gillingham (1966) 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 (1941) 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 (1965) 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 (1966) 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: (1) mechanisms of contact exchange, (2) the effective concentration of ions in the growing medium, and (3) the renewal rate of nutrients in the growing medium (Tisdale and Nelson, 1966).

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 (1954) 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 (1960). Plant nutrients in the soil may reach the plant root by: (1) root extension, (2) mass flow, and (3) 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 (Barber et al., 1963, and Oliver and Barber, 1966). The relative rate of diffusion of potassium is expected to become greater with an increase in soil moisture (Barber, 1964).

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 (1960), 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

Vlaminis and Davis (1944) and Lawton (1945) demonstrated the effect of aeration on the uptake of 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 deficiency 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 (1964).

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 (Evans and Sorger, 1966, and Fujiwara, 1964), 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. (1963), the excised roots of Sudangrass, peas, and soybeans absorbed more potassium from 0.005 N KCl solution when the solution temperature was raised from 5° to 25°C. Weber and Caldwell (1964) showed that the sorghum plant absorbed more potassium as the soil temperature was raised from 60° to 90° F. The effect 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  $\text{CO}_2$  by the excised root of Worley et al. (1963) increased linearly from  $5^\circ$  to  $25^\circ\text{C}$ , although there were variations above  $25^\circ\text{C}$ , 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 (Kardos, 1964). 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  $\text{K}_2\text{O}$  contents are 3.13,

3.24, 1.32 and 0.33 percent, respectively (Clark and Washington, 1924).

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  $\text{Al}(\text{OH})_3$  (Jackson, 1964).

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  $K_2O$  (Jackson, 1964).

## 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 environmental factors.

Soil potassium is generally divided into three broad categories: difficult, moderate 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 difficulty replaceable cations including H, Fe, and Al block potassium absorption sites of illite and vermiculite (Stanford, 1947, and Page and Ganjle, 1964).

### b. Soil Moisture Level

Reitemeir et al. (1948) and Khanna and Datta (1968) reported that soils release nonexchangeable potassium in the moist condition. On the other hand Attoe (1947) 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. (1948), 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 (1947). 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 (Dennis and Ellis, 1962).

Potassium release from nonexchangeable forms was reported upon drying soils by Stanford (1947), Luebs et al.

(1956) and Bates (1962), whereas Stanford (1947) obtained potassium fixation in drying some of his soils. Experiments with repetition of wetting and drying soil affected fixation of potassium according to Volk (1934), and Powell and Hutcheson (1965).

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 (Raman and Jackson, 1965). Potassium fixation was caused by the contraction of montmorillonite interlayer space (Kardos, 1964).

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 (Fine et al., 1940). 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 (Reitmeir et al., 1948).

#### d. Organic Matter

Addition of organic matter to soil reduced the potassium release upon drying (Bates, 1962; and Bates and Scott,

1964), because organic matter reduced the surface tension of water.

Mortland (1961) reported that aniline hydrochloride and 2,4-diaminophenol 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 (1955).

According to Page and Baver (cited by Kardos, 1964), 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 (Welch and Scott, 1961) and when ammonium was applied before potassium to the soil, potassium fixation was prevented (Bartlett and Simpson, 1967).

Calcium and magnesium, the most abundant cations in soil, also have some connection with potassium fixation or release. Powell and Hutcheson (1965) 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 (1955), and easily penetrated into interstice of clays, thus releasing previously trapped potassium, and preventing entrapment 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 (Wiklander, 1964). There are, however, variations in the order of cation adsorption by soil. For instance, vermiculite favorably adsorbed magnesium to calcium when magnesium saturation exceeded about 35% (Peterson, 1965).

### 3. Mechanisms of Potassium Release and Fixation in the Soil

Potassium is released mainly from potassium bearing minerals such as feldspars, micas, 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 (Jackson, 1964), 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: (1) 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 (2) reduction of electric charges by oxidation of the ferric ion in the octahedral layer and by proton addition of an hydronium ion to octahedrally charged oxygen (Jackson, 1964). When potassium is continuously removed from the surrounding solution, mica releases a quantity of potassium as demonstrated in the experiment by Ellis and Mortland (1959).

Potassium fixation may be explained by the "lattice hole" theory and intensity of negative charge in the inter-layer surface of clay minerals (Kardos, 1964). 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  $2.66 \text{ \AA}$ , just fits in the hexagonal space of the oxygen sheet of the silica tetrahedral layer of the clay (size -  $2.8 \text{ \AA}$  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<sup>0</sup> respectively. Therefore, potassium fixation is observed in both moist and dry conditions 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: difficulty, 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

Biological methods are: (1) the Neubauer method using rye as an indicator plant; (2) the Stanford and DeMent method intensifying potassium deficiency in plant seedlings then transferring them onto the soil to be tested; and (3) greenhouse pot and field plot methods.

### a. Neubauer Method

The Neubauer method 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 (Thornton, 1931, 1935, McGeorge, 1946, and Pettinge and Thornton, 1934).

### b. Stanford and DeMent Method

Stanford and DeMent improved the Neubauer method and devised a more efficient way to test nutrient availability in the soil, first for phosphorus (Stanford and DeMent, 1947) and then for potassium (DeMent *et al.*, 1959). Since then the method has been employed by many investigators.

### c. Greenhouse and Field Method

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 is said 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 1 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 methods are considered very useful when correlated with greenhouse and field tests. Although various chemical reagents are used to extract available potassium, neutral 1 normal 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 (Bray, 1948, Hanway et al., 1962).

### b. Extraction with Boiling 1 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 1 N nitric acid extraction (Deturk et al., 1943, Reitemeir et al., 1948, and Schmitz and Pratt, 1953).

Other methods in determining nonexchangeable potassium in micaceous soils include the extraction method with sodium tetraphenylborate (NaTPB) solution (Reed and Scott, 1961 and 1962, Scott and Welch, 1961, Scott and Reed, 1962a, 1962b, and Schulte and Corey, 1963 and 1965).

### 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,  $-\Delta K^0 / AR_e^k$ , was proposed as a measure of soil ability to maintain the activity ratio against potassium depletion by the plant (Matthew and Beckett, 1962, Beckett, 1964a, and 1964b). According to Beckett (1967, p. 32), 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 half-time measured in minutes or less.

In the calculation of potential buffering capacity ( $PBC^k$ ),  $-\Delta K^0$  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  $AR_e^k$  is the activity ratio at an equilibrium where no gain or loss of potassium by soil takes

place ( $\Delta K_e = 0$ ).

Since the values for  $-\Delta K^0$  and  $AR_e^k$  were difficult to determine, they were obtained from a graph drawn with various activity ratios  $AR^k = \frac{a_K}{\sqrt{a_{(Ca + Mg)}}}$  against changes in the exchangeable potassium ( $\Delta K_e$ ) by extrapolating the linear portion of the asymptotic curve to cross the ordinate for  $-\Delta K^0$  value and by interpolating the curve to cross the  $\Delta K_e = 0$  line for  $AR_e^k$  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 (1965) found good correlations ( $r = +0.92$ ) between potassium uptake by plants and  $-\Delta K^0$  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  $AR_e^k$ . Correlation between  $PBC^k$  and nonexchangeable potassium measured with boiling 1 N  $HNO_3$  was  $+0.52$ .

Wild et al. (1969) 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  $-\Delta K^0$  value by  $PBC^k$  value, than between potassium uptake and exchangeable potassium (Zandstra and MacKenzie, 1968). When the  $PBC^k$  is multiplied by  $-\Delta K^0$  value, the  $-\Delta K^0$  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.

## CHAPTER II

### 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 sandy 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.<sup>1)</sup> 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 Brookston loam, whose 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.

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<sup>1)</sup>Personal communication with Dr. E. P. Whiteside, Crop and Soil Sciences Department, Michigan State University.

### a. Soil Collection

Brookston 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  $\frac{1}{4}$  of SW  $\frac{1}{4}$ , 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  $\frac{1}{4}$  of SW  $\frac{1}{4}$  of NW  $\frac{1}{4}$ , 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 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.

### 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 gram sample of soil which was saturated with calcium by repeated centrifugings with 1 N  $\text{CaCl}_2$  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  $\text{MgCl}_2$  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 gram sample with 20 ml. of Bray  $\text{P}_1$  solution consisting of 0.3 N  $\text{NH}_4\text{F}$  and 0.25 N  $\text{HCl}$ . To the extractant 5 drops of ammonium molybdate solution and 5 drops of F-S reducing solution, which consisted of 1-amino-2-naphthol-4-sulfonic acid (Eastman 360), sodium sulfite ( $\text{NaSO}_4$ ) and sodium meta-bi-sulfite ( $\text{Na}_2\text{S}_2\text{O}_5$ ), were added to develop a blue color the intensity of which was compared on a colorimeter at a wave length of 500  $\text{m}\mu$  with a set of standard phosphorus solutions.

Table 1. Chemical analysis of the experimental soil<sup>a</sup>

Soil	pH	CEC.	P	K	Ca	Mg	Zn	Mn	Cu	Organic matter
		Me./100g		Lbs./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

<sup>a</sup>All values are averages of 3 determinations on air-dried samples except for CECs (cation exchange capacities) which are means of 2 determinations and converted to the oven-dry basis.

## 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 in 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 gram sample by shaking for 10 minutes with 20 ml. of 0.1 N HCl. Copper was extracted by shaking a 2 gram sample of the soil for 1 hour with 20 ml. of 1.0 N HCl. 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. 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  $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ ; phosphorus as  $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot 4\text{H}_2\text{O}$ ; and potassium as  $\text{KCl}$ ; 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.

Only nitrogen was applied in solution; other nutrient element were applied in the solid form. Since the phosphorus content of the soils varied (Table 1), phosphorus rates equivalent to 44 pounds per acre were added to Brookston loam, 66 pounds per acre were applied to Genesee loam, and 22 pounds per acre were applied to both Kalamazoo sandy loam and Landes-Abscota sandy loam to insure this element was not limiting on the basis of recommendation in the Michigan State University Extension Bulletin E-550 (1966).

Potassium was applied as  $\text{KCl}$  to the respective soils at five levels equivalent to 0, 200, 400, 800, and 1,600 pounds of 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.

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
Lbs. element/A					
1st crop (Wheat)	N	50	50	50 (25) <sup>a</sup>	50 (25) <sup>a</sup>
	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	88	99	44	44
	Mn	10	10	10	10
4th crop (Sorghum)	N	100 (50) <sup>a</sup>	100 (50) <sup>a</sup>	100 (50) <sup>a</sup>	100 (50) <sup>a</sup>
	P	88	99	44	44
	Mn	5	5	5	5
5th crop (Sorghum)	N	100 (25) <sup>a</sup>	100 (25) <sup>a</sup>	100 (25) <sup>a</sup>	100 (25) <sup>a</sup>
	P	88	99	44	44
	Mn	5	5	5	5
6th crop (Tomatoes)	N	70 <sup>b</sup>	70 <sup>b</sup>	70 <sup>b</sup>	70 <sup>b</sup>
	P	100	100	100	100
	Mn	20	20	20	20

<sup>a</sup>Additional nitrogen applied.

<sup>b</sup>Split application; 35 lbs. before planting and the remainder during the growing period.

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 1st crop only. Manganese was applied in a band as a solution of  $MnSO_4 \cdot H_2O$  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 1st through the 3rd crops; sorghum (Sorghum vulgae var. pioneer 885) 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 (1928), Lewis and Eisenmenger (1948) and Drake and Scarseth (1939).

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 1st 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 pounds of N 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 1st 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 (sorghum) 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 pounds 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 (Ahlgren, 1956). The plant growth of the sorghum plants is depicted in Appendices B to E.

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 K=0 (no K added) and K=200 (200 lbs. K/A.) treatments showed potassium deficiency symptoms resulting in yellowing of the older leaves, burned edges, and less vigorous growth. The K=800 and K=1,600 treatments resulted in larger, healthier plants. The K=400 treatment produced plants intermediate in growth.

Additional nitrogen equivalent to 25 pounds of N per acre was applied during the 5th week before nitrogen deficiency developed. The growth difference of the 5th crop are illustrated 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 pound 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 K=0 treatment. The plants grown on Genesee loam showed potassium deficiency following the K=0, K=200, and K=400 treatments. The deficiency was most prominent on the K=0 treatment where excessive leaf 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 with 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 the 6th 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 1 N HNO<sub>3</sub> 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 HCl in 100 ml. volumetric flasks and the extract used for potassium, calcium, and magnesium determinations.

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 pounds 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,  $-15^{\circ}$  to  $-30^{\circ}\text{C}$ ; Fisher Scientific Company) on the cryostat at  $-18^{\circ}\text{C}$ . The thin cross sections (16  $\mu\text{m}$  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 1st 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 significant 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 (1960). 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.

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

In Brookston loam, the initial exchangeable potassium, 151 pounds per acre (Table 1), and nonexchangeable potassium, 31.9 mg. per 100 g.<sup>2)</sup>, seemed to be sufficient to supply the 1st 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 environmental effects. Sorghum plants appeared to be higher than wheat in potassium absorbing power as suggested by Drake and Scarseth (1939) 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

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<sup>2)</sup>See Table 21.

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. <sup>a</sup>							
(.05)	N.s. <sup>b</sup>	N.s.	0.73	N.s.	N.s	0.76	
(.01)			1.02			1.26	

<sup>a</sup>The least significant difference at 5% and 1% levels of probability, respectively.

<sup>b</sup>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. <sup>a</sup>							
(.05)	N.s. <sup>b</sup>	N.s.	0.39	1.94	1.09	0.95	
(.01)			0.55	2.72	1.52	1.57	

<sup>a</sup>The least significant difference at 5% and 1% levels of probability, respectively.

<sup>b</sup>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. <sup>a</sup>							
(.05)	N.s. <sup>b</sup>	1.33	0.47	1.88	0.98	0.58	
(.01)		1.86	0.66	2.64	1.38	0.97	

<sup>a</sup>The least significant difference at 5% and 1% levels of probability, respectively.

<sup>b</sup>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. <sup>a</sup>							
(.05)	0.42	N.s. <sup>b</sup>	0.48	2.03	0.38	1.67	
(.01)	0.58		0.68	2.85	0.53	2.76	

<sup>a</sup>The least significant difference at 5% and 1% levels of probability, respectively

<sup>b</sup>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 <sup>a</sup>	Linear regression equation	Simple correlation coefficient <sup>b</sup> (r)
<u>Brookston loam</u>		
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**
<u>Genesee loam</u>		
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**

Table 7 (cont'd.)

Crop <sup>a</sup>	Linear regression equation	Simple correlation coefficient <sup>b</sup> (r)
<u>Kalamazoo sandy loam</u>		
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**
<u>Landes-Abscota sandy loam</u>		
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**

<sup>a</sup>Each crop had 4 replicates except for the 6th crop which had only 2.

<sup>b</sup>\* and \*\* indicate significance at 5% and 1% probability levels respectively.

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 temperature 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; Figures A2 and A3).

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 (1948). 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 A5 of Appendix B.

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

Genesee loam contained only 93 pounds of exchangeable potassium per acre (Table 1) which, however, appeared to be sufficient to supply adequate potassium to the 1st and 2nd crops (Tables 4 and 7, and Figure A6). 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 A10 in contrast with the 6th crop (tomatoes) which showed remarkable benefit from the potassium treatments (Tables 4 and 7, and Figure A9).

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

Since the initial exchangeable potassium was as high as 275 pounds 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.<sup>3)</sup>

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

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<sup>3)</sup>See Table 23.

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 A14 and A15).

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

This 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 (Fried and Broeshart, 1967). 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 A16 to A19). The discussion on the general high yield of the 4th crop in Brookston loam may also apply.

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) <sup>a</sup>	
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) <sup>b</sup>	N.s. <sup>c</sup>	N.s.	N.s.	N.s.

<sup>a</sup>All values are averages of 2 replicates.

<sup>b</sup>The least significant difference at 5% level of probability.

<sup>c</sup>No significant difference.

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 A20 of Appendix D). 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 Concentrations in the Plants

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

#### 1) Potassium, Calcium, and Magnesium Concentrations in the Plants

The plant concentrations 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).

## 2) Relationship between Concentrations of Potassium and Calcium

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

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

## 5) Relationship between Potassium and Calcium plus Magnesium

This relationship coincides with that of potassium versus calcium.

## 6) Relationship between Potassium and the Square Root of Calcium plus Magnesium Concentrations

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 (1964a). The relation of potassium concentration and the square root of calcium plus magnesium

Table 9. Potassium, calcium, and magnesium concentrations of plant material as affected by potassium treatments on Brookston loam<sup>a</sup>

K treatment <sup>b</sup>	K	Ca	Mg	K	Ca	Mg	K	Ca	Mg
	%			%			%		
Lbs./A.	<u>1st crop-wheat</u>			<u>2nd crop-wheat</u>			<u>3rd crop-wheat</u>		
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
	<u>4th crop-sorghum</u>			<u>5th crop-sorghum</u>			<u>6th crop-tomato</u>		
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

<sup>a</sup>All values are averages of 4 replicates except for the 6th crop which had only 2.

<sup>b</sup>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<sup>a</sup>

K treatment <sup>b</sup>	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

<sup>a</sup>All values are averages of 4 replicates except for the 6th crop which had only 2.

<sup>b</sup>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<sup>a</sup>

K treatment <sup>b</sup>	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

<sup>a</sup>All values are averages of 4 replicates except for the 6th crop which had only 2.

<sup>b</sup>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<sup>a</sup>

K treatment <sup>b</sup>	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

<sup>a</sup>All values are averages of 4 replicates except for the 6th crop which had only 2.

<sup>b</sup>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 coefficient (r)						
<u>Brookston loam</u>						
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. $\sqrt{\text{Ca} + \text{Mg}}$	-0.30	-0.37	-0.95**	-0.90**	-0.49*	-0.50
<u>Genesee loam</u>						
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. $\sqrt{\text{Ca} + \text{Mg}}$	-0.25	-0.91**	-0.97**	-0.84**	-0.80**	-0.31
<u>Kalamazoo sandy loam</u>						
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. $\sqrt{\text{Ca} + \text{Mg}}$	0.74**	0.83**	-0.76**	-0.91**	-0.93**	0.02

Table 13 (cont'd)

Comparison	Crop					
	1	2	3	4	5	6
Simple correlation coefficient (r)						
<u>Landes-Abscota sandy loam</u>						
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. $\sqrt{\text{Ca} + \text{Mg}}$	-0.63**	-0.49*	-0.95**	-0.71**	-0.80**	-0.52

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 Magnesium

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 pound per acre potassium respectively. The following instrumental parameters were employed: 25 kv accelerating voltage, and 0.025  $\mu$ a 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 8 to 10) and by line scans (Figures 5 and 6). The cellular detail of 200  $\mu$ m portions of the stems obtained from Brookston and Genesee soils are shown in Figure 1 and 7, respectively.

A contrast is shown in these figures. The potassium concentration of the stem tissue obtained from Brookston loam is greater than calcium or magnesium. 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 obtained from the K=0 treatment on Genesee loam (Figures 7 to 9). 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 1.10% 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 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 (Figures 5 and 6) represent the relative intensity of potassium, calcium, and magnesium across the 200  $\mu\text{m}$  portion of the stem tissues from points A to B of Figures 1 and 7 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

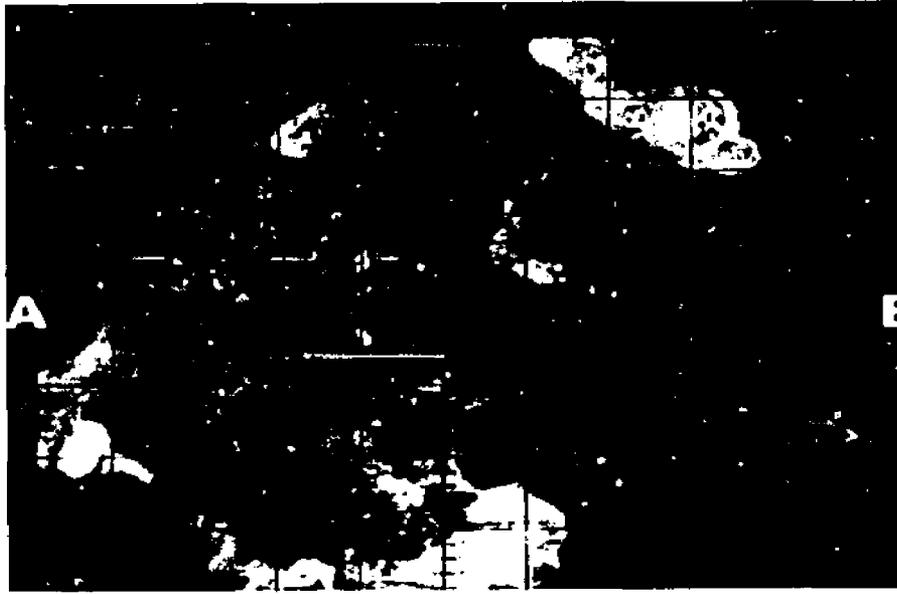


Figure 1. Cellular detail of a 200  $\mu\text{m}$  portion of wheat stem obtained from Brookston loam receiving 400 pounds of potassium per acre (Reverse sample current, magnification 425x)

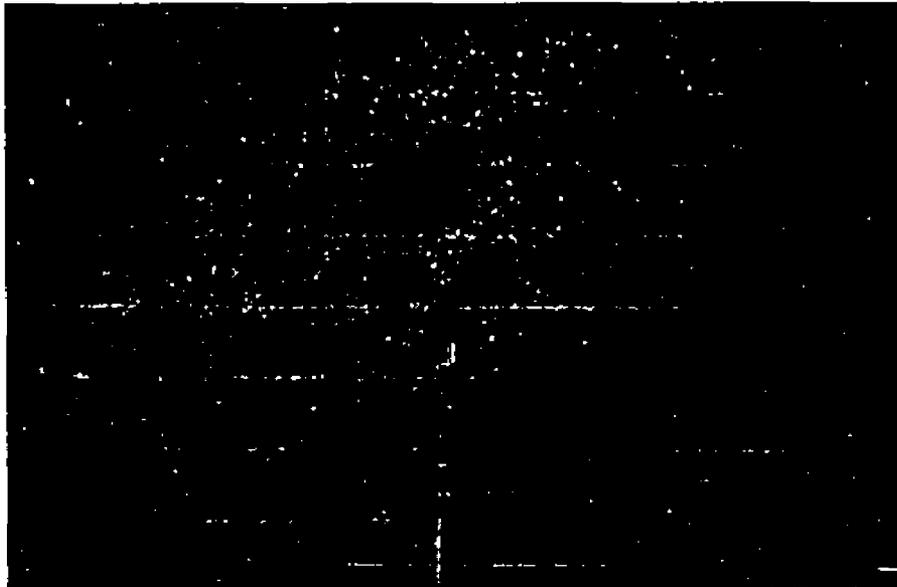


Figure 2. Potassium X-ray oscillogram showing the distribution of potassium in a 200  $\mu\text{m}$  portion of wheat stem obtained from Brookston loam receiving 400 pounds of potassium per acre

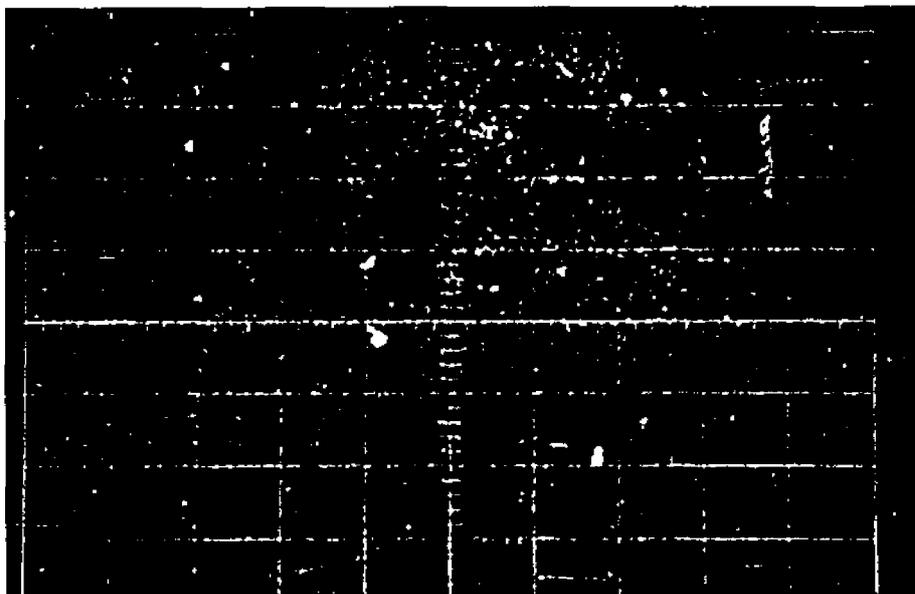


Figure 3. Calcium X-ray oscillogram showing the distribution of calcium in a 200  $\mu\text{m}$  portion of wheat stem obtained from Brookston loam receiving 400 pounds of potassium per acre



Figure 4. Magnesium X-ray oscillogram showing the distribution of magnesium in a 200  $\mu\text{m}$  portion of wheat stem obtained from Brookston loam receiving 400 pounds of potassium per acre

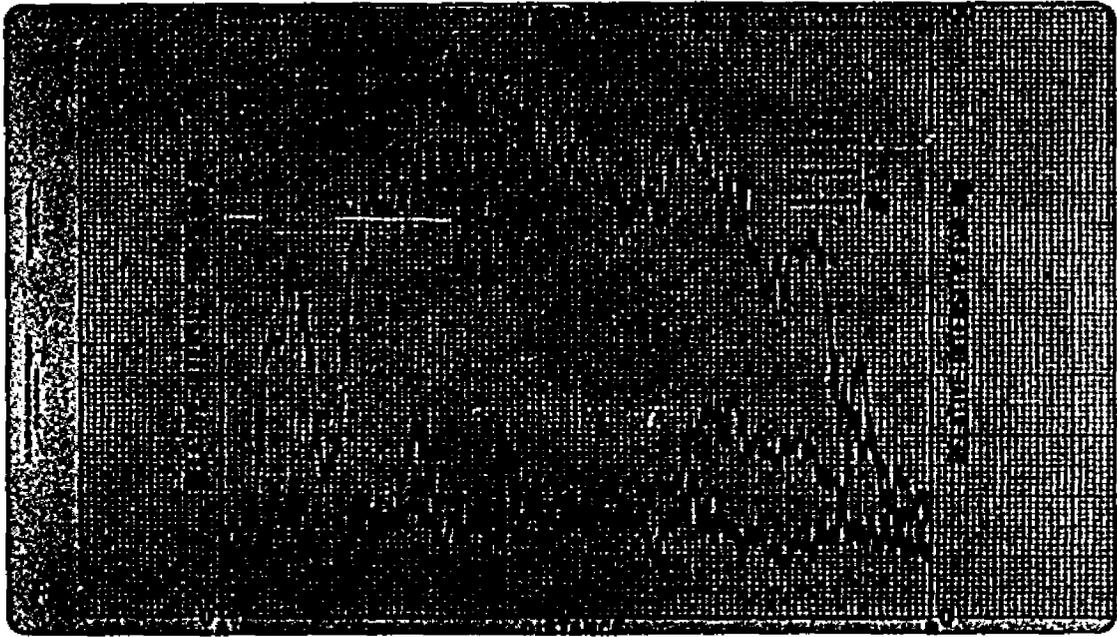


Figure 5. Relative intensity measurements of potassium, calcium, and magnesium in a 200  $\mu\text{m}$  portion of wheat stem tissue grown on Brookston loam receiving 400 pounds of potassium per acre (Points A to B of Figure 1)

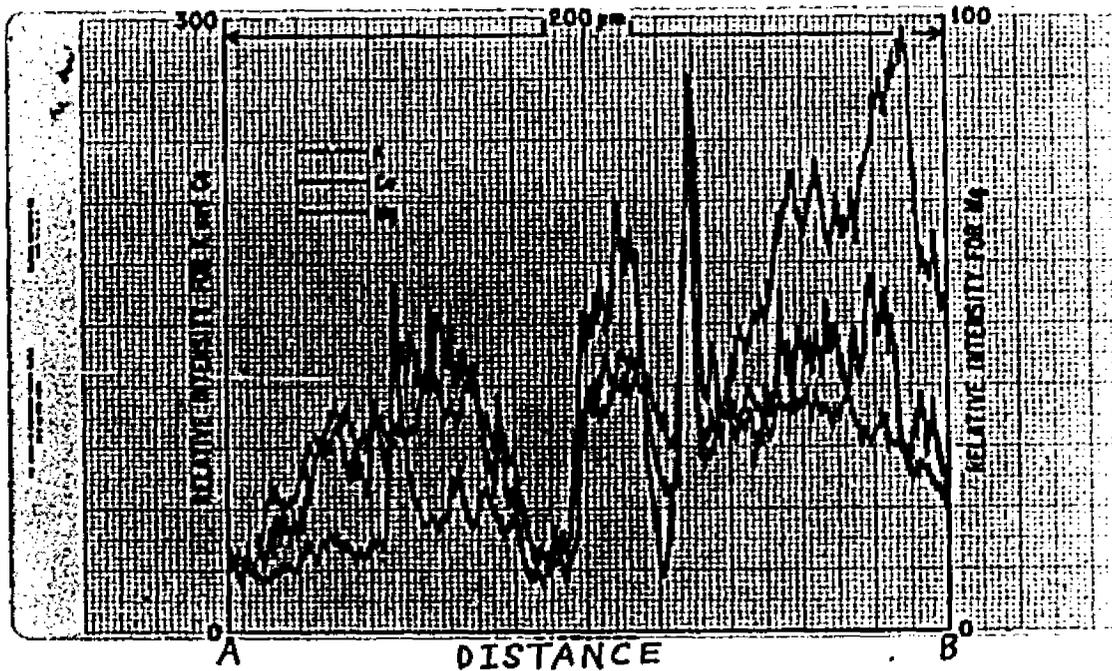


Figure 6. Relative intensity measurements of potassium, calcium, and magnesium in a 200  $\mu\text{m}$  portion of wheat stem tissue grown on Genesee loam receiving 0 pounds of potassium per acre (Points A to B of Figure 7)



Figure 7. Cellular detail of a 200  $\mu\text{m}$  portion of wheat stem obtained from Genesee loam receiving 0 pounds of potassium per acre (Reverse sample current, magnification 425x)

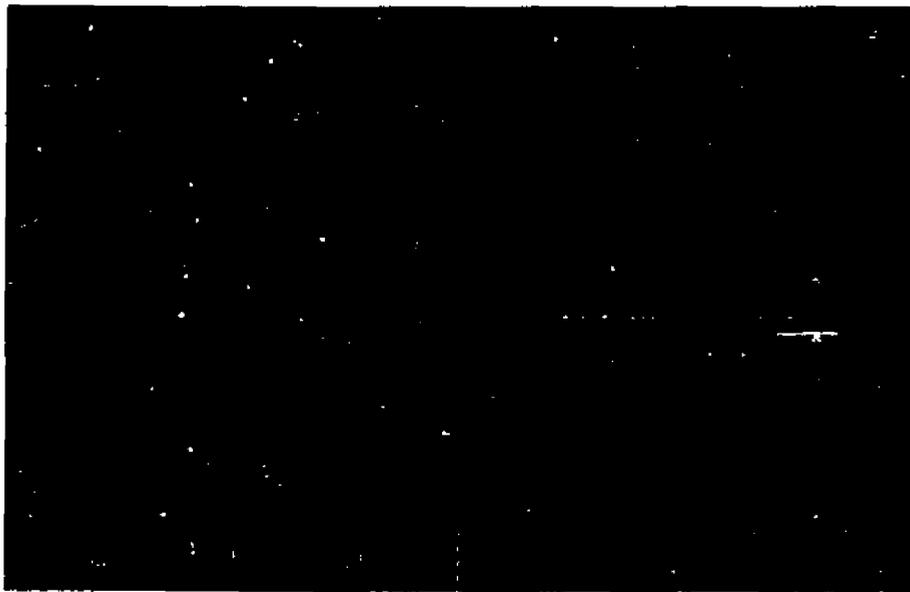


Figure 8. Potassium X-ray oscillogram showing the distribution of potassium in a 200  $\mu\text{m}$  portion of wheat stem obtained from Genesee loam receiving 0 pounds of potassium per acre



Figure 9. Calcium X-ray oscillogram showing the distribution of potassium in a 200  $\mu\text{m}$  portion of wheat stem obtained from Genesee loam receiving 0 pounds of potassium per acre

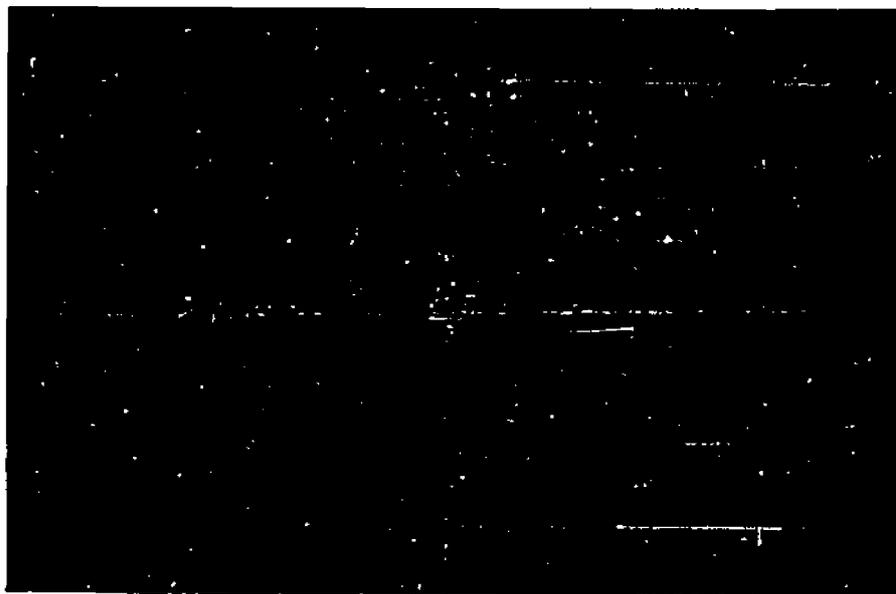


Figure 10. Magnesium X-ray oscillogram showing the distribution of potassium in a 200  $\mu\text{m}$  portion of wheat stem obtained from Genesee loam receiving 0 pounds of potassium per acre

at xylem, phloem, and their related tissue, through which inorganic ions and metabolic products are translocated respectively as known in plant physiology (Briggle, 1967, and Levitt, 1969). The high peak resulting in the line scan for calcium at about 44  $\mu\text{m}$  from point A of Figure 6 is suspected to be due to a contaminant as indicated in Figure 7.

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 (Fried and Broeshart, 1967). 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 (Rasmussen, 1968; and Rasmussen et al., 1968) 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.

#### 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 concentration 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.

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					
	1	2	3	4	5	6
	Wheat			Sorghum		Tomato
Simple correlation coefficient (r)						
<u>Brookston loam</u>						
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**
$K/\sqrt{Ca + Mg}$	0.36	-0.14	0.74**	0.27	0.26	0.89**
<u>Genesee loam</u>						
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**	0.90**
K/Ca + Mg	-0.01	0.58**	0.84**	0.36	0.85**	0.76*
$K/\sqrt{Ca + Mg}$	0.01	0.59**	0.86**	0.35	0.85**	0.68*

Table 14 (cont'd)

Relationships of plant yields and concs. of elements	Crop					
	1 Wheat	2	3	4 Sorghum	5	6 Tomato
	Simple correlation coefficient (r)					
	<u>Kalamazoo sandy loam</u>					
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**
$K/\sqrt{Ca + Mg}$	-0.13	-0.51*	0.78**	0.63**	0.85**	0.87**
	<u>Landes-Abscota sandy loam</u>					
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**

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 positively 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" (Thompson, 1959). Additions of a certain nutrient element increase the yields of a plant without a great increase in the element to a certain 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 affected by potassium treatments on Brookston, Genesee, Kalamazoo, and Landes-Abscota soils

K treatment <sup>a</sup>	Crop						Total
	1	2	3	4	5	6	
	Wheat			Sorghum		Tomato	
(Lbs./A.)	(Mg.K/pot) <sup>b</sup>						
	<u>Brookston loam</u>						
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. <sup>c</sup>							
(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	
	<u>Genesee loam</u>						
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	300.5	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. <sup>c</sup>							
(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 <sup>a</sup>	Crop						Total
	1	2 Wheat		3	4 Sorghum		
(Lbs./A.)	(Mg.K/pot) <sup>b</sup>						
<u>Kalamazoo sandy loam</u>							
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. <sup>c</sup>							
(0.05)	N.s. <sup>d</sup>	50.82	15.25	34.81	22.51	18.99	
(0.01)		71.24	21.39	48.81	31.56	31.50	
<u>Landes-Abscota sandy loam</u>							
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. <sup>c</sup>							
(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	

<sup>a</sup> Potassium was applied to the first crop only

<sup>b</sup> All values of uptake are averages of 4 replicates except for the 6th crop which had 2.

<sup>c</sup> The least significant difference at 5% and 1% levels of probability, respectively.

<sup>d</sup> 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 <sup>a</sup>	Crop			Crop			Total
	1	2	3	4	5	6	
(Lbs./A.)	Wheat			Sorghum			Tomato
	(Mg.Ca/pot) <sup>b</sup>						
	<u>Brookston loam</u>						
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. <sup>c</sup> (0.05)	N.s. <sup>d</sup>	N.s.	N.s.	16.12	N.s.	N.s.	
(0.01)				22.59			
	<u>Genesee loam</u>						
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	695.7
L.s.d. <sup>c</sup> (0.05)	11.49	N.s. <sup>d</sup>	4.32	21.48	N.s.	53.81	
(0.01)	16.11		6.06	30.11		89.24	

Table 16 (cont'd.)

K treatment <sup>a</sup>	Crop						Total
	1	2	3	4	5	6	
(Lbs.k/A.)	Wheat		Sorghum			Tomato	
	(Mg.Ca/pot) <sup>b</sup>						
	<u>Kalamazoo sandy loam</u>						
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. <sup>c</sup>							
(0.05)	11.20	17.34	3.14	N.s. <sup>d</sup>	16.57	83.09	
(0.01)	15.70	24.32	4.40		23.24	137.80	
	<u>Landes-Abscota sandy loam</u>						
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. <sup>c</sup>							
(0.05)	6.80	18.95	N.s. <sup>d</sup>	N.s.	13.30	N.s.	
(0.01)	9.53	26.57			18.65		

<sup>a</sup>Potassium was applied to the first crop only.

<sup>b</sup>All values of uptake are averages of 4 replicates except for the 6th crop which had 2.

<sup>c</sup>The least significant difference at 5% and 1% levels of probability, respectively.

<sup>d</sup>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 <sup>a</sup>	Crop						Total
	1	2	3	4	5	6	
(Lbs.K/A.)	Wheat		Sorghum			Tomato	
	(Mg.Mg/pot) <sup>b</sup>						
	<u>Brookston loam</u>						
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. <sup>c</sup>							
(0.05)	N.s. <sup>d</sup>	7.08	2.80	19.76	N.s.	N.s.	
(0.01)		9.92	3.92	27.71			
	<u>Genesee loam</u>						
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. <sup>c</sup>							
(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	

Table 17 (cont'd.)

K treatment <sup>a</sup>	Crop						Total
	1	2	3	4	5	6	
(Lbs.K/A.)	Wheat			Sorghum			Tomato
	(Mg.Mg/pot) <sup>b</sup>						
	<u>Kalamazoo sandy loam</u>						
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. <sup>c</sup>							
(0.05)	N.s. <sup>d</sup>	N.s.	1.32	11.29	11.14	6.73	
(0.01)			1.85	15.83	15.62	11.16	
	<u>Landes-Abscota sandy loam</u>						
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. <sup>c</sup>							
(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	

<sup>a</sup>Potassium was applied to the first crop only.

<sup>b</sup>All values of uptake are averages of 4 replicates except for the 6th crop which had 2.

<sup>c</sup>The least significant difference at 5% and 1% levels of probability, respectively.

<sup>d</sup>No significant difference in magnesium uptake as detected by F test with analysis of variance.

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 1st crop (wheat) in all soils since the 2nd crop was grown in the spring season during more favorable conditions than the 1st crop.

Tomatoes (6th crop) absorbed more potassium than sorghum (5th crop) on all potassium treatments applied to Brookston loam, on K=1,600 (1,600 lbs. K/A.) treatment in Genesee loam, on K=400, K=800, and K=1,600 treatments in Kalamazoo sandy loam, and on K=800 and K=1,600 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. 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 1st, 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 potassium 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 (Cook, 1962). 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 plants. The soil was originally rich in exchangeable potassium containing 275 pounds 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) <sup>a</sup>					
	<u>Brookston loam</u>					
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**
	<u>Genesee loam</u>					
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**
	<u>Kalamazoo sandy loam</u>					
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**
	<u>Landes-Abscota sandy loam</u>					
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**

<sup>a</sup>\* 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 yields 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 1st 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 (1941), and Oya (1965). The factors which induced the positive correlation between potassium and calcium for the 1st 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 1st crop grown on Brookston loam, for the 5th crop on Genesee loam, for the 1st 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.

### 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 Nonexchangeable 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

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)						
<u>Brookston loam</u>						
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. $\frac{Ca + Mg}{\sqrt{Ca + Mg}}$	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*
<u>Genesee loam</u>						
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. $\frac{Ca + Mg}{\sqrt{Ca + Mg}}$	-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**
<u>Kalamazoo sandy loam</u>						
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. $\frac{Ca + Mg}{\sqrt{Ca + Mg}}$	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**
<u>Landes-Abscota sandy loam</u>						
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. $\frac{Ca + Mg}{\sqrt{Ca + Mg}}$	-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

soils, the amount of potassium (mg.) taken up from K=0 treatment by the respective crops per pot were converted to pounds of plant potassium per acre from which the exchangeable 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 1st, 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 non-exchangeable 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 pounds per acre for Brookston loam, Genesee loam, and Kalamazoo sandy loam respectively, appeared to be a sufficient source of potassium for the 1st 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 11 to 14).

#### 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

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 <sup>a</sup>	Crop						Total
	1	2	3	4	5	6	
	<u>Brookston loam</u>						
	(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 forms	27.9	438.4	68.8	43.9	29.6	50.5	659.1
	<u>Genesee loam</u>						
	(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
	<u>Kalamazoo sandy loam</u>						
	(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
	<u>Landes-Abscota sandy loam</u>						
	(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

<sup>a</sup> K release from nonexchangeable forms = (plant uptake of K from K=0 plots) - (exchangeable K before cropping)<sup>b</sup>

<sup>b</sup> 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).

levels of the potassium treatment in the same way for Table 20 and presented in Figures 11 to 14.

In Brookston loam, the amounts of nonexchangeable soil potassium released to the plants were 659, 614, 664, 588, and 106 pounds per acre from K=0, K=200, K=400, K=800, and K=1,600 treatments respectively (Figure 11). From Figure 11, 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 K=0, K=200, K=400, and K=800 treatments reached similar amounts. The lower release from the K=1,600 treatment than from 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 11, it may be expected that nonexchangeable soil potassium will be released from the K=1,600 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 K=200, K=400, and K=800 treatments than in the K=0 treatment (Figure 12). The clay

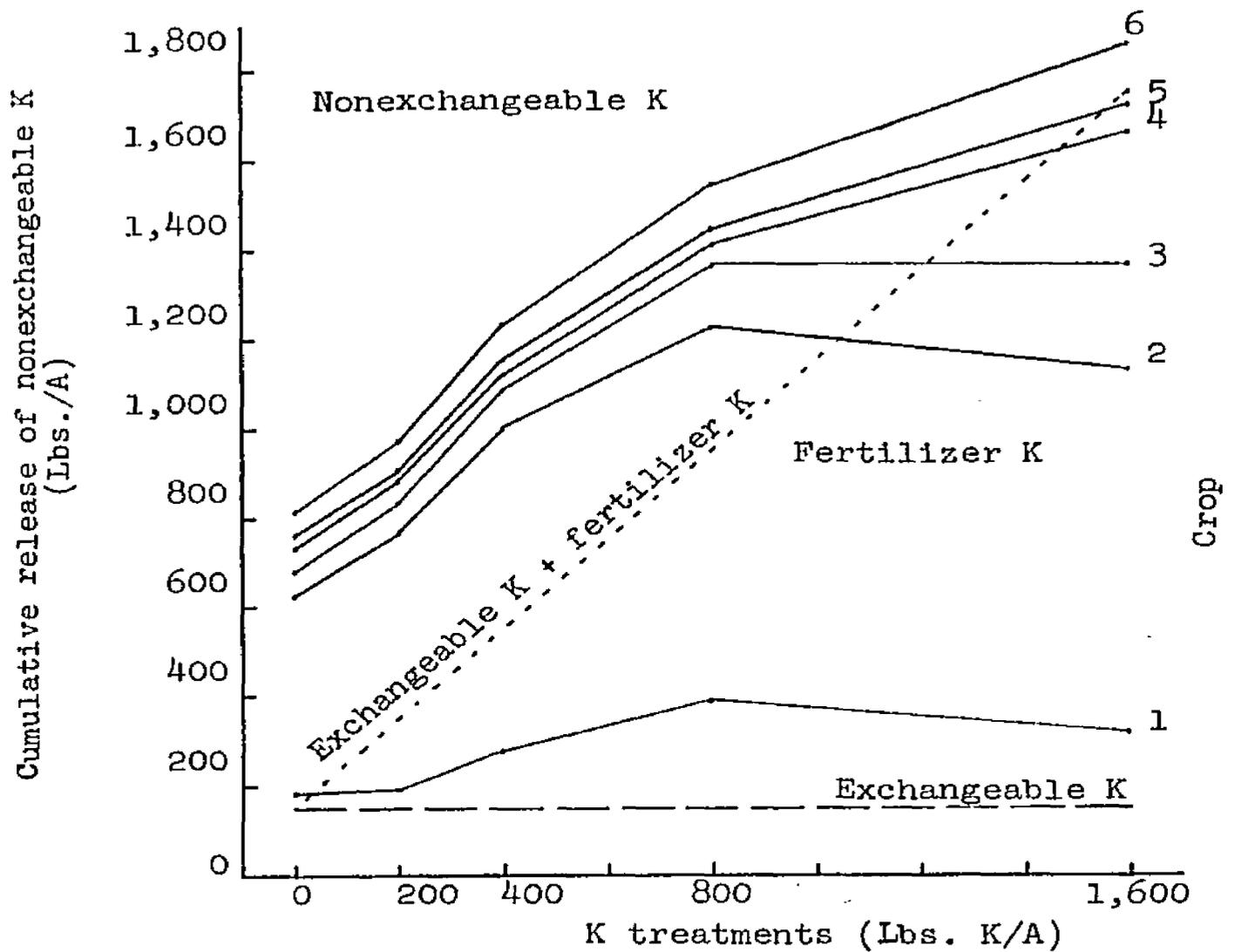


Figure 11. Release of nonexchangeable potassium to the plants at various levels of potassium treatment for Brookston loam<sup>a</sup>

<sup>a</sup>The broken line indicates the original level of exchangeable K. The dotted line indicates exchangeable K plus fertilizer K.

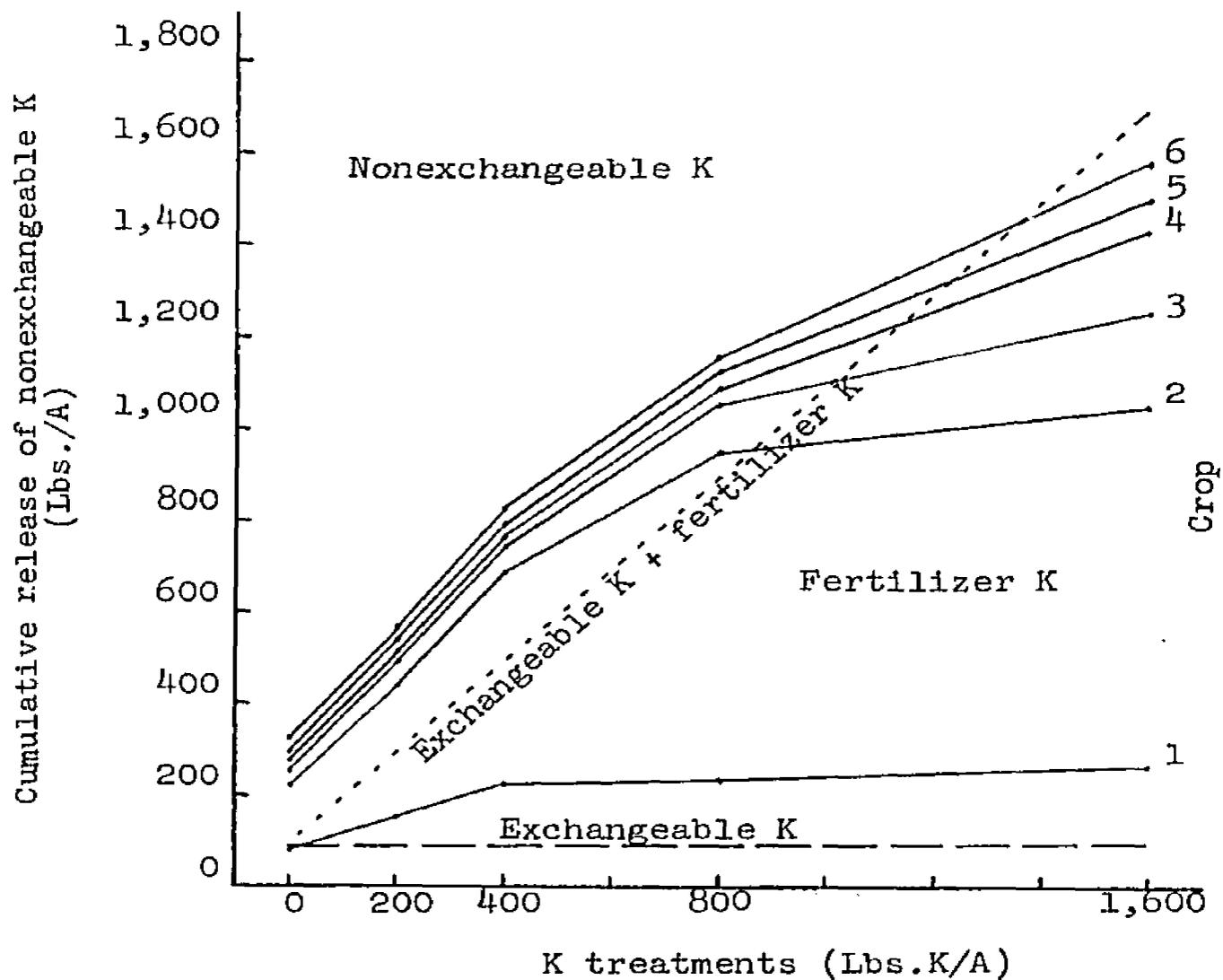


Figure 12. Release of nonexchangeable potassium to the plants at various levels of potassium treatment for Genesee loam<sup>a</sup>

<sup>a</sup>The broken line indicates the original level of exchangeable K. The dotted line indicates exchangeable K plus fertilizer K.

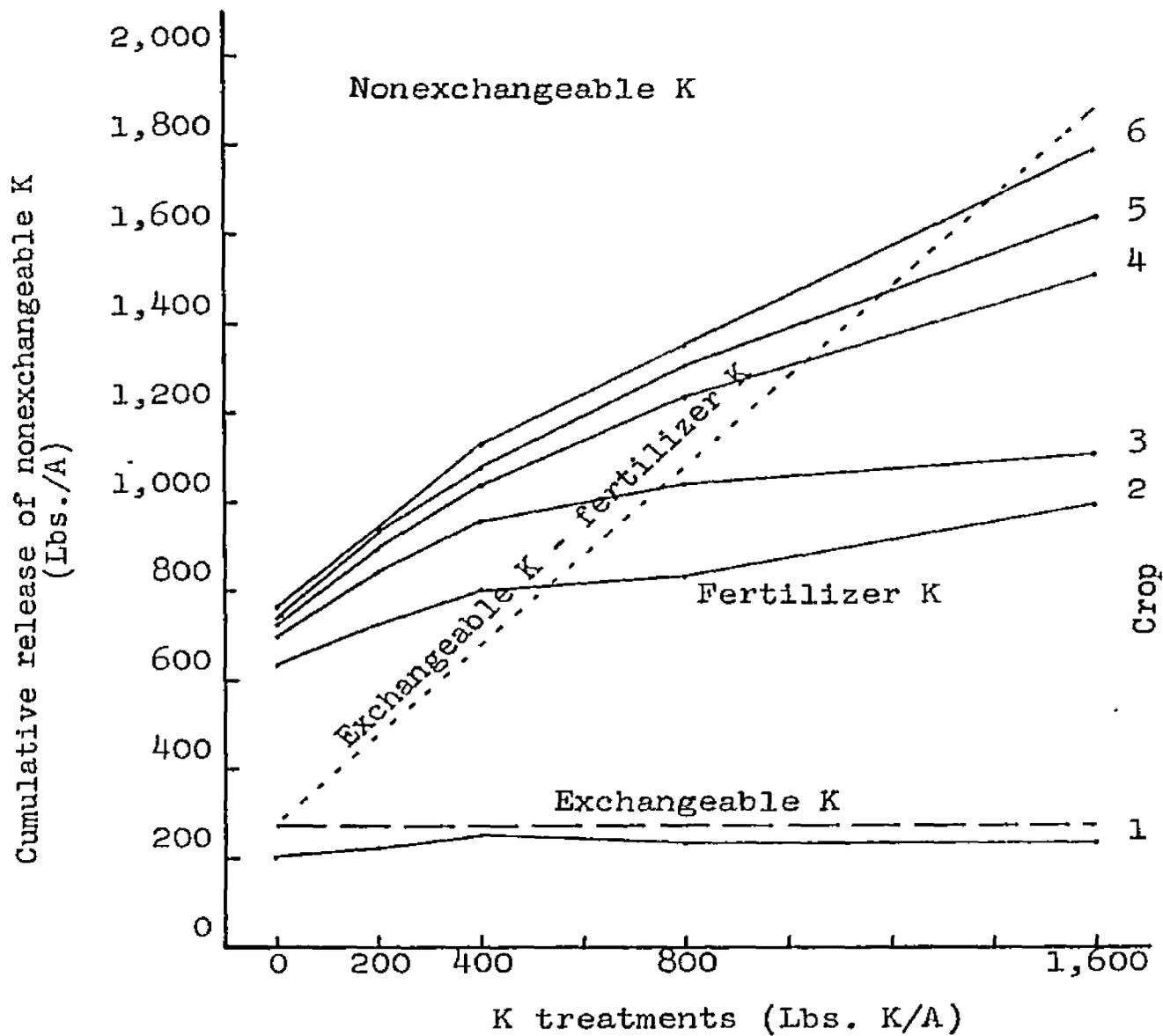


Figure 13. Release of nonexchangeable potassium to the plants at various levels of potassium treatment for Kalamazoo sandy loam<sup>a</sup>

<sup>a</sup>The broken line indicates the original level of exchangeable K. The dotted line indicates exchangeable K plus fertilizer K.

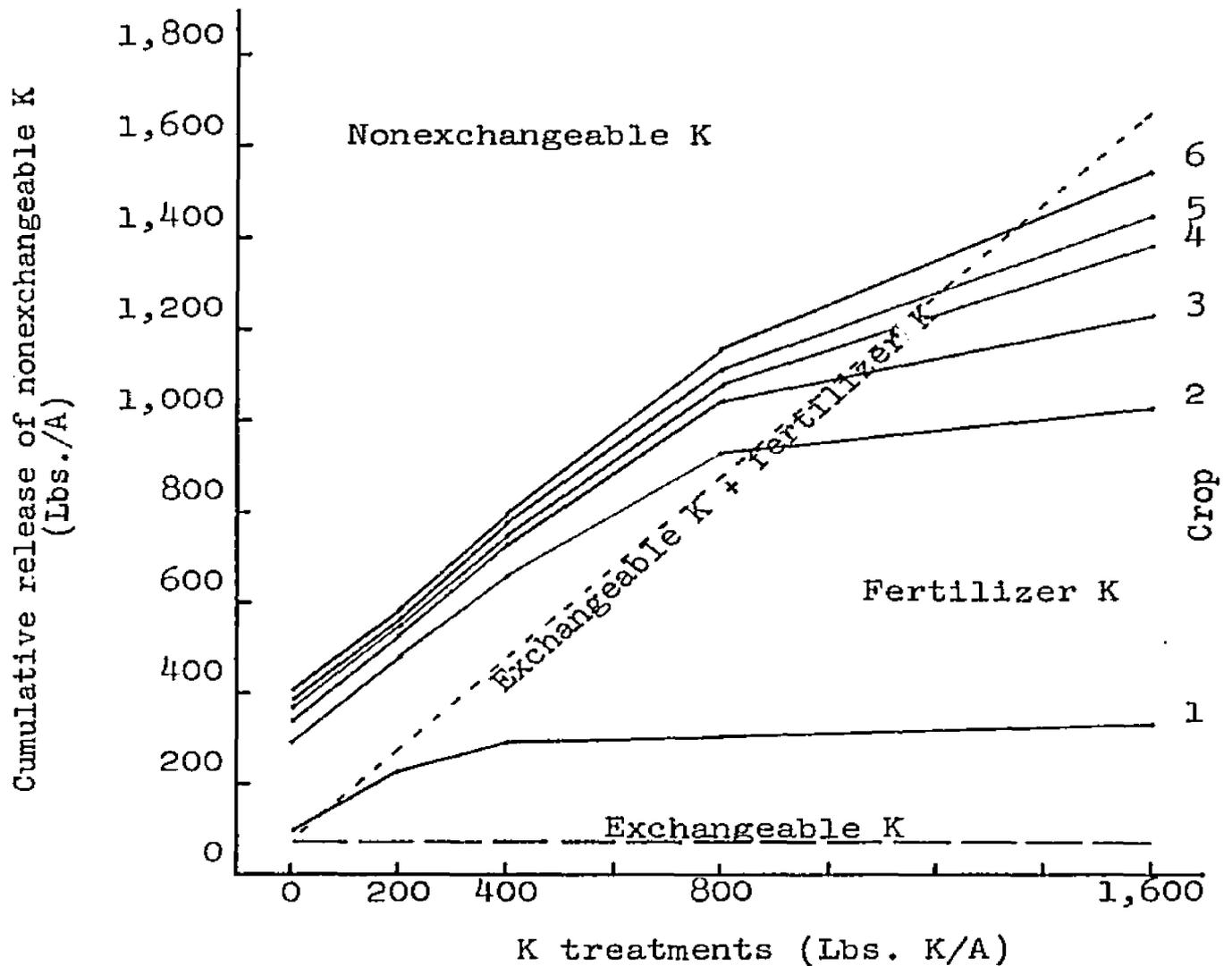


Figure 14. Release of nonexchangeable potassium to the plants at various levels of potassium treatment for Landes-Abscota sandy loam<sup>a</sup>

<sup>a</sup>The broken line indicates the original level of exchangeable K. The dotted line indicates exchangeable K plus fertilizer K.

minerals such as vermiculite-chlorite-montmorillonite interstratified minerals and mica (or illite) present in Genesee loam<sup>4)</sup> seemed to promote the release of nonexchangeable soil potassium by stimulated root growth, which may have intensified plant weathering of the mica or illite (Mortland, et al., 1956, and Conyers and McLean, 1968), by the application of potassium. Genesee loam containing 10% vermiculite and 18% mica in its clay fraction<sup>5)</sup> also appeared to fix the applied potassium at the K=1,600 treatment where the original amount of nonexchangeable soil potassium was not released at all during 6 croppings (Figure 12).

The release of nonexchangeable soil potassium from Kalamazoo sandy loam was much lower in K=800 and K=1,600 treatments than in K=0, K=200, and K=400 treatments (Figure 13) which released from 437 to 480 pounds 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 K=800 and K=1,600 treatments. The exchangeable soil potassium was initially as high as 275 pounds per acre and potassium fixing clay was low (1.7%) in the clay fraction (13.5%).<sup>6)</sup>

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4) See Table 31.

5) See Table 31.

6) See Table 29 and 31.

In Landes-Abscota sandy loam, as shown in Figure 14, nearly the same amounts of nonexchangeable soil potassium were released from the K=0 to K=800 treatments where the potassium release ranged from 319 pounds to 275 pounds per acre. At the K=1,600 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<sup>7)</sup>. Fixed potassium by vermiculite is released at a slower rate than native potassium in biotite (Ellis and Mortland, 1959). 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 (1970), 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 pounds of potassium per acre be applied broadcast and sidedressed respectively to obtain 44,000 pound per acre fresh market yield for transplanted C1327 tomatoes.

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<sup>7)</sup>See Table 31.

## CHAPTER III

### 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 gram sample of the soil with 20 ml. of neutral 1 N  $\text{NH}_4\text{OAc}$  solution for 1 minute and by centrifuging the suspension to collect the clear supernatant. The soil was washed 3 more times with  $\text{NH}_4\text{OAc}$  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  $\text{HNO}_3$  solution.

A 2.5 gram sample of the soil was boiled with 1 N  $\text{HNO}_3$  in a 100 ml. beaker on the hot plate for 25 minutes (Pratt and Morse, 1954). The soil was then filtered and washed with 0.1 N  $\text{HNO}_3$ . 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 periods. The method employed was essentially the same as that of Volk (1934).

A 2.5 gram sample of the soil was placed in a 125 ml. Erlenmyer flask to which 2.5 ml. of 0.1 N  $\text{KCl}$  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  $70^\circ\text{C}$  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  $\text{NH}_4\text{OAc}$  solution and transferred to a centrifuge tube for centrifugal separation of the clear supernatant. The soil was washed 4 more times with  $\text{NH}_4\text{OAc}$  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 KCl solution. The control was kept moist with 2.5 ml. of 0.1 N KCl solution added for two days during the period of the wetting-drying treatment.

### 3. Potassium Release and Fixation by Freezing and Thawing Treatment

Potassium release or fixation by freezing-thawing treatments were studied on the original soils with the similar method to Fine et al., (1940).

A  $2\frac{1}{2}$  gram 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 lbs./in.<sup>2</sup>) 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  $-23^{\circ}\text{C}$  ( $-9.4^{\circ}\text{F}$ ). The soil was then thawed at room temperature of  $25.6^{\circ}\text{C}$  ( $78^{\circ}\text{F}$ ) for 1 hour. Subsequent to 10 freezing-thawing treatments, the soil was washed 5 times with neutral 1 N  $\text{NH}_4\text{AOC}$  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 (1962).

Five gram samples of the soil were placed into five 125 ml. Erlenmeyer flasks and shaken for 1 hour with 0.002 M.  $\text{CaCl}_2$  solution in various concentrations of KCl: 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  $25^\circ\text{C}$ . 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,

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

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,  $0.3281 \times 10^8$  at 25°C,

$a_i$  is a constant which varies for different ions,

$3 \times 10^{-8}$  for  $K^+$ ,  $6 \times 10^{-8}$  for  $Ca^{++}$ ,  $8 \times 10^{-8}$  for  $Mg^{++}$ , and  $3 \times 10^{-8}$  for  $Cl^-$  (Klotz, 1958), and

$\mu$  is ionic strength.

The ionic strength was calculated by the formula,

$$\mu = \frac{1}{2} \sum C_M Z_M^2$$

where:

$C_M$  is the concentration of ion M, and

$Z_M$  is valance of ion M.

Further, activity ratio ( $AR^K$ ) such as  $a_K / \sqrt{a_{(Ca + Mg)}}$

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, defined as  $\Delta Ke$ . The relationship between the  $AR^K$  and  $\Delta Ke$  are presented graphically in Figures A21 to A24. The  $AR^K$  values are on the abscissa and  $\Delta Ke$  values on the ordinate. The activity ratio of the equilibrating solution at  $\Delta Ke = 0$ , which is the point where the soil shows no gains or losses of potassium, was obtained by interpolating the curve to cross the  $\Delta Ke = 0$  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  $\Delta K_e - AR^K$  relationship to cross the  $AR^K = 0$  line and was defined as  $-\Delta K^0$ .

The potential buffering capacity ( $PBC^K$ ) for soil potassium was calculated by dividing the  $-\Delta K^0$  value by the  $AR_e^K$  value as a measure of the capacity of the soil to maintain the potassium availability (Beckett 1964a).

The potassium potential as proposed by Zandstra and Mackenzie (1968) was obtained by multiplying the  $-\Delta K^0$  value by the  $PBC^K$  value.

## B. Results and Discussion

### 1. Exchangeable and Nonexchangeable Potassium

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

As shown in Table 21, the exchangeable potassium decreased by cropping except for Landes-Abscota sandy loam of K=1,600 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.

Application of more than 200 pounds of potassium per acre on all soils increased nonexchangeable potassium over the respective original soils except for Kalamazoo sandy loam where only the K=1,600 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 K=0 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 K=800 and K=1,600 treatments (Table 21).

Nonexchangeable potassium in the incubated soil at K=1,600 treatment for Brookston, Genesee and Landes-Abscota soils, and K=200 treatment for Kalamazoo soil were 156 %, 184 %, 186 % and 101 % respectively, when compared with that of K=0 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%

Table 21. Exchangeable and nonexchangeable potassium in original, cropped and, incubated soils<sup>a</sup>

K treatment	Exchange-able K	Nonexchange-able K	Exchange-able K	Nonexchange-able K
(Lbs./A.)	(Mg./100 g.)			
<u>Brookston loam</u>				
	<u>Original sample</u>			
	10.6	31.9		
	<u>After 5 crops</u>		<u>After incubation</u>	
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
<u>Genesee loam</u>				
	<u>Original sample</u>			
	5.7	24.3		
	<u>After 5 crops</u>		<u>After incubation</u>	
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

Table 21. (cont'd.)

K treatment	Exchange-able K	Nonexchange-able K	Exchange-able K	Nonexchange-able K
(Lbs./A.)	(Mg./100 g.)			
<u>Kalamazoo sandy loam</u>				
<u>Original sample</u>				
	15.0	26.7		
<u>After 5 crops</u>			<u>After incubation</u>	
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
<u>Landes-Abscota sandy loam</u>				
<u>Original sample</u>				
	4.4	20.8		
<u>After 5 crops</u>			<u>After incubation</u>	
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

<sup>a</sup>All values are averages of 2 determinations.

vermiculite in the clay fraction<sup>8)</sup>. Its original nonexchangeable potassium was 31.9 mg. per 100 g. soil (Table 20). 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 K=200 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 HNO<sub>3</sub> before the incubation became extractable and significant as nonexchangeable potassium during the incubation period since nonexchangeable potassium at K=0 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

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8) See Tables 29 and 31.

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 K=0 treatments 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 1st crop responded little to the applied potassium in all the soils (Table 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 K=0 treatment in Brookston loam, Genesee loam, and Landes-Abscota sandy loam. However, the percentage ratios at higher potassium treatments 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.

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

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

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 non-exchangeable potassium approached the limit or that more external potassium was required to satisfy the nonexchangeable potassium holding capacity of the soils approaching the limit.

## 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 KCl solution. The potassium fixation was in the order of Landes-Abscota > 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 100 g. soil higher than the 0.39 me. exchangeable potassium of the soil (Table 24).

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,<sup>9)</sup> 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,

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<sup>9)</sup> See Tables 29 and 31.

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 (%) <sup>b</sup>
		(Mg./100 g.) <sup>a</sup>		
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

<sup>a</sup>All values are averages of 2 determinations.

<sup>b</sup>Percentage of change = (released or fixed K / original K + added K) x 100.

"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

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

Soil	CEC. <sup>a</sup>	Exchange- able K <sup>b</sup>	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

<sup>a</sup>The cation exchange capacity of the soils was taken from Table 1.

<sup>b</sup>The exchangeable K(mg./100 g.) was taken from Table 24 and converted to me./100 g. basis.

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 soils, 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.

Freezing and thawing treatments had only a slight effect on the soils to fix or release potassium. Montmorillonite rich soil, Brookston loam, and kaolinite 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 soil, 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 ( $\Delta K_e$ ) in the equilibrating solution on the ordinate.<sup>10)</sup> The linear portion of the asymptotic curve was extrapolated to cross the points of  $AR^k=0$  and  $\Delta K_e=0$ . The cross points of the curve and  $AR^k=0$ , and the curve and  $\Delta K_e=0$  were determined as  $-\Delta K^0$  and  $AR_e^k$  respectively. The  $-\Delta K^0$  represents the changes of potassium concentration in the equilibrating

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<sup>10)</sup> See Figures A21 to A24.

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

Treatment	Soil	Exchangeable K		Release (-) or fixation (+)	Change <sup>b</sup> (%)
		Before treatment <sup>a</sup>	After treatment		
		—————(Mg. K/100 g.) <sup>c</sup> —————			
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

<sup>a</sup>Exchangeable k before treatment was determined on air-dry samples.

<sup>b</sup>Percentage of change = (released or fixed K/originally exchangeable K) x 100.

<sup>c</sup>All values are averages of 2 determinations.

solution when the activity ratio,  $AR^k = a_K / \sqrt{a(Ca + Mg)}$ , 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 (1962). 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 A21 to A24. The values of  $-\Delta K^0$ ,  $AR_e^k$ ,  $PBC^k$  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  $-\Delta K^0$  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 (1964a), 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 occurred. 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,<sup>11)</sup> a more rapid release

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<sup>11)</sup> See Table 22.

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

Sample	K treatment	$\Delta K^0$	$AR_e^k$	PBC <sup>k</sup>	K potential
	(Lbs./A.)	$\left(\frac{.Me.}{100\ g.}\right)$	$\left(\frac{M.}{I.}\right)^{\frac{1}{2}}$	$\frac{-\Delta K^0}{(AR_e^k)}$	$(-\Delta K^0 \times PBC^k)$
<u>Brookston loam</u>					
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
<u>Genesee loam</u>					
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	0.0008	62.5	3.1
	800	0.050	0.0008	62.5	3.1
	1,600	0.070	0.0012	58.3	4.1

Table 26 (cont'd.)

Sample	K treatment	$-\Delta K^0$	$AR_e^k$	$PBC^k$	K potential
	(Lbs./A.)	$\left(\frac{Me.}{100\ g.}\right)$	$\left(\frac{M.}{1.}\right)^{\frac{1}{2}}$	$\frac{-\Delta K^0}{(AR_e^k)}$	$(-\Delta K^0 \times PBC^k)$
<u>Kalamazoo sandy loam</u>					
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
<u>Landes-Abscota sandy loam</u>					
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 (Lbs./A.)	$-\Delta K^O$ $\left(\frac{\text{Me.}}{100 \text{ g.}}\right)$	$AR_e^k$ $\left(\frac{\text{M.}}{\text{l.}}\right)^{\frac{1}{2}}$	$PBC^k$ $\frac{-\Delta K^O}{(AR_e^k)}$	K potential $(-\Delta K^O \times PBC^k)$
<u>Brookston loam</u>					
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
<u>Genesee loam</u>					
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	0.0159	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

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.

Table 27 (cont'd.)

Period of incubation	K treatment (Lbs./A.)	$-\Delta K^O$ ( $\frac{\text{Me.}}{100 \text{ g.}}$ )	$AR_e^k$ ( $\frac{\text{M.}}{1.}$ ) <sup>1/2</sup>	$PBC^k$ ( $\frac{-\Delta K^O}{AR_e^k}$ )	K potential ( $-\Delta K^O \times PBC^k$ )
<u>Kalamazoo sandy loam</u>					
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
<u>Landes-Abscota sandy loam</u>					
6 months	0	0.080	0.0012	66.7	5.3
	200	0.120	0.0016	75.0	9.0
	400	0.140	0.0022	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

In the incubated soils, both the  $-\Delta K^O$  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  $-\Delta K^O$  and  $AR_e^k$  values was not clear. This suggests that adequate equilibrium between nonexchangeable and exchangeable potassium ( $-\Delta K^O$ ) and potassium in the soil solution could be attained at least within 6 months.

The potassium potential which was obtained by multiplying the  $-\Delta K^O$  value by the  $PBC^k$  value to magnify 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 measurements are the best indicators of soil potassium availability, simple correlation coefficients were calculated for potassium uptake of the respective crops and the various measurements of soil potassium, and presented in Table 28. The values shown in Tables 9 to 12 were used for the plant uptake of potassium;  $-\Delta K^O$ ,  $AR_e^k$ ,  $PBC^k$  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 $-\Delta K^O$ and $AR_e^k$

In general, both  $-\Delta K^O$  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  $-\Delta K^0$  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 potassium and the  $-\Delta K^0$  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 correlate 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  $-\Delta K^0$  by  $PBC^k$  values, appeared to be correlated with plant uptake of potassium. The K potential values, however, were generally inferior to  $-\Delta K^0$  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

Table 28. Relationships 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 coefficient (r) <sup>a</sup>						
<u>Brookston loam</u>						
<u>After the 2nd crop</u>						
$-\Delta K^0$	0.28	0.62	0.98**	0.97**	0.99**	0.98*
AR <sub>e</sub> <sup>k</sup>	0.26	0.62	0.97**	0.98**	0.99**	0.97*
PBC <sub>e</sub> <sup>k</sup>	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
<u>After the 5th crop</u>						
$-\Delta K^0$	0.79*	0.94*	0.93*	0.70	0.85	0.93*
AR <sub>e</sub> <sup>k</sup>	0.70	0.89*	0.97**	0.78	0.90*	0.96*
PBC <sub>e</sub> <sup>k</sup>	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*	0.98**	0.98*
Nonex- changeable 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*
<u>Genesee loam</u>						
<u>After the 2nd crop</u>						
$-\Delta K^0$	0.65	0.73	0.95*	0.99**	0.97**	0.98*
AR <sub>e</sub> <sup>k</sup>	0.62	0.72	0.95*	0.99**	0.97**	0.98*
PBC <sub>e</sub> <sup>k</sup>	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*
<u>After the 5th crop</u>						
$-\Delta K^0$	0.13	0.35	0.67	0.84	0.72	0.74
AR <sub>e</sub> <sup>k</sup>	0.52	0.68	0.88*	0.92*	0.92*	0.92*
PBC <sub>e</sub> <sup>k</sup>	-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
Exchangeable K	0.49	0.64	0.92*	0.98**	0.92*	0.93*
Nonex- changeable 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) <sup>a</sup>					
	Kalamazoo sandy loam					
<u>After the 2nd crop</u>						
$-\Delta K^0$	0.43	0.93*	0.85	1.00**	1.00**	1.00**
$AR_{eK}^k$	0.36	0.90*	0.81	1.00**	1.00**	1.00**
PBC <sup>K</sup>	-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**
<u>After the 5th crop</u>						
$-\Delta K^0$	0.31	0.83	0.70	0.96**	0.97**	0.97**
$AR_{eK}^k$	0.25	0.80	0.67	0.96**	0.97**	0.96**
PBC <sup>K</sup>	-0.01	-0.75	-0.65	-0.93**	-0.90*	-0.89*
K potential	0.46	0.85	0.74	0.94*	0.96*	0.96**
Exchange- able K	0.29	0.83	0.70	0.97*	0.98**	0.97**
Nonexchange- able 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					
<u>After the 2nd crop</u>						
$-\Delta K^0$	0.74	0.89*	0.97**	0.93*	1.00**	0.97**
$AR_{eK}^k$	0.65	0.82	0.96**	0.98**	0.99**	0.99**
PBC <sup>K</sup>	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*
<u>After the 5th crop</u>						
$-\Delta K^0$	0.91*	0.94*	0.92*	0.80	0.95*	0.89*
$AR_{eK}^k$	0.87	0.95*	0.96**	0.83	0.97**	0.92*
PBC <sup>K</sup>	-0.27	-0.69	-0.77	-0.68	-0.65	-0.75
K potential	0.95*	0.90*	0.87	0.74	0.91*	0.83
Exchange- able 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*
Total K	0.77	0.84	0.95*	0.93*	0.98**	0.95*

<sup>a</sup>\* and \*\* indicate significance at 5% and 1% probability levels respectively.

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 Genesee 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.

## CHAPTER IV

### PHYSICAL AND MINERALOGICAL PROPERTIES OF THE 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 (1965).

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 ( $20.5^{\circ}\text{C}$ ). 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 calculated with sedimentation

time and sedimentation parameters suggested by Day (1965).

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 K=0 treatment and K=1,600 treatment, and samples collected from the K=1,600 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 (1965). Clay films for the X-ray diffraction studies were prepared according to the method designed by Mortland (1969).

### 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 acetic 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%  $H_2O_2$  was added and the mixture was carefully stirred. A second 5 ml. increment of  $H_2O_2$  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  $H_2O_2$  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 solution. 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 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 magnesium. 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 magnesium-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 Fraction

The cation exchange capacity and total potassium of the clay fractions were determined according to the method designed by Mortland (1969).

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 (Ca/Mg) was determined by saturating the clay with calcium ion and then replacing it with the magnesium ion. Secondly, the cation exchange capacity (K/NH<sub>4</sub>) was determined by saturating the clay with potassium ion and then replacing it with the 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 =  $((\text{CEC. by Ca/Mg} - \text{CEC. by K/NH}_4) / 153.9) \times 100$ .

For the determination of total potassium, the clay was digested with hydrofloric 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 (Soil Survey Manual, 1953).

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

Separate	Size	Soil			
		Brookston	Genesee	Kalamazoo	Landes-Abscota
	Mm.	% of separate <sup>a</sup>			
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

<sup>a</sup>All values are averages of 2 determinations.

## 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 (Ca/Mg) of the whole soil (Table 1) is: Brookston loam > Genesee loam > Landes-Abscota 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.

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. (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.

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) <sup>a</sup>	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)

<sup>a</sup>The values in the parentheses show the percentages of CEC. derived from the respective 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. The Cation Exchange Capacities, and Kinds and Relative Amounts of Minerals Present in the Clay Fractions of the Original Soils

The cation exchange capacity values (CECs.) determined by Ca/Mg and K/NH<sub>4</sub> 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 A25 to A46.

It was found when the CECs. are higher, the amount of montmorillonite and vermiculite were higher. The reported CEC. values 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 (Grim, 1953).

Since the clay fraction of Brookston loam contained a large quantity of montmorillonite plus vermiculite, it shows a higher CEC. (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 (Ca/Mg). The clay fraction of Kalamazoo sandy loam showed lower activity in the CEC. (Ca/Mg) and in the fixation of potassium, which was indicated by the difference between the CECs. by Ca/Mg and by K/NH<sub>4</sub>, when compared with the other soils. Vermiculite-chlorite interstratified minerals were dominant in the 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

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 <sup>a</sup> and relative amounts <sup>b</sup> of minerals present in clay fraction
	Ca/Mg	K/NH <sub>4</sub>				
	Me./100 g.		%	%	%	
<u>Brookston loam</u>						
Original soil	45.1	32.4	8.3	2.3	27.6	++++ ++ ++ ++ ++ + Mo>V>Mi>Q>Ka>Ch
5 crops with 0 lbs.K/A.	48.1	33.3	9.6	1.9	22.8	++++ ++ ++ ++ ++ + Mo>V>Mi>Ka>Q>Ch
5 crops with 1,600 lbs.K/A.	43.2	31.2	7.8	1.9	22.8	++++ ++ ++ ++ ++ + Mo>V>Mi>Q>Ka>Ch
Incubated with 1,600 lbs.K/A.	41.5	32.6	5.9	2.3	27.6	++++ ++ ++ ++ ++ + Mo>V>Mi>Q>Ka>Ch
<u>Genesee loam</u>						
Original soil	43.1	27.7	10.0	1.5	18.0	+++    ++    +    + Ka>V-ch-mo >Mi >Q
5 crops with 0 lbs.K/A.	44.5	28.6	10.3	1.5	18.0	+++    ++    +    + Ka>V-ch-mo>Mi>Q
5 crops with 1,600 lbs.K/A.	45.3	32.8	8.2	1.7	20.4	+++    ++    ++    + Ka>V-ch-mo>Mi>Q
Incubated with 1,600 lbs.K/A.	43.2	33.1	6.6	1.7	20.4	+++    ++    ++    + Ka>V-ch-mo>Mi>Q

Table 31. (cont'd.)

K treatment and cropping	CEC.		Vermiculite	Total K	Mica	Kinds <sup>a</sup> and relative amounts <sup>b</sup> of minerals present in clay fraction
	Ca/Mg	K/NH <sub>4</sub>				
	Me./100 g.		%	%	%	
			<u>Kalamazoo sandy loam</u>			
Original soil	28.2	25.5	1.7	1.5	18.0	+++ +++ ++ + + V-ch > Ka > Q > Mi > Ch
5 crops with 0 lbs.K/A	25.2	22.4	1.8	1.4	16.8	+++ +++ ++ + + V-ch > Ka > Q > Mi > Ch
5 crops with 1,600 lbs.K/A.	26.0	23.9	1.4	1.5	18.0	+++ ++ ++ + + V-ch > Ka > Q > Mi > Ch
Incubated with 1,600 lbs.K/A.	30.0	27.3	1.8	1.5	18.0	++++ ++ ++ + + V-ch > Ka > Q > Mi > Ch
			<u>Landes-Abscota sandy loam</u>			
Original soil	42.7	29.0	8.9	2.4	28.8	+++ ++ ++ + V-ch > Mi > Ka > Q
5 crops with 0 lbs. K/A.	46.6	27.9	12.2	2.0	24.0	+++ ++ ++ ++ + V > Mi > Ka > V-ch-mo > Q
5 crops with 1,600 lbs.K/A.	41.7	28.5	8.6	2.4	28.8	+++ ++ ++ + + V > Mi > Ka > Mo-ch > Q
Incubated with 1,600 lbs.K/A.	37.6	28.5	5.9	2.7	32.4	+++ ++ ++ + + Mi > V-ch > Ka > Mo-ch > Q

<sup>a</sup>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= vermiculite-chlorite-montmorillonite interstratified minerals.

<sup>b</sup>Number of + indicates relative quantity of the minerals; ++++= very high, +++= high, ++= medium and += low.

soils in the CEC. and potassium fixation, although it must be studied in the future, was probably that: (1) 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, (2) gibbsite-like layers may have been formed in vermiculite-chlorite interstratified minerals of Kalamazoo sandy loam but brucite-like layers in that of Landes-Abscota sandy loam, and (3) 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: (1) the potassium fixation (the difference between the cation exchange capacity by Ca/Mg and K/NH<sub>4</sub>) was caused only by vermiculite; and (2) 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 Brookston 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), 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 (Mortland et al., 1956, and Conyers and McLean, 1968), 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.<sup>12)</sup> The percentage of vermiculite markedly decreased when the soil was incubated for 13 months with K=1,600 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  $10 \text{ \AA}$  peak was recognized in the X-ray diffraction pattern (Figure A27) indicating the change of vermiculite to mica (or illite). The alteration of clay minerals appears more sensitively reflected in the X-ray diffraction pattern than in the potassium content of the clay minerals (Mortland et al., 1956). Mineralogical changes occurring in Genesee loam were not detected from potassium exhaustion by cropping. This is likely to mean that the soil potassium had already been depleted before the experiment was initiated. The decrease in the percentage

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<sup>12)</sup> See Tables 3 and 6.

of vermiculite and the increase in the percentage of mica (or illite) took place when the soil was cropped with enough potassium ( $K=1,600$ ) and also when incubated with this rate of potassium, indicating the changes of vermiculite to mica (or illite) after fixing applied potassium as observed by Rich and Lutz (1965).

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  $K=1,600$  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 rates.<sup>13)</sup> If the rate of release is too slow, it may become a barrier for potassium supply of the soils to plants,<sup>14)</sup> as suggested by Mortland (1958).

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<sup>13)</sup> See Figures 11, 12, and 14.

<sup>14)</sup> See Figures 12 and 14.

## 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 pounds 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 powers 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 magnesium, 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 K=0 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 electron microprobe X-ray technique. A higher concentration of potassium but a lower concentration of calcium and magnesium was obtained for the sample from the K=400 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 K=0 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 pounds 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 pounds 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  $-\Delta K^0$  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  $-\Delta K^0$  by  $PBC^k$  values tended to increase with the levels of applied potassium in both cropped and incubated soils but decreased by cropping.

When  $-\Delta K^0$ ,  $AR_e^k$ ,  $PBC^k$ , K potential, and exchangeable, nonexchangeable, and total potassium (the sum of exchangeable and nonexchangeable potassium) were correlated with the plant uptake of potassium,  $-\Delta K^0$ ,  $AR_e^k$  and exchangeable potassium offered better measurements 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  $-\Delta K^0$ ,  $AR_e^k$  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 grams 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 respectively.

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 pounds 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 cropping, most remarkably in Landes-Abscota sandy loam.

The percentage of mica in the clay fractions tended to increase in Kalamazoo and Landes-Abscota soils when the soils were incubated with 1,600 pounds of potassium 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 6 crops with K=1,600 treatment.

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## APPENDICES

## APPENDIX A

### DESCRIPTIONS OF THE SOILS

#### 1. Brookston Loam

The poorly drained Brookston series developed from loam or silt loam parent materials (Whiteside et al., 1963). 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 <sub>1g</sub>	9 - 21"	Clay loam; gray (5Y 5/1); moderate; medium, subangular blocky structure; firm; pH 7.5; clear smooth boundary.
B <sub>2g</sub>	21 - 34"	Silt loam; yellowish brown (10YR 5/6) to brown (7.5YR 5/3) with dark brown (7.5YR 3/2) mottles; weak, coarse, subangular blocky structure; friable; pH 7.8; abrupt wavy boundary.
C <sub>g</sub>	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 (Schneider et al., 1967). 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 <sub>2</sub>	8 - 26"	Loam; dark reddish brown (5YR 3/4); moderate, medium subangular blocky structure; friable; pH 7.0; abrupt wavy boundary.
IIC <sub>1</sub>	26 - 45"	Sandy loam; yellowish brown (10YR 5/6); weak, medium subangular blocky structure; friable; pH 7.5; clear wavy boundary.
IIIC <sub>2</sub>	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 (Kerr et al., 1927). The soil profile description of Kalamazoo sandy loam at the collection site follows:

Horizons	Depth	Descriptions
Ap	0 - 8"	Sandy loam; dark reddish brown (5YR 3/2); weak, fine granular structure; very friable; pH 7.1; abrupt smooth boundary.
B <sub>21t</sub>	8 - 15"	Clay loam; dark reddish brown (5YR 3/4); weak, fine, subangular blocky structure; friable; pH 6.7; gradual wavy boundary.
B <sub>22t</sub>	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 <sub>23</sub>	20 - 25"	Loamy sand; dark brown (7.5YR 4/4); weak, fine, subangular blocky structure; very friable; pH 5.4; clear wavy boundary.
B <sub>3</sub>	25 - 50"	Loamy sand to sand; dark brown (7.5YR 4/4); single grain structure; 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 characteristics 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 (Kerr et al., 1927, and Schneider et al., 1967). 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 <sub>12</sub>	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 <sub>3</sub>	12 - 14"	Loamy sand; dark reddish brown (5YR 3/3); weak, fine granular structure; very friable; pH 7.8; clear wavy boundary.
B <sub>21</sub>	14 - 20"	Loamy sand; dark reddish brown (5YR 3/4); weak, very fine subangular blocky structure; very friable; pH 8.0; clear wavy boundary.
B <sub>22</sub>	20 - 32"	Sand; strong brown (7.5YR 5/6); single grain structure; loose; pH 8.0; abrupt wavy structure.
IIC	32 - 42"	Fine sand and silt; light brownish gray (10YR 6/2); stratified; friable; calcareous; abrupt wavy boundary.

Horizons	Depth	Description
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

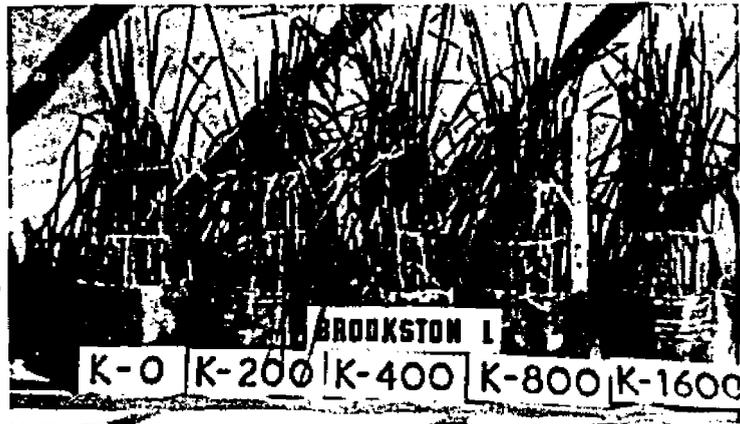
PHOTOGRAPHS OF THE GROWTH RESPONSE OF WHEAT, SORGHUM,  
AND TOMATOES TO POTASSIUM ON BROOKSTON LOAM

Figure 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).

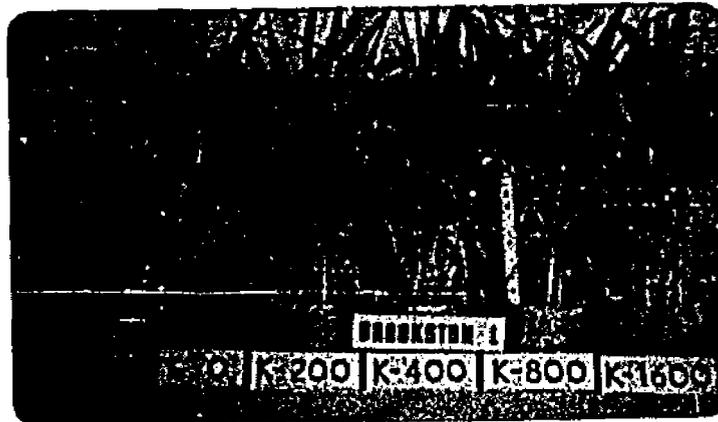


Figure A2. The 4th crop (sorghum) at 48 days of growth on Brookston loam. Potassium treatments had no effect on plant yields (Tables 3 and 7).

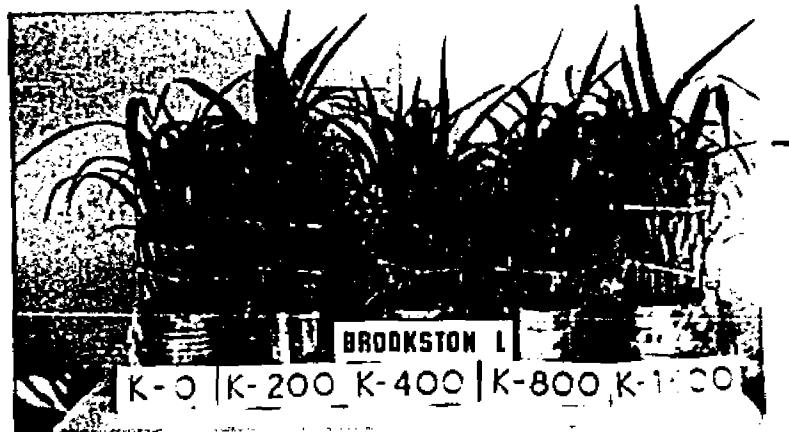


Figure A3. The 5th crop (sorghum) at 70 days of growth on Brookston loam. Potassium treatments had no effect on plant yields (Tables 3 and 7).

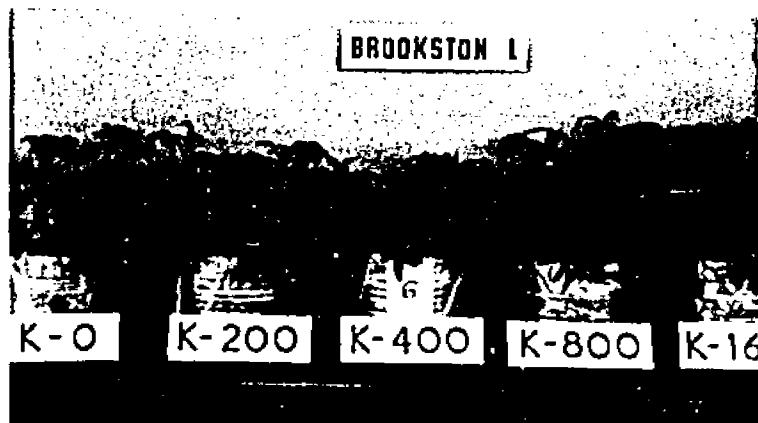


Figure A4. The 6th crop (tomato) at 40 days of growth on Brookston loam. Potassium treatments significantly affected plant yields (Tables 3 and 7).

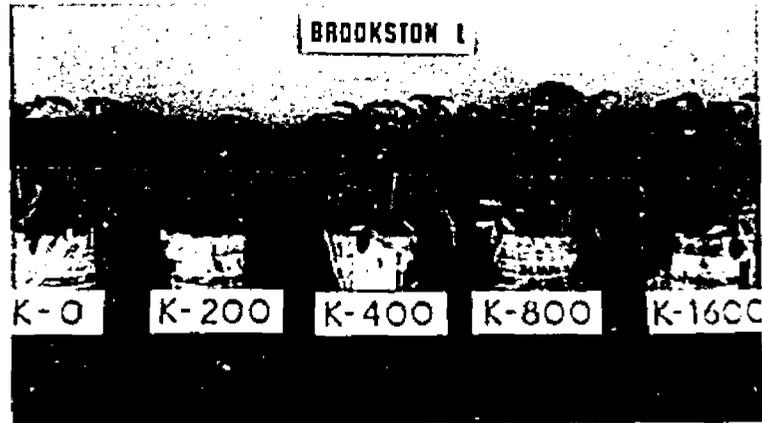


Figure A5. Tomato plants at 40 days of growth on the uncropped soil of Brookston loam. Plant yields were not affected by potassium treatments (Table 8).

## APPENDIX C

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

Figure A6. The 2nd crop (wheat) at 40 days of growth on Genesee loam. Potassium treatments had no effect on plant yields (Tables 4 and 7).



Figure A7. The 4th crop (sorghum) at 48 days of growth on Genesee loam. Potassium treatments significantly affected plant yields (Tables 4 and 7).

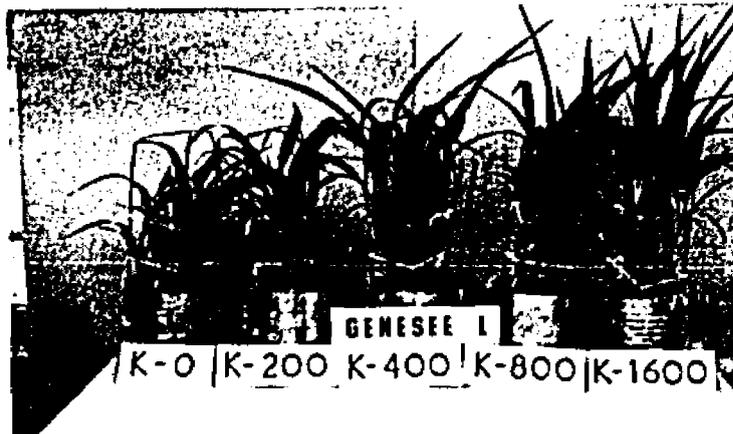


Figure A8. The 5th crop (sorghum) at 70 days of growth on Genesee loam. Potassium treatments significantly affected plant yields (Tables 4 and 7).

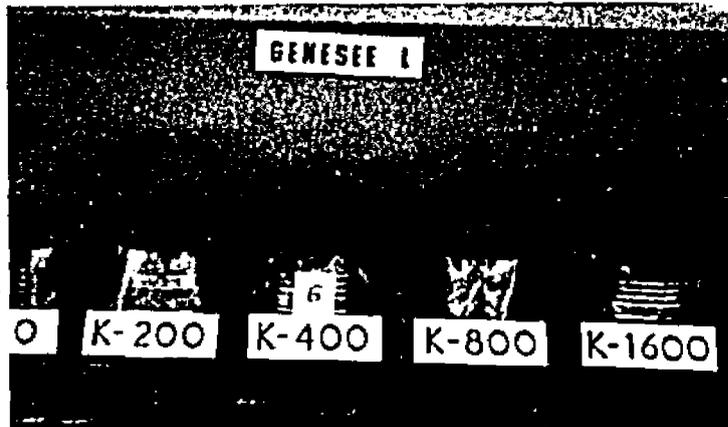


Figure A9. The 6th crop (tomato) at 40 days of growth on Genesee loam. Potassium treatments significantly affected plant yields (Tables 4 and 7).

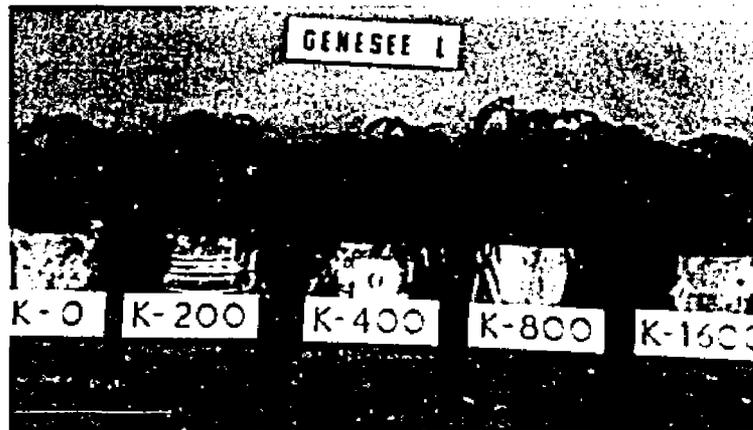


Figure A10. Tomato plants at 40 days of growth on the uncropped soil of Genesee loam. Potassium treatments had no effect on plant yields (Table 8).

## APPENDIX D

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

Figure A11. 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).

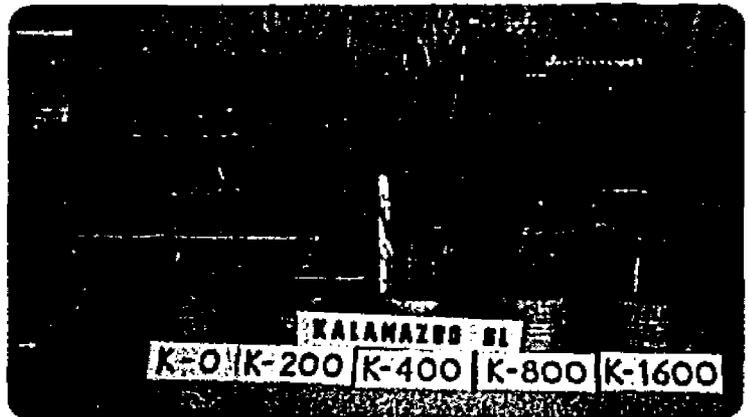


Figure A12. The 4th crop (sorghum) at 48 days of growth on Kalamazoo sandy loam. Potassium treatments significantly affected plant yields (Tables 5 and 7).



Figure A13. The 5th crop (sorghum) at 70 days of growth on Kalamazoo sandy loam. Potassium treatments significantly affected plant yields (Tables 5 and 7).



Figure A14. The 6th crop (tomato) at 40 days of growth on Kalamazoo sandy loam. Potassium treatments significantly affected plant yields (Tables 5 and 7).

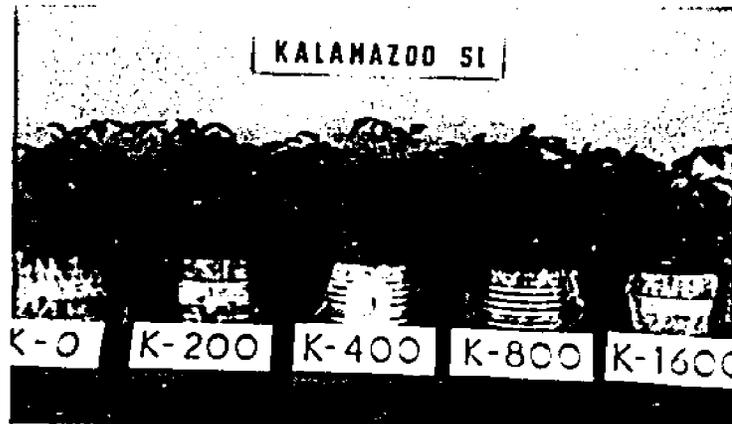


Figure A15. Tomato plants at 40 days of growth on the uncropped soil of Kalamazoo sandy loam. Potassium treatments had no effect on plant yields (Table 8).

## APPENDIX E

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



Figure A16. 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).

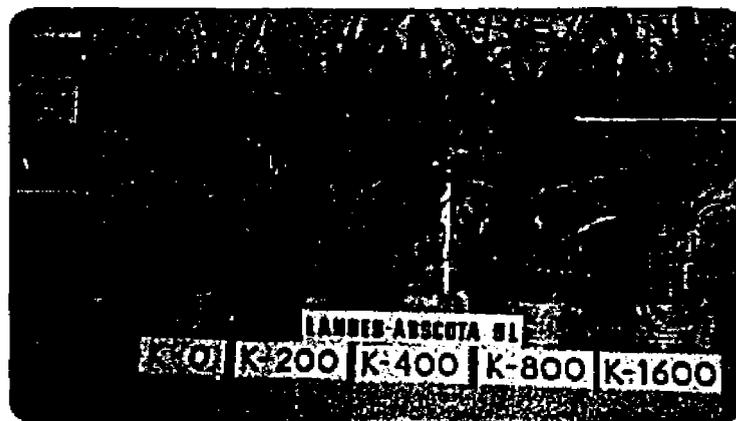


Figure A17. The 4th crop (sorghum) at 48 days of growth on Landes-Abscota sandy loam. Potassium treatments significantly affected plant yields (Tables 6 and 7).

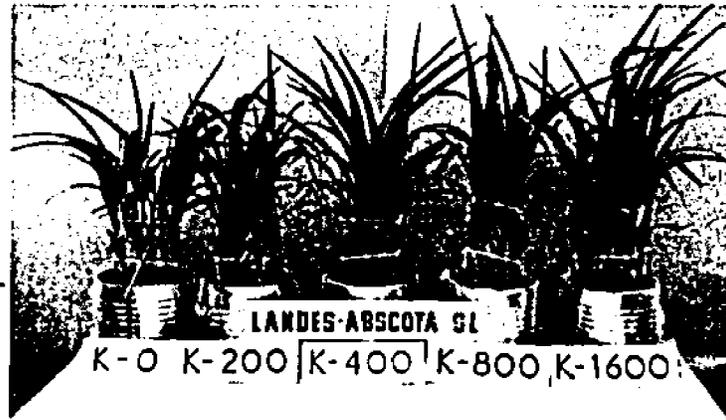


Figure A18. The 5th crop (sorghum) at 70 days of growth on Landes-Abscota sandy loam. Potassium treatments significantly affected plant yields (Tables 6 and 7).

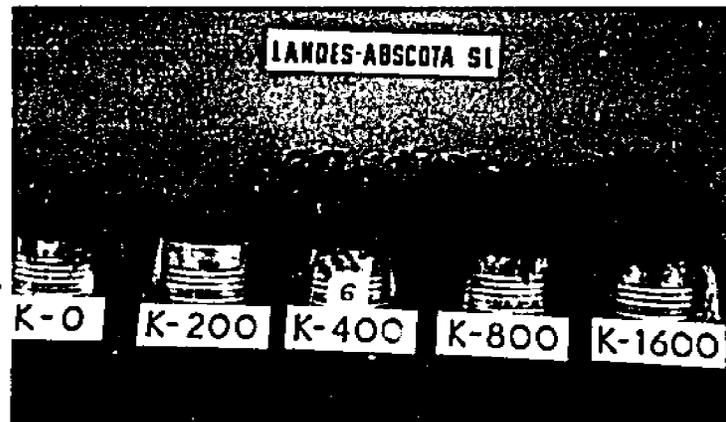


Figure A19. The 6th crop (tomato) at 40 days of growth on Landes-Abscota sandy loam. Potassium treatments significantly affected plant yields (Tables 6 and 7).

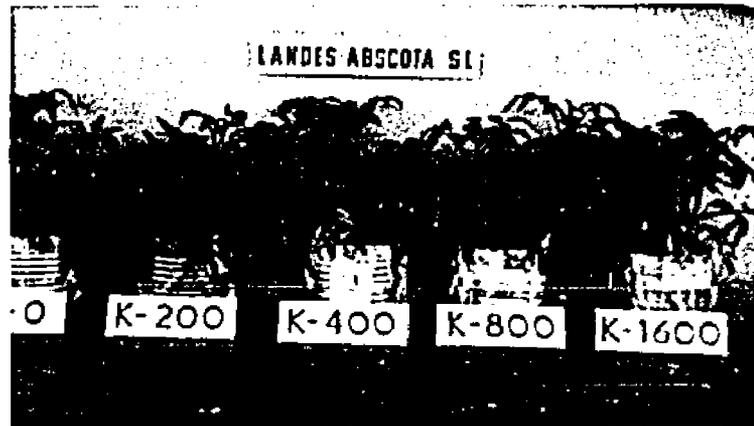


Figure A20. Tomato plants at 40 days of growth on the uncropped soil of Landes-Abscota sandy loam. Potassium treatments had no effect on plant yields (Table 8).

## APPENDIX F

RELATIONSHIPS OF POTASSIUM ACTIVITY RATIO ( $AR^k$ )  
TO POTASSIUM ADSORPTION OR RELEASE ( $\Delta K_e$ )  
ON THE UNCROPPED SOILS

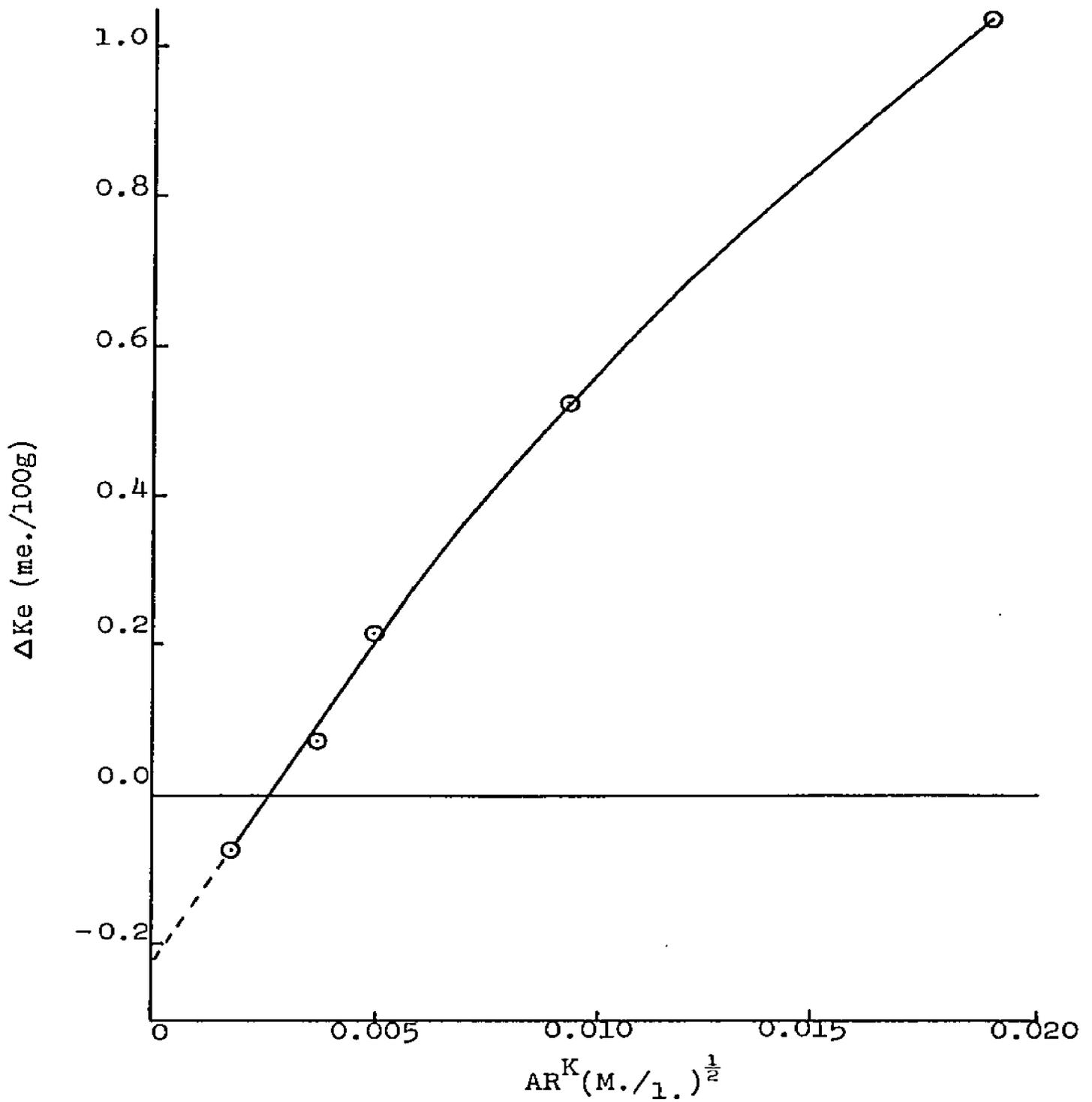


Figure A21. Relationship of potassium activity ratio ( $AR^K$ ) to potassium adsorption or release ( $\Delta K_e$ ) on Brookston loam

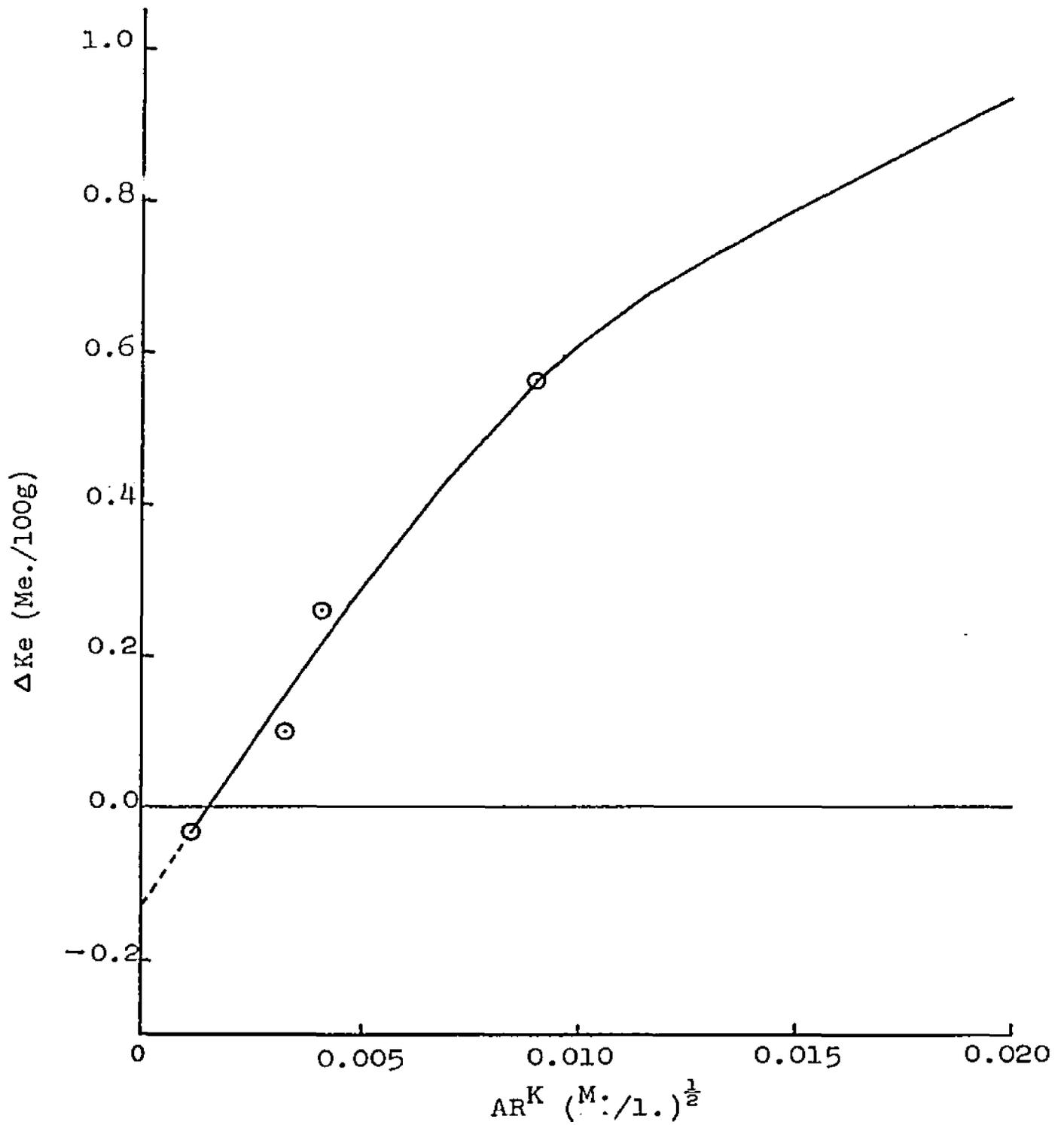


Figure A22. Relationship of potassium activity ratio ( $AR^K$ ) to potassium adsorption or release ( $\Delta K_e$ ) on Genesee loam

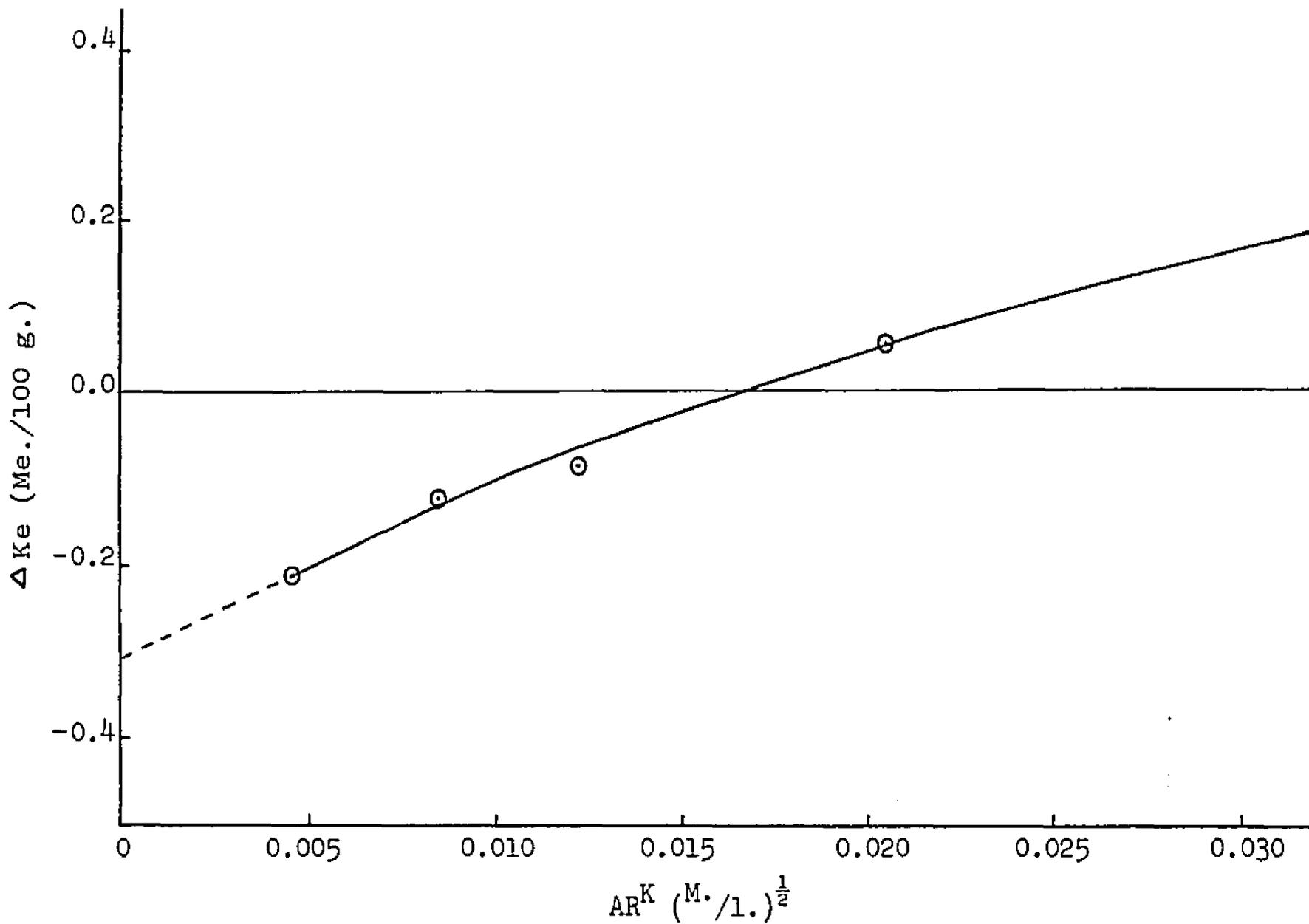


Figure A23. Relationship of potassium activity ratio ( $AR^K$ ) to potassium adsorption or release ( $\Delta Ke$ ) on Kalamazoo sandy loam

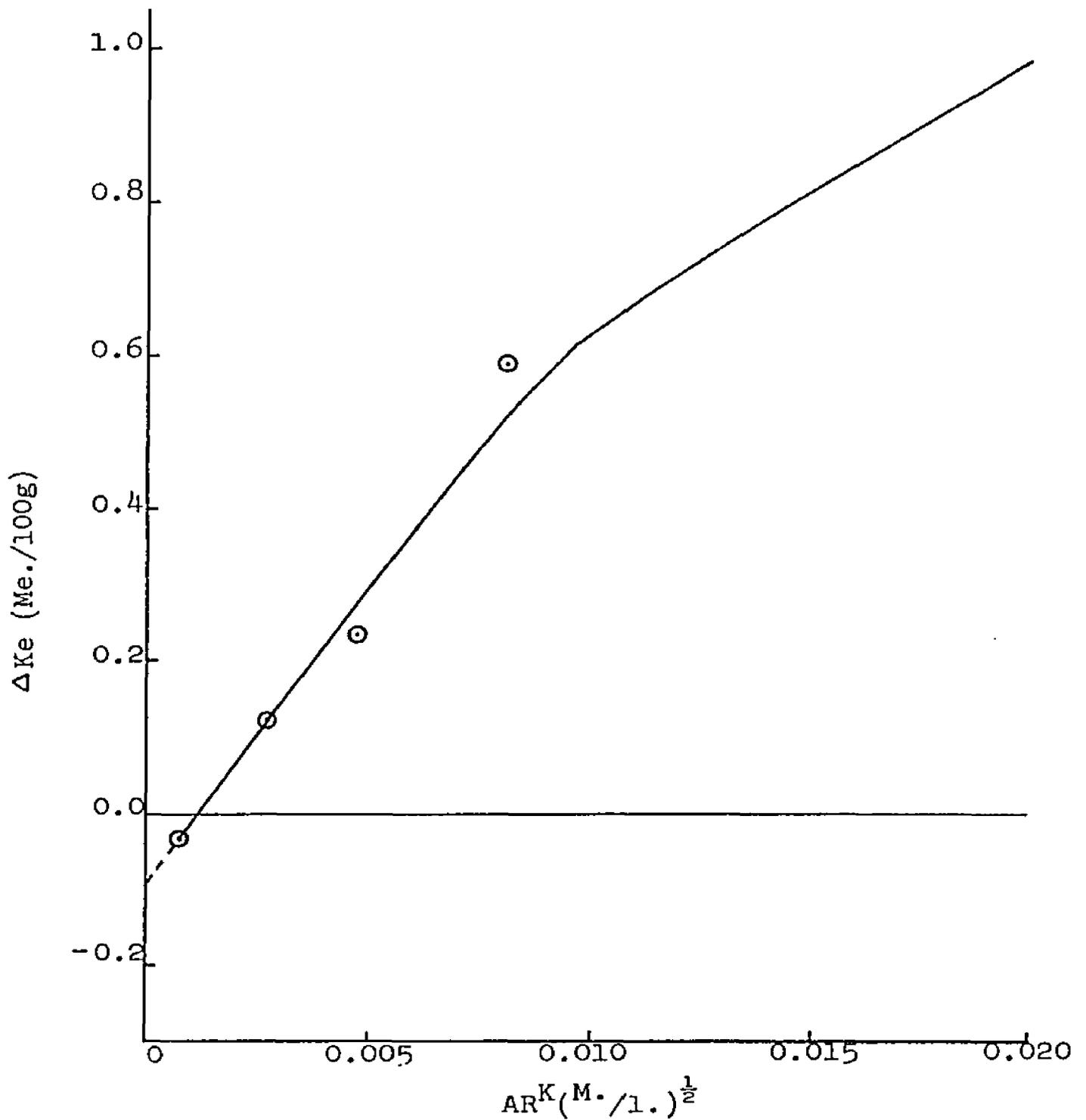


Figure A24. Relationship of potassium activity ratio ( $AR^K$ ) to potassium adsorption or release ( $\Delta K_e$ ) on Landes-Abscota loam

## 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.

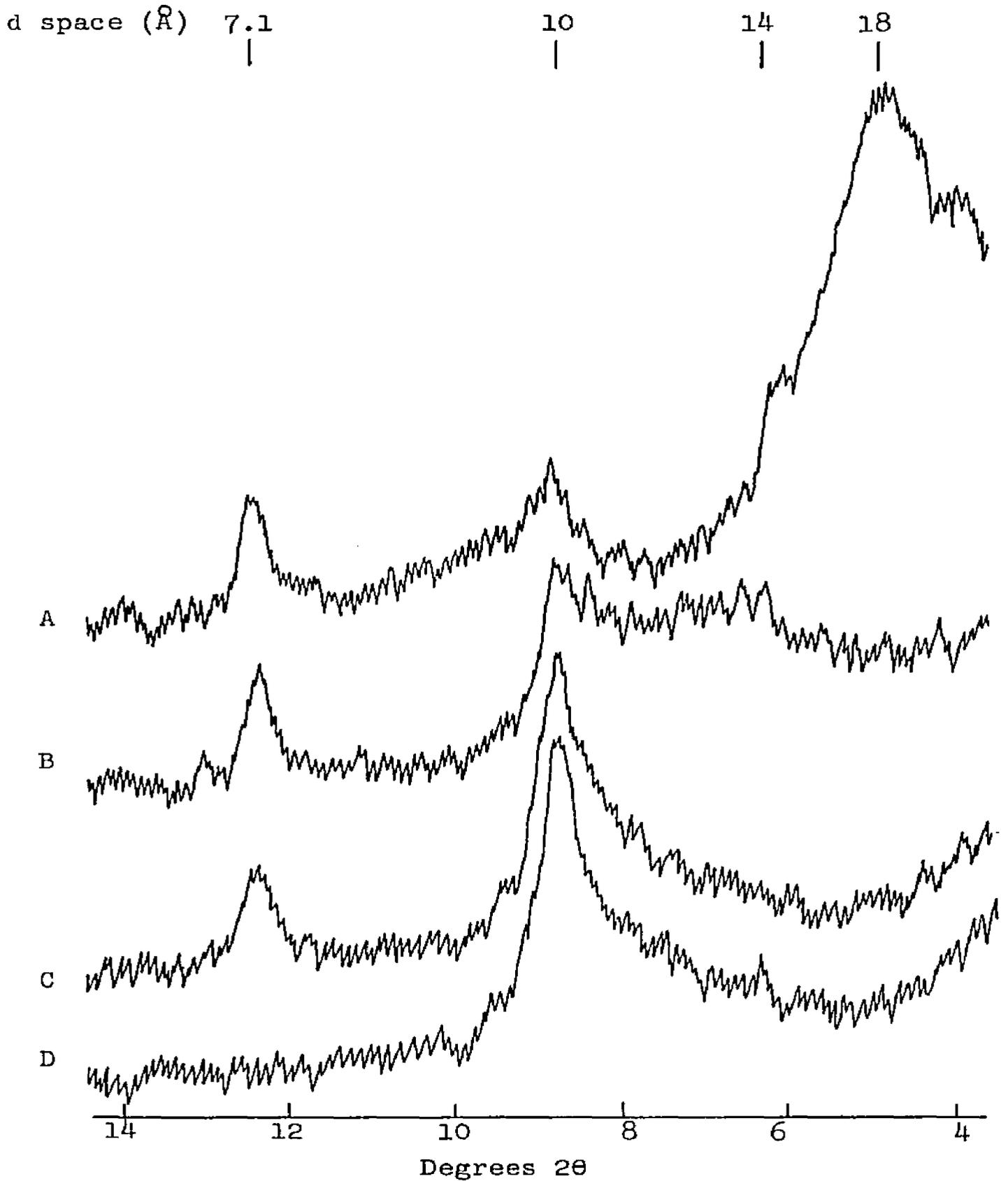


Figure A25. X-ray diffraction pattern of the clay fraction of Brookston loam before cropping

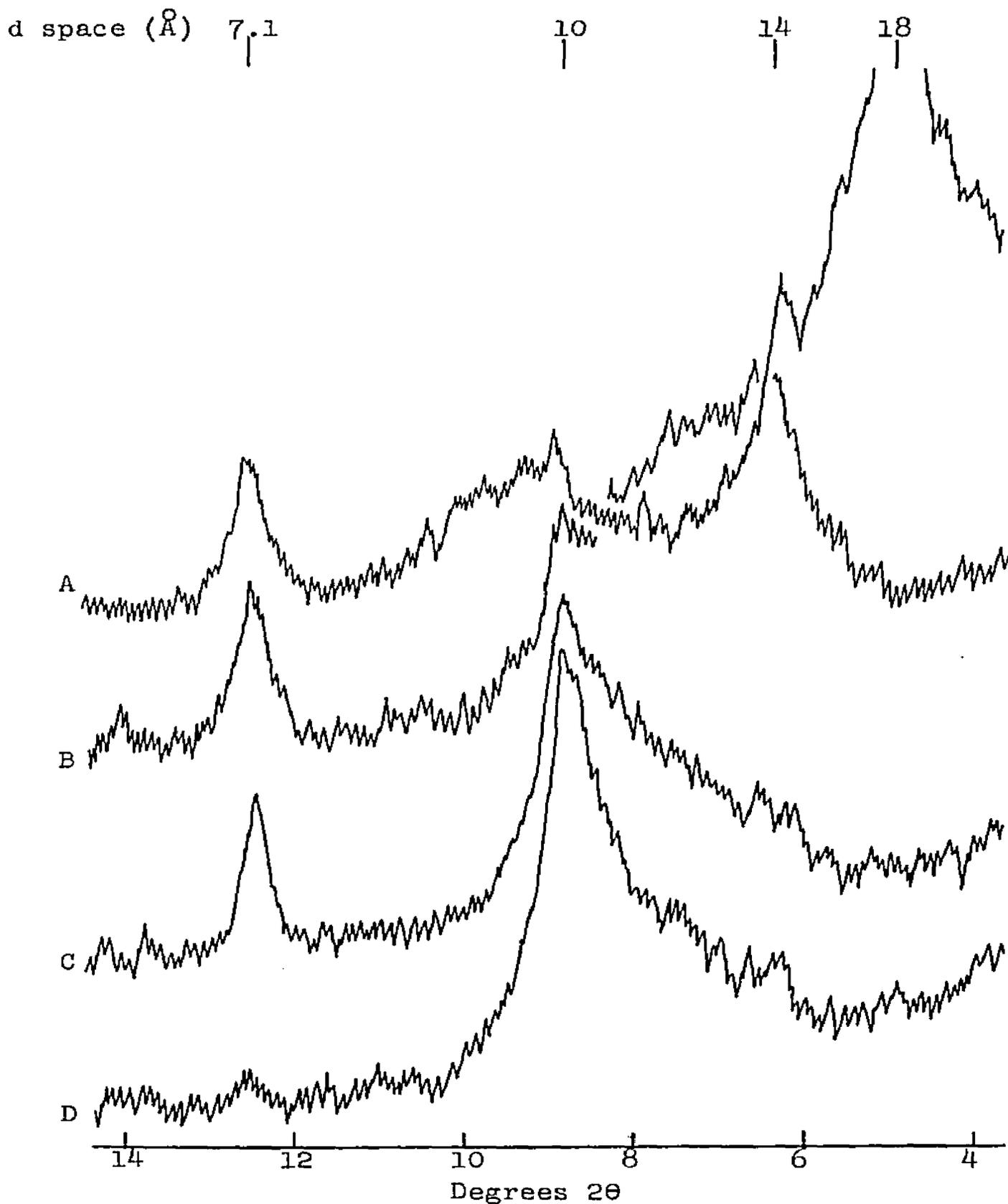


Figure A26. X-ray diffraction pattern of the clay fraction of Brookston loam after the 5th crop on the 0 potassium treatment

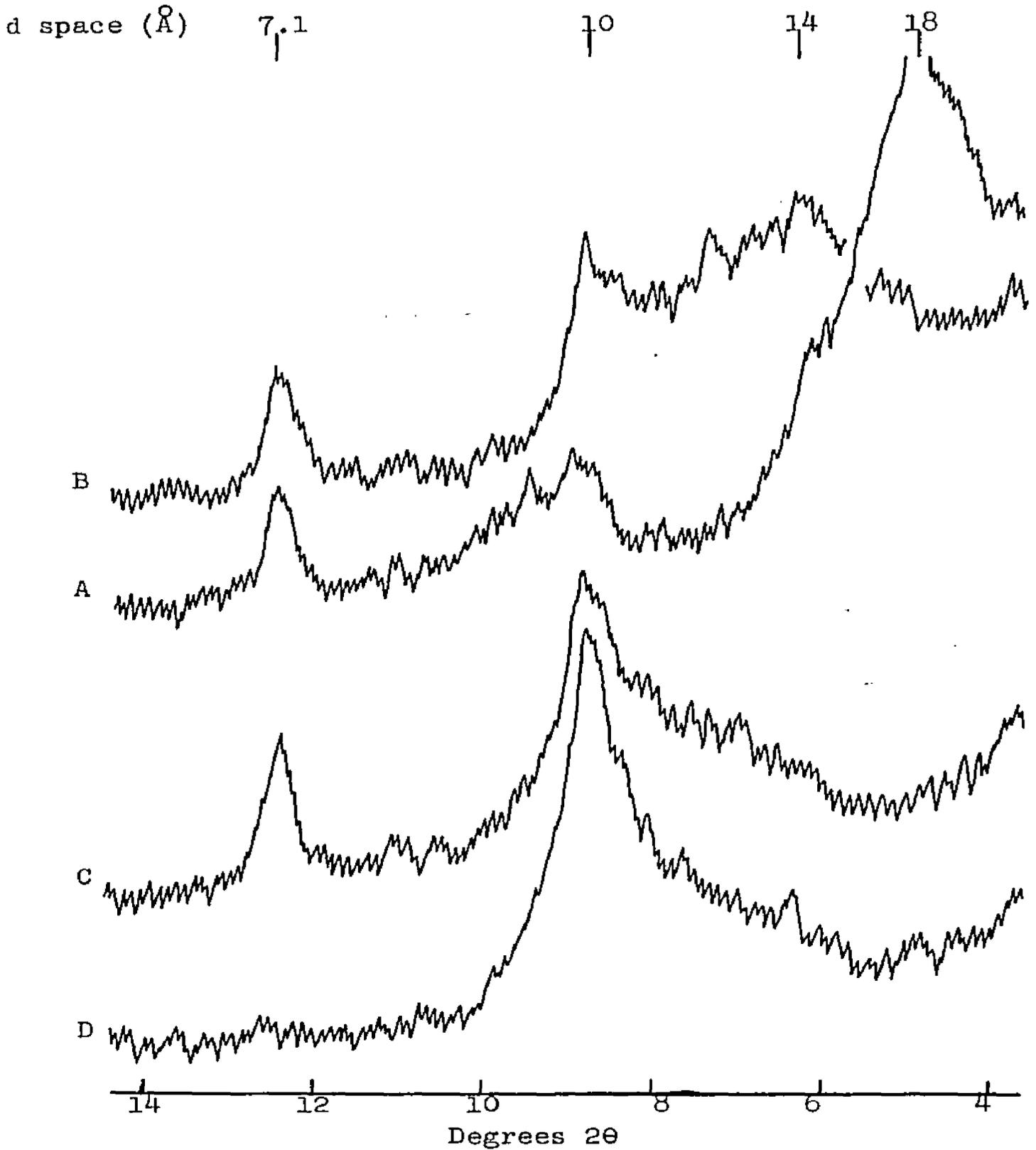


Figure A27. X-ray diffraction pattern of the clay fraction of Brookston loam after the 5th crop on the 1,600 pound per acre potassium treatment



## 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.

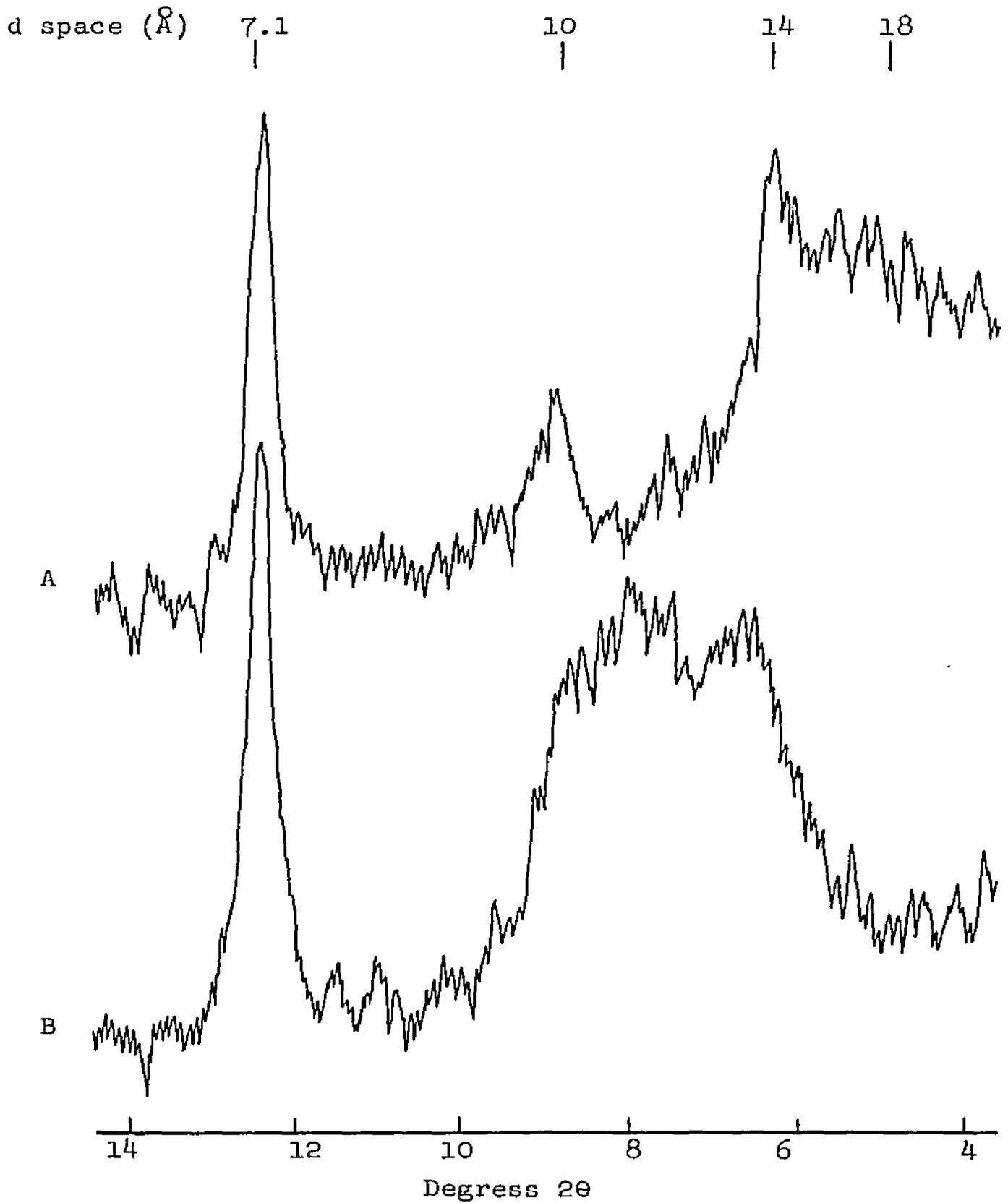


Figure A29. X-ray diffraction pattern of the clay fraction of Genesee loam before cropping

d space ( $\text{\AA}$ ) 7.1

10

14

18

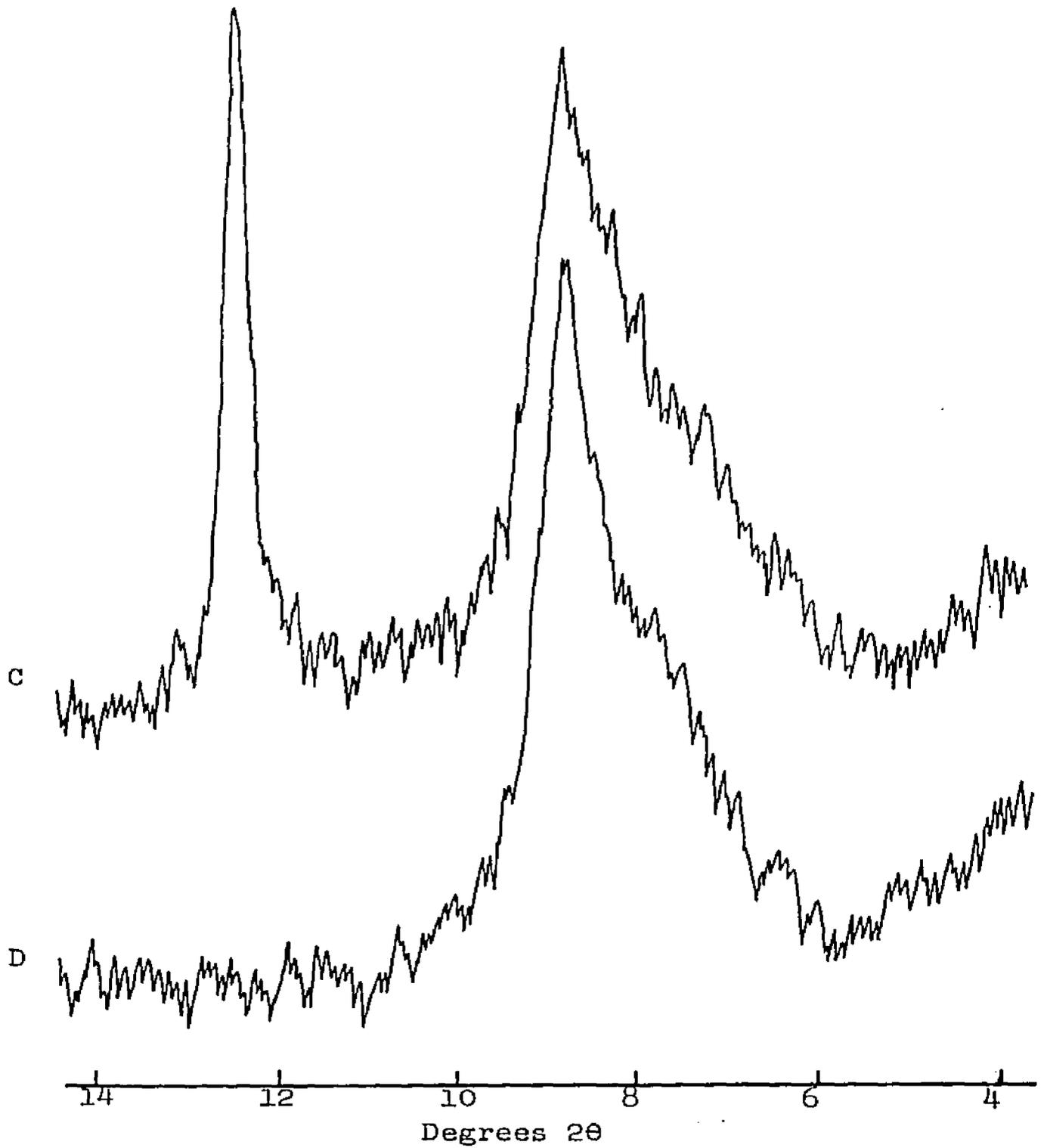


Figure A29 (cont'd.)





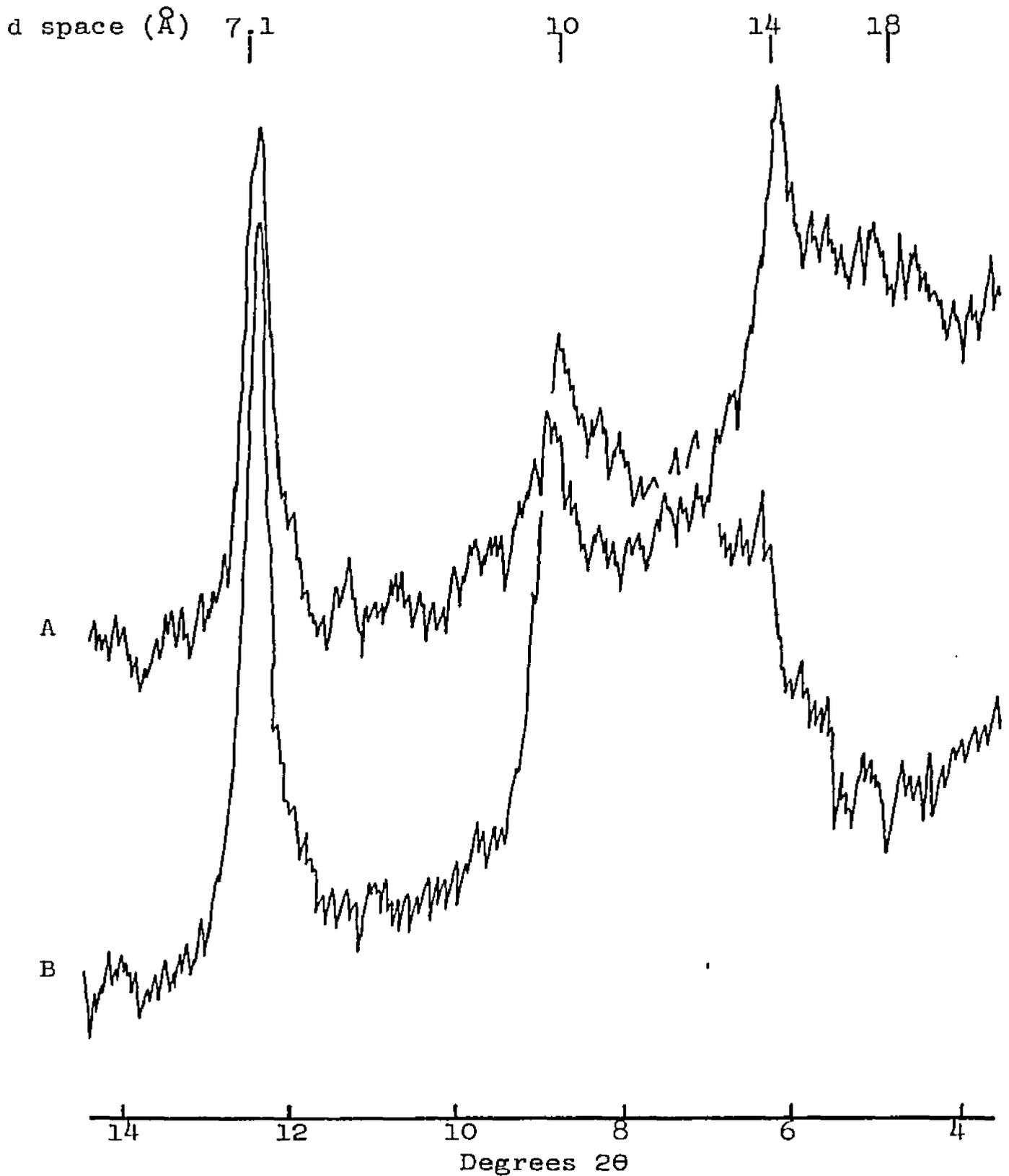


Figure A31. X-ray diffraction pattern of the clay fraction of Genesee loam after the 5th crop on the 1,600 pound per acre potassium treatment

d space ( $\text{\AA}$ ) 7.1

10

14

18

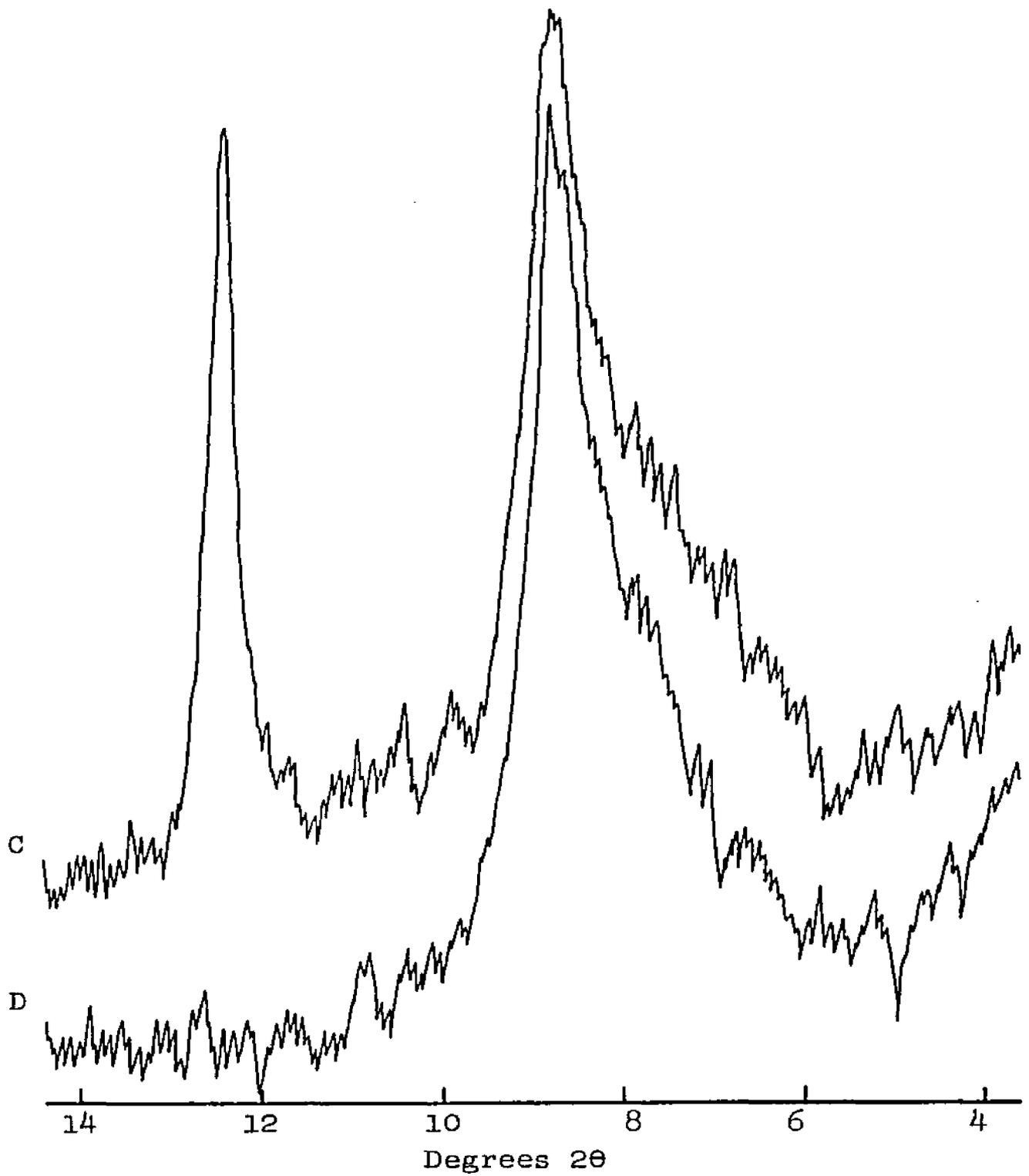


Figure A31 (cont'd.)

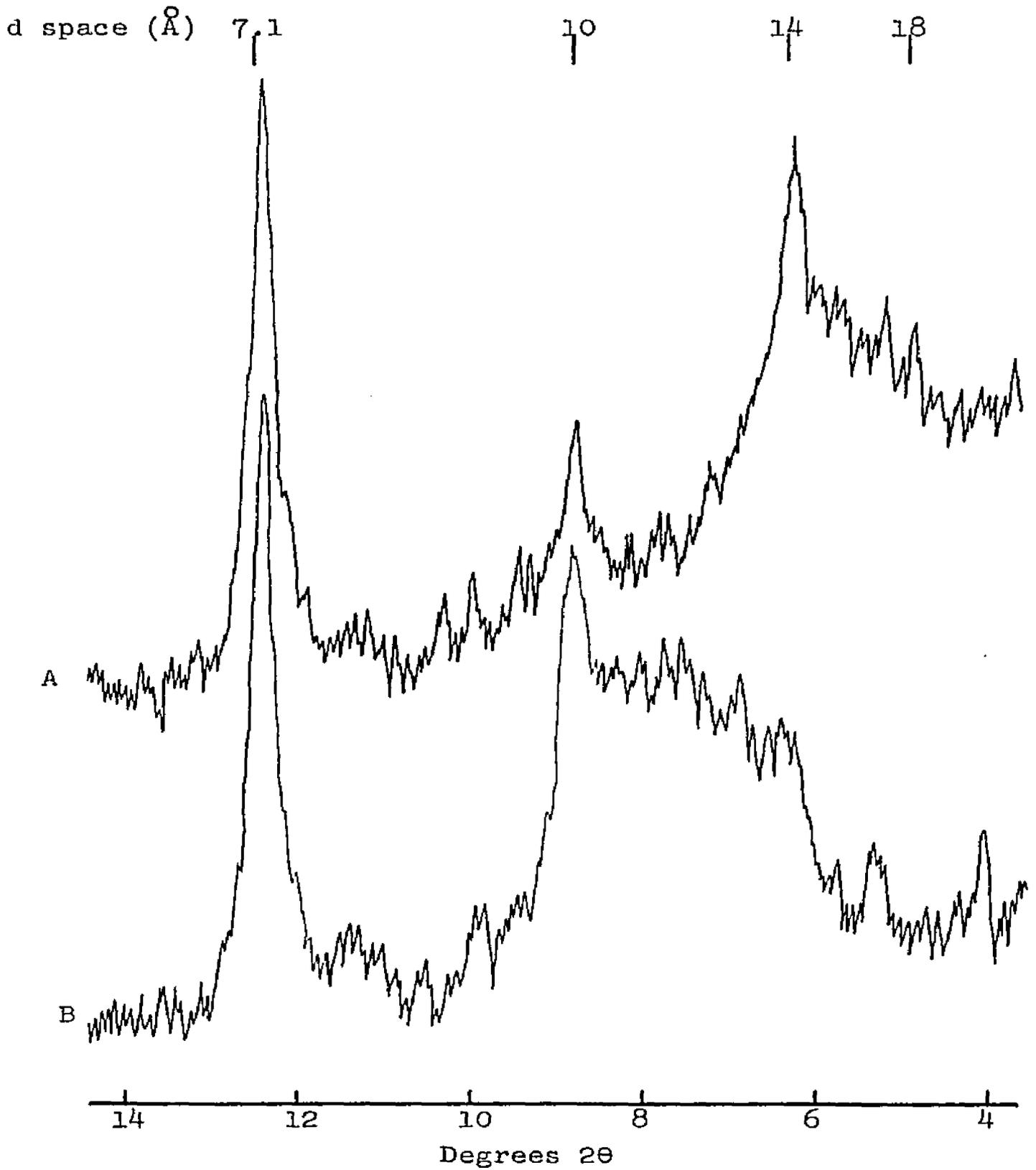


Figure A32. X-ray diffraction pattern of the clay fraction of Genesee loam after a 13-month incubation period with 1,600 pounds of potassium per acre

d space ( $\text{\AA}$ ) 7.1

10

14

18

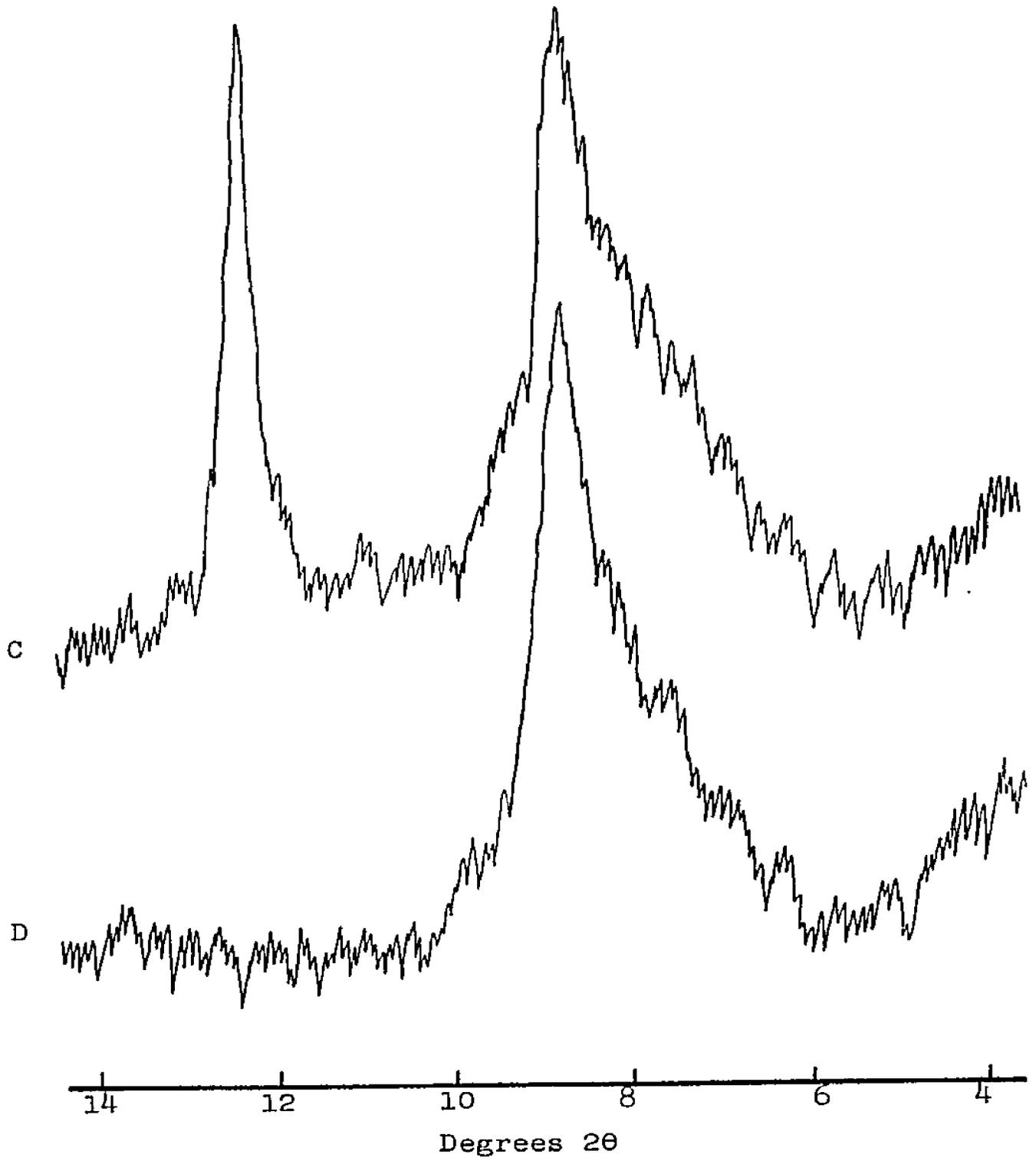


Figure A32 (cont'd.)

## APPENDIX I

X-RAY DIFFRACTION PATTERNS OF 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.

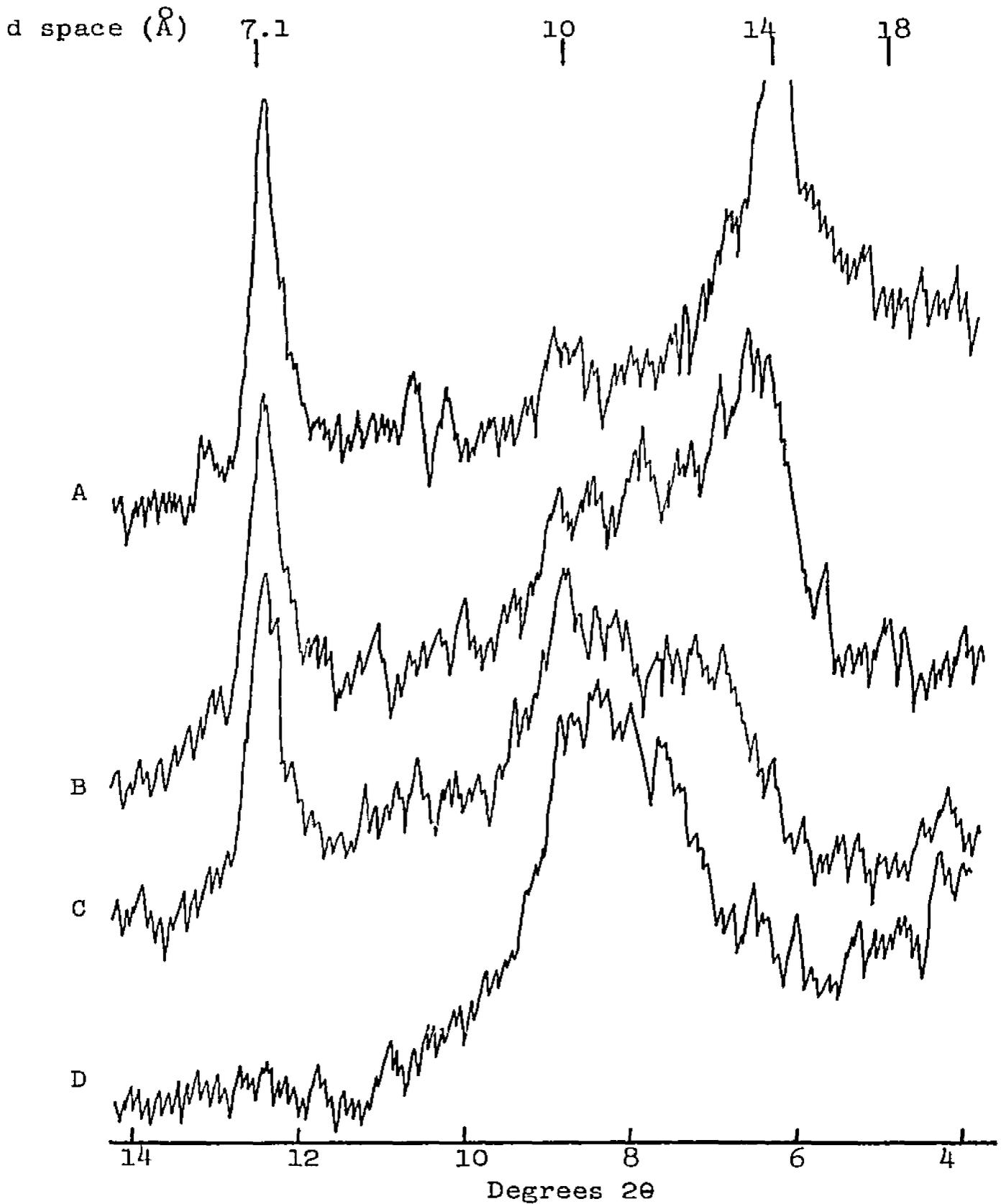


Figure A33. X-ray diffraction pattern of the clay fraction of Kalamazoo sandy loam before cropping

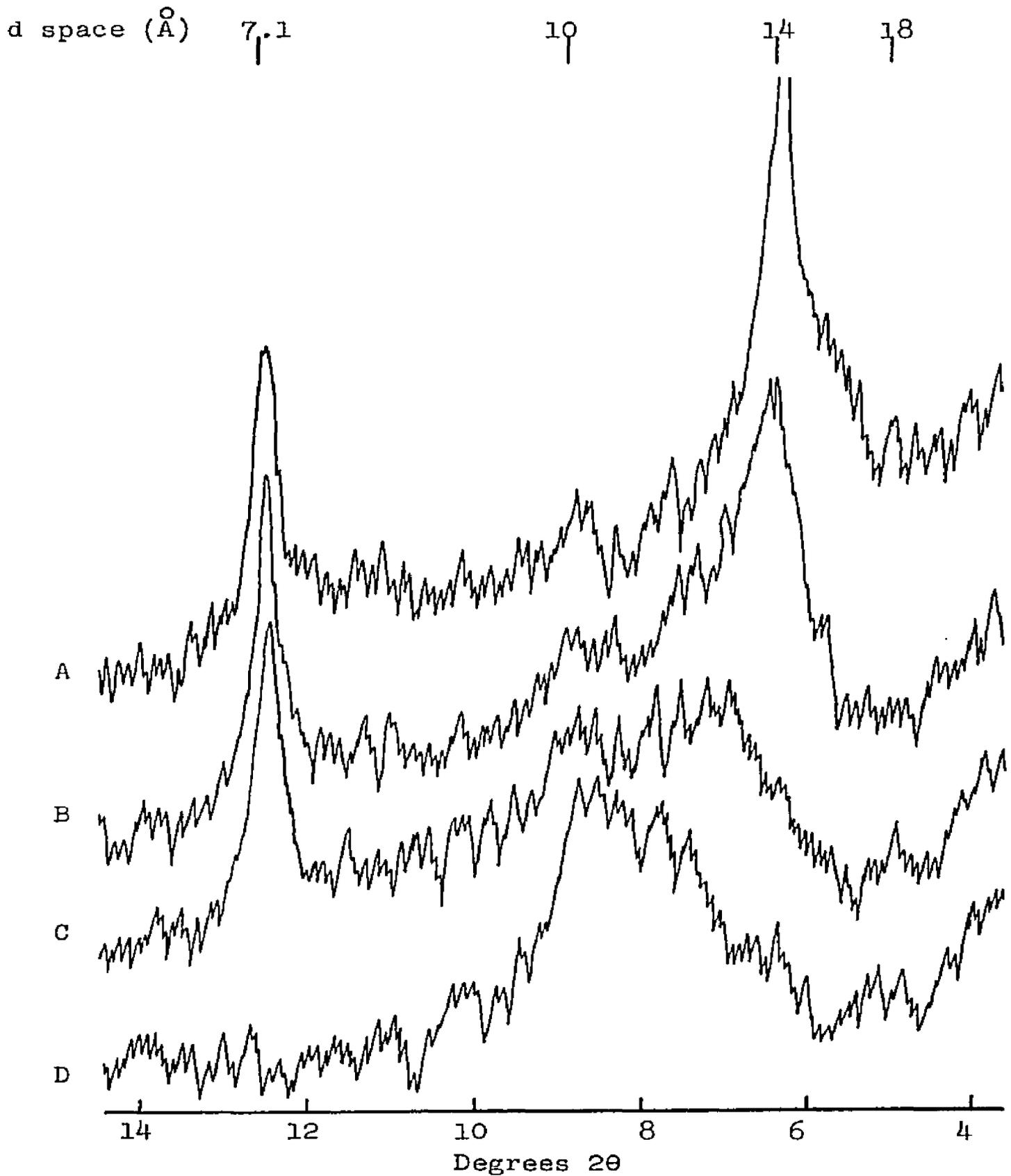


Figure A34. X-ray diffraction pattern of the clay fraction of Kalamazoo sandy loam after the 5th crop on the 0 potassium treatment

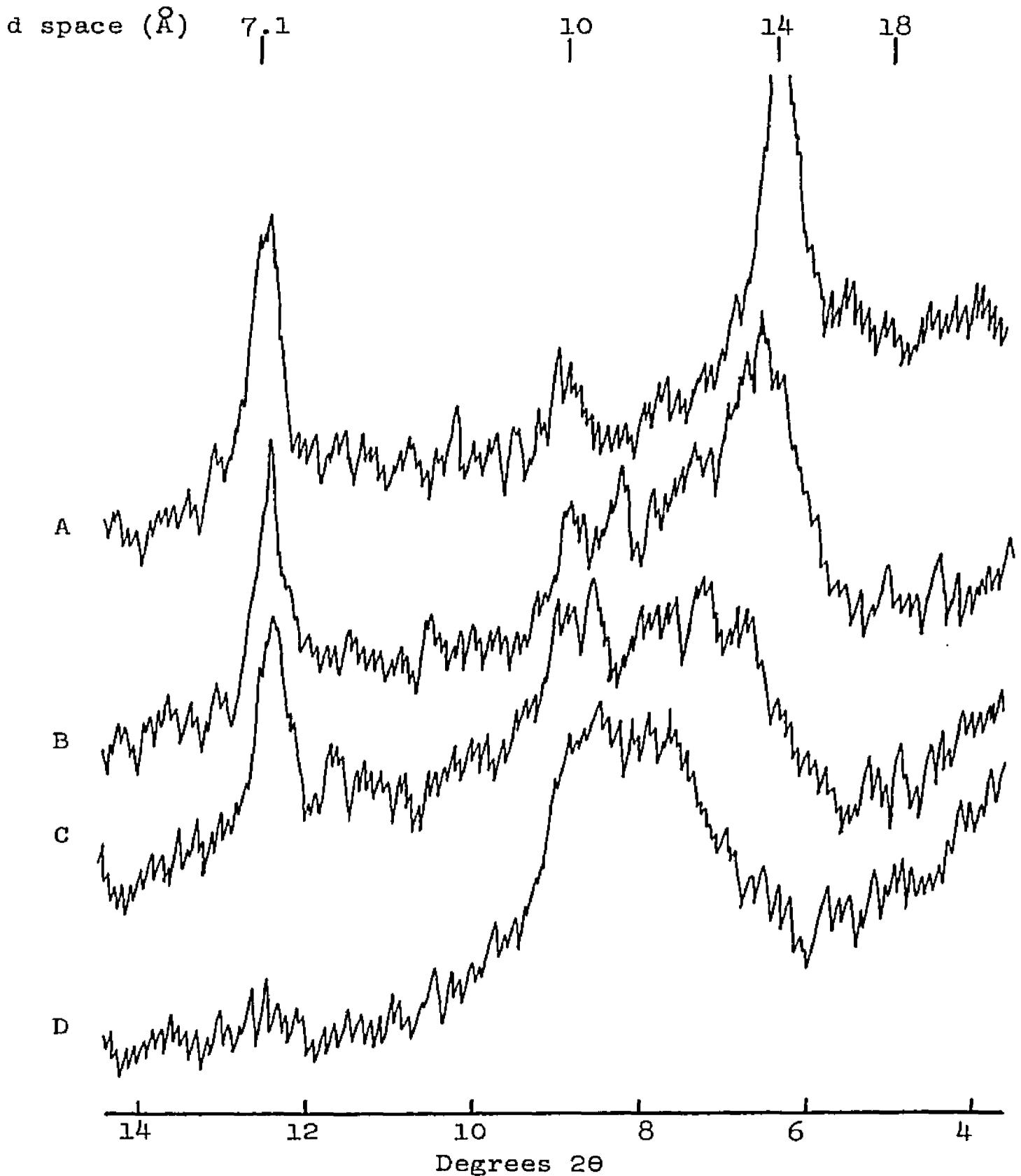


Figure A35. X-ray diffraction pattern of the clay fraction of Kalamazoo sandy loam after the 5th crop on the 1,600 pound per acre potassium treatment

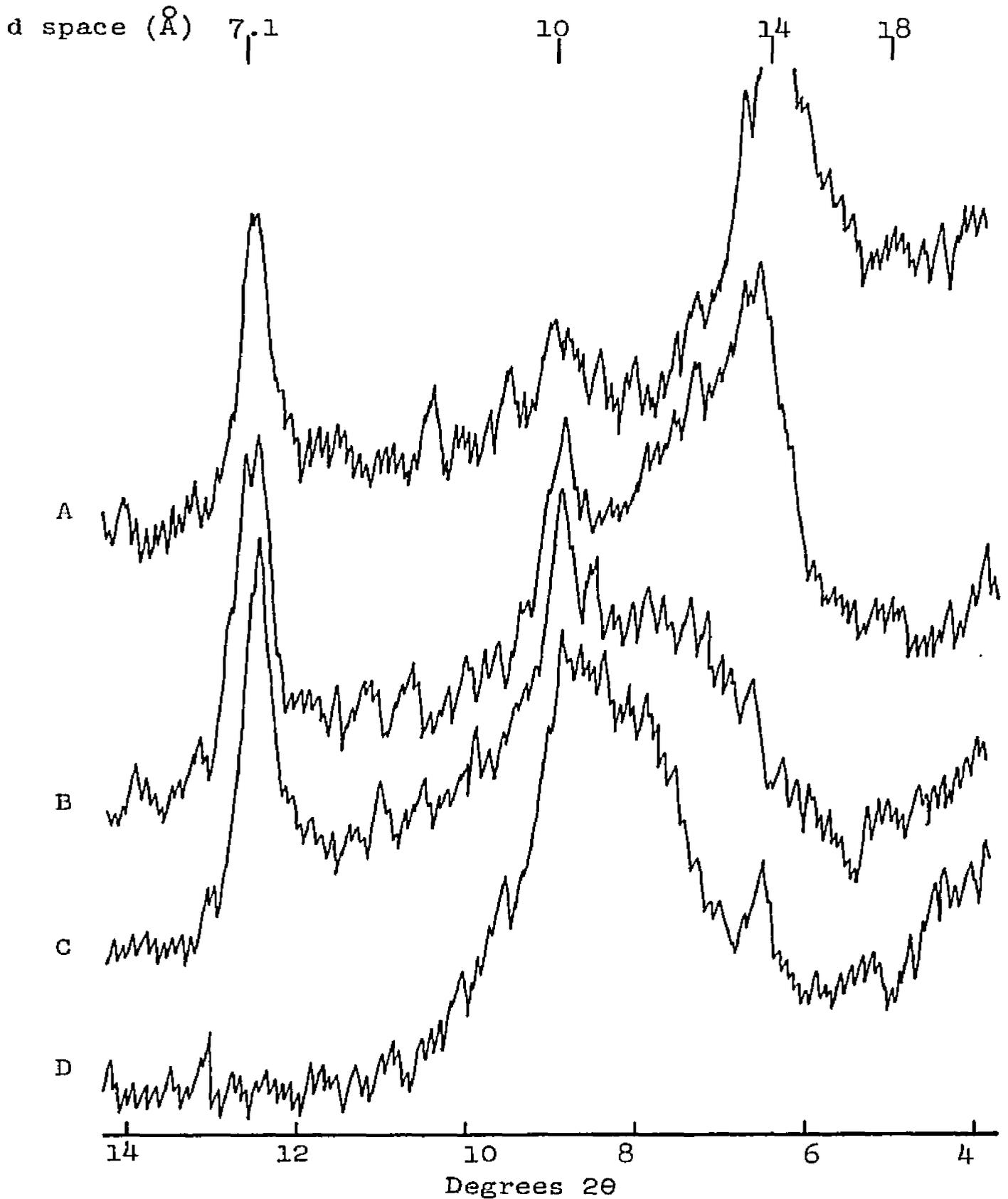


Figure A36. X-ray diffraction pattern of the clay fraction of Kalamazoo sandy loam after a 13-month incubation period with 1,600 pounds of potassium per acre

## APPENDIX J

X-RAY DIFFRACTION 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.

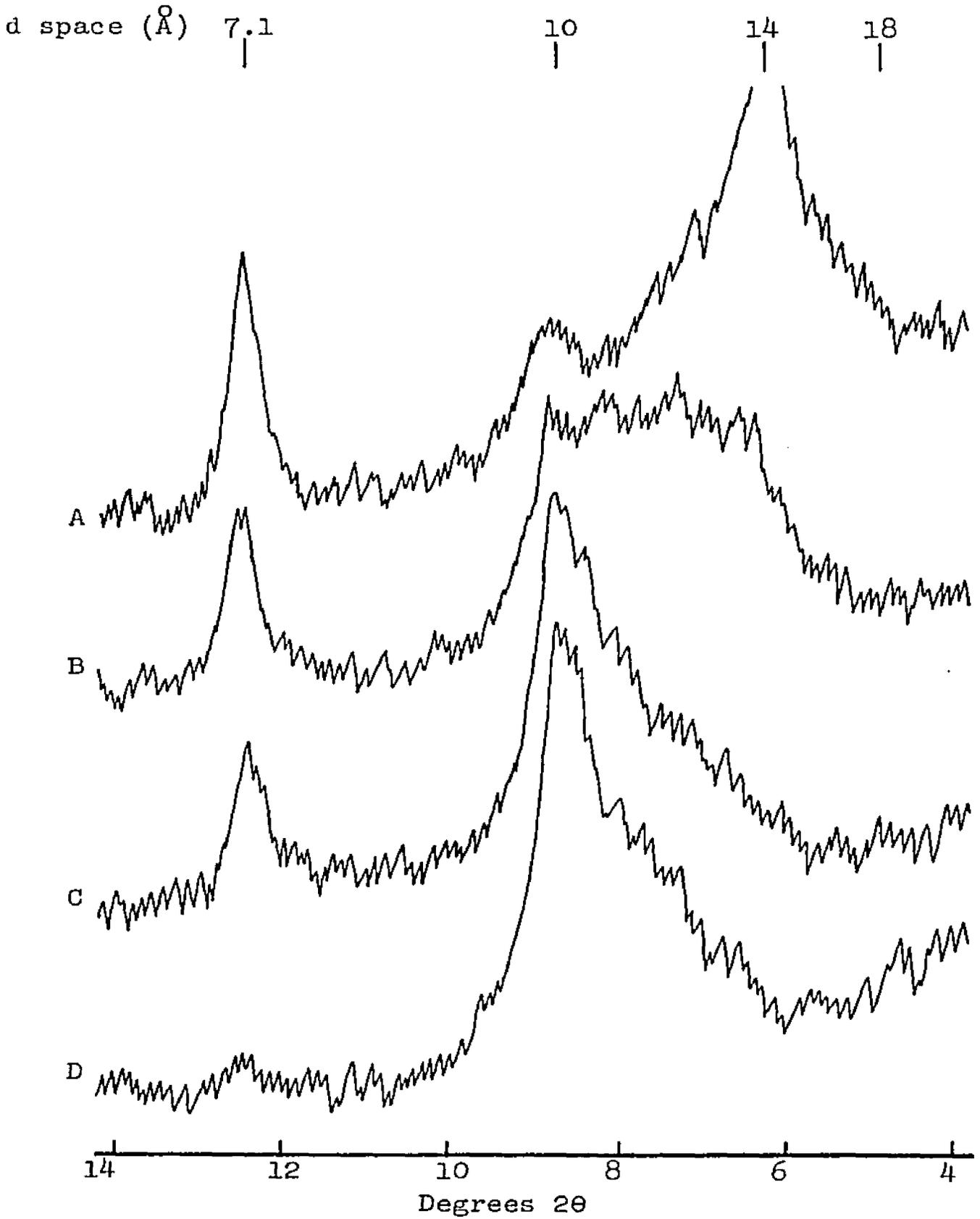


Figure A37. X-ray diffraction pattern of the clay fraction of Landes-Abscota sandy loam before cropping

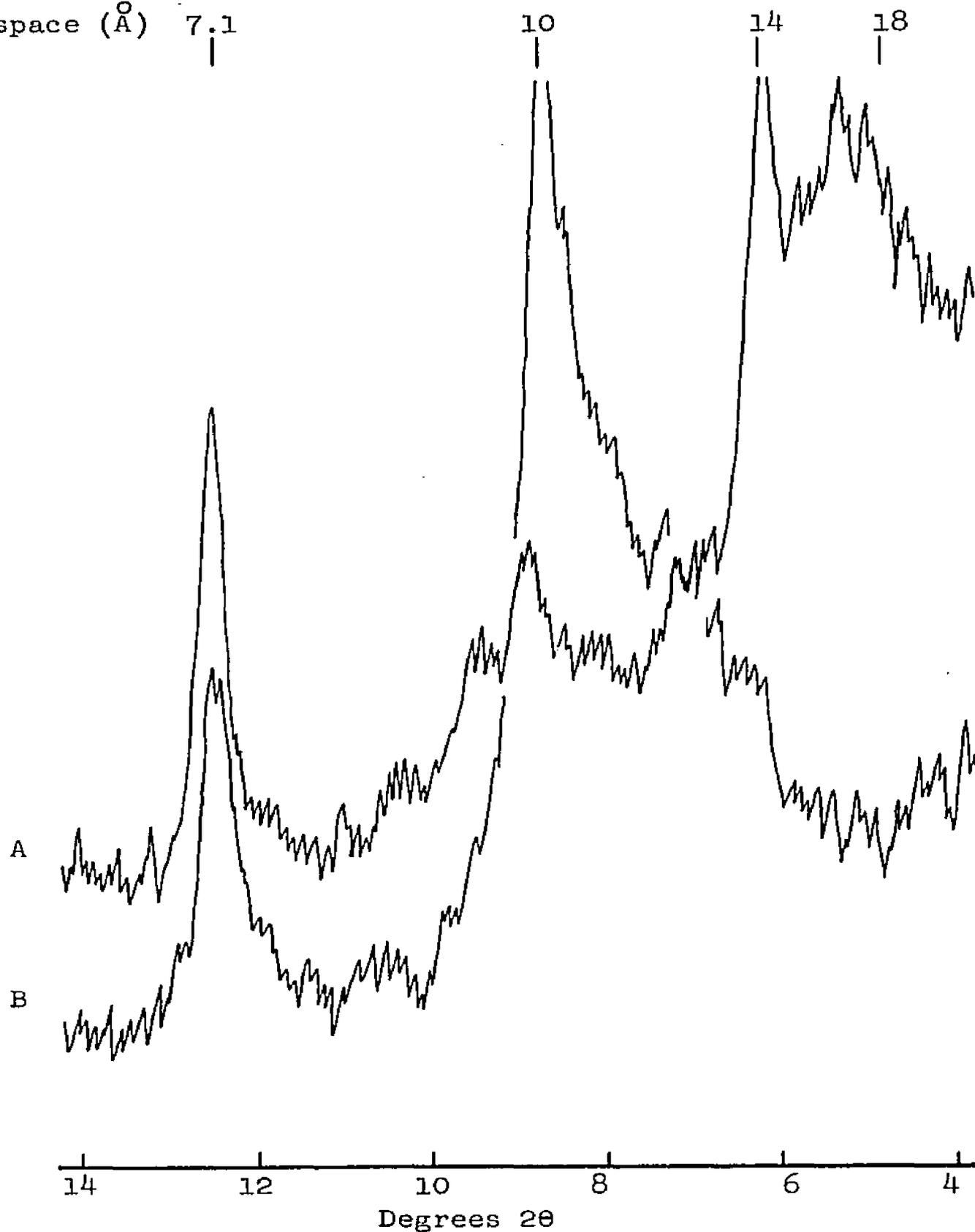
d space ( $\text{\AA}$ ) 7.1

Figure A38. X-ray diffraction pattern of the clay fraction of Landes-Abscota sandy loam after the 5th crop on the 0 potassium treatment

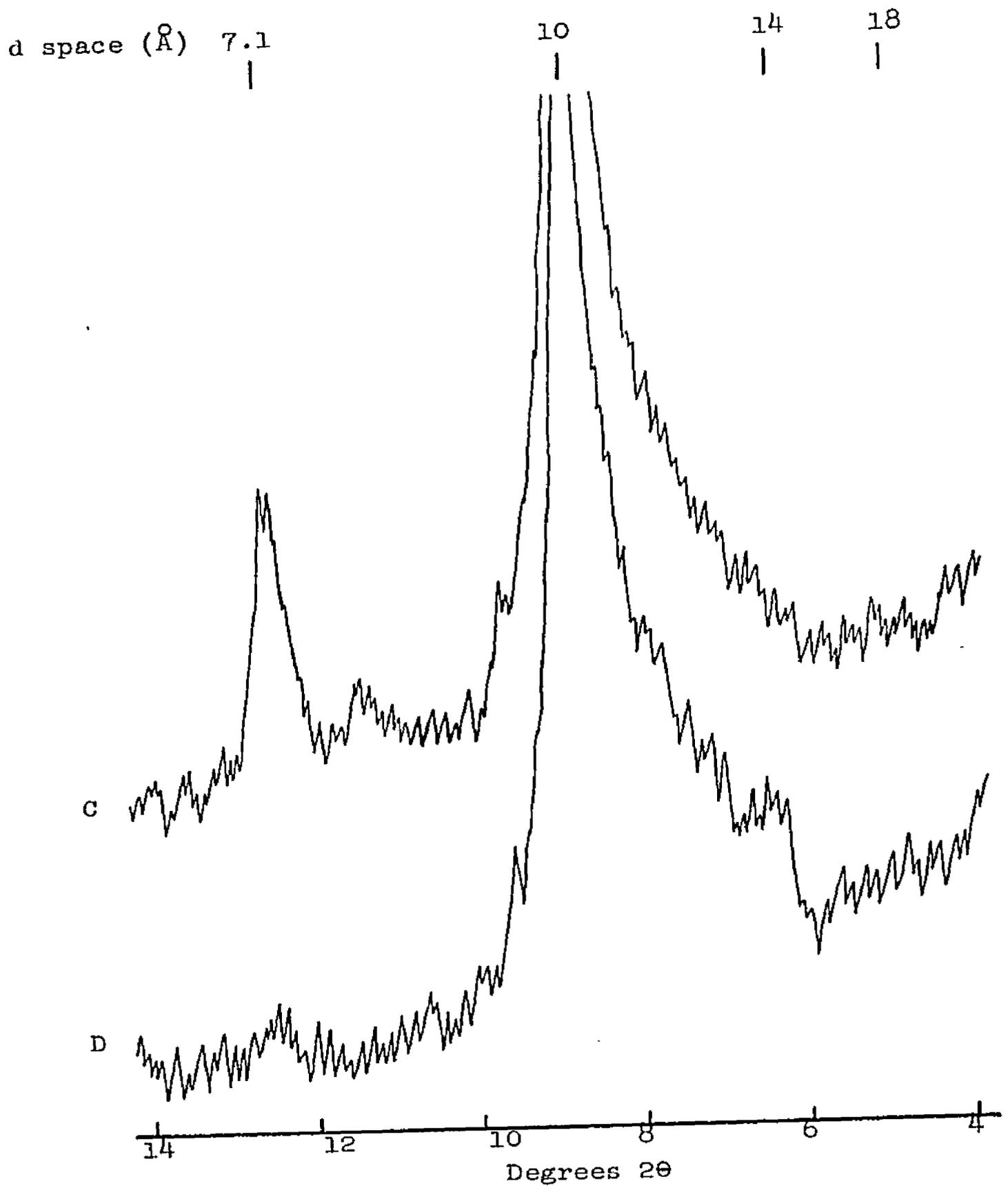


Figure A38 (cont'd.)

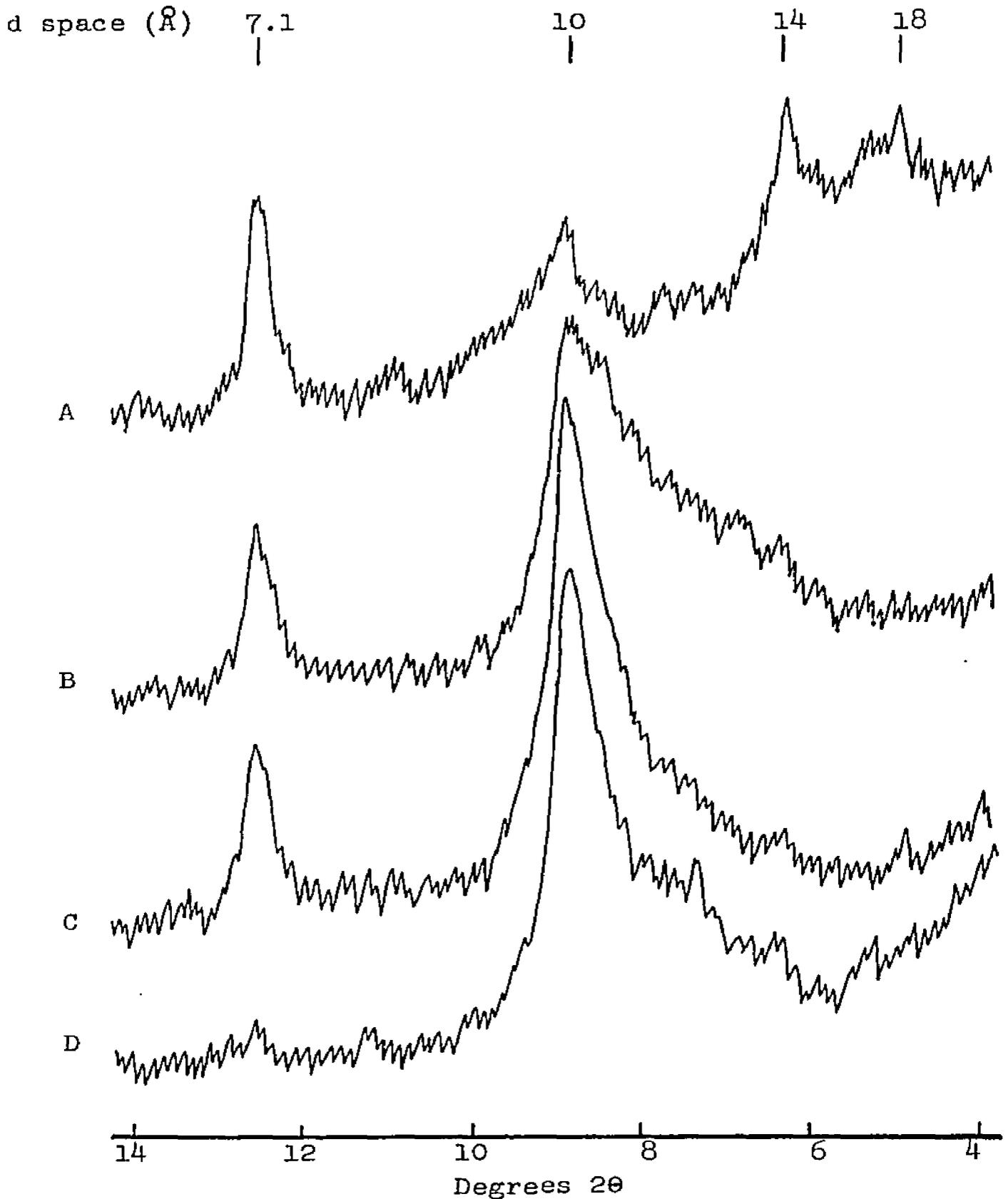


Figure A39. X-ray diffraction pattern of the clay fraction of Landes-Abscota sandy loam after the 5th crop on the 1,600 pound per acre potassium treatment

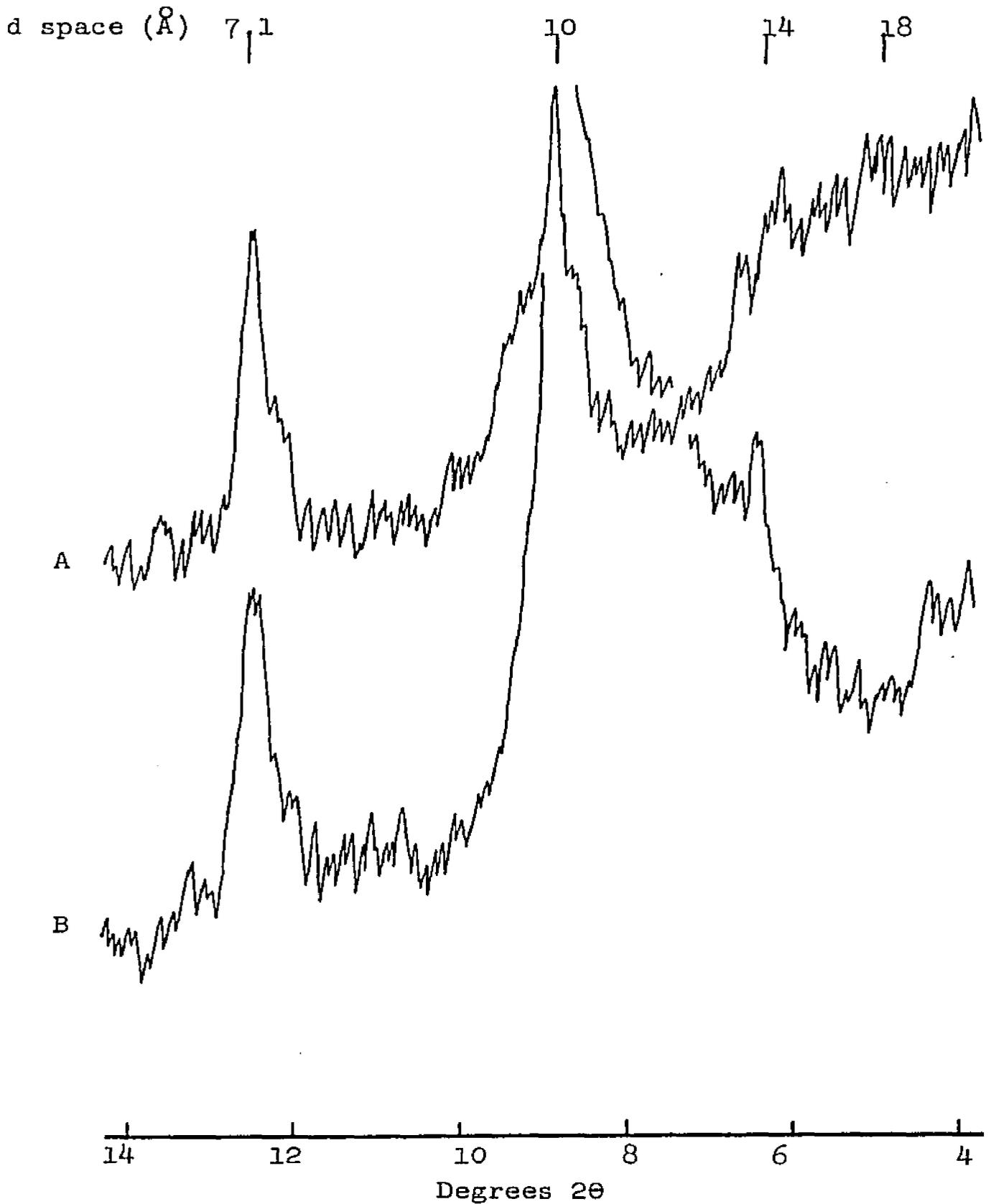


Figure A40. X-ray diffraction pattern of the clay fraction of Landes-Abscota sandy loam after a 13-month incubation period with 1,600 pounds of potassium per acre

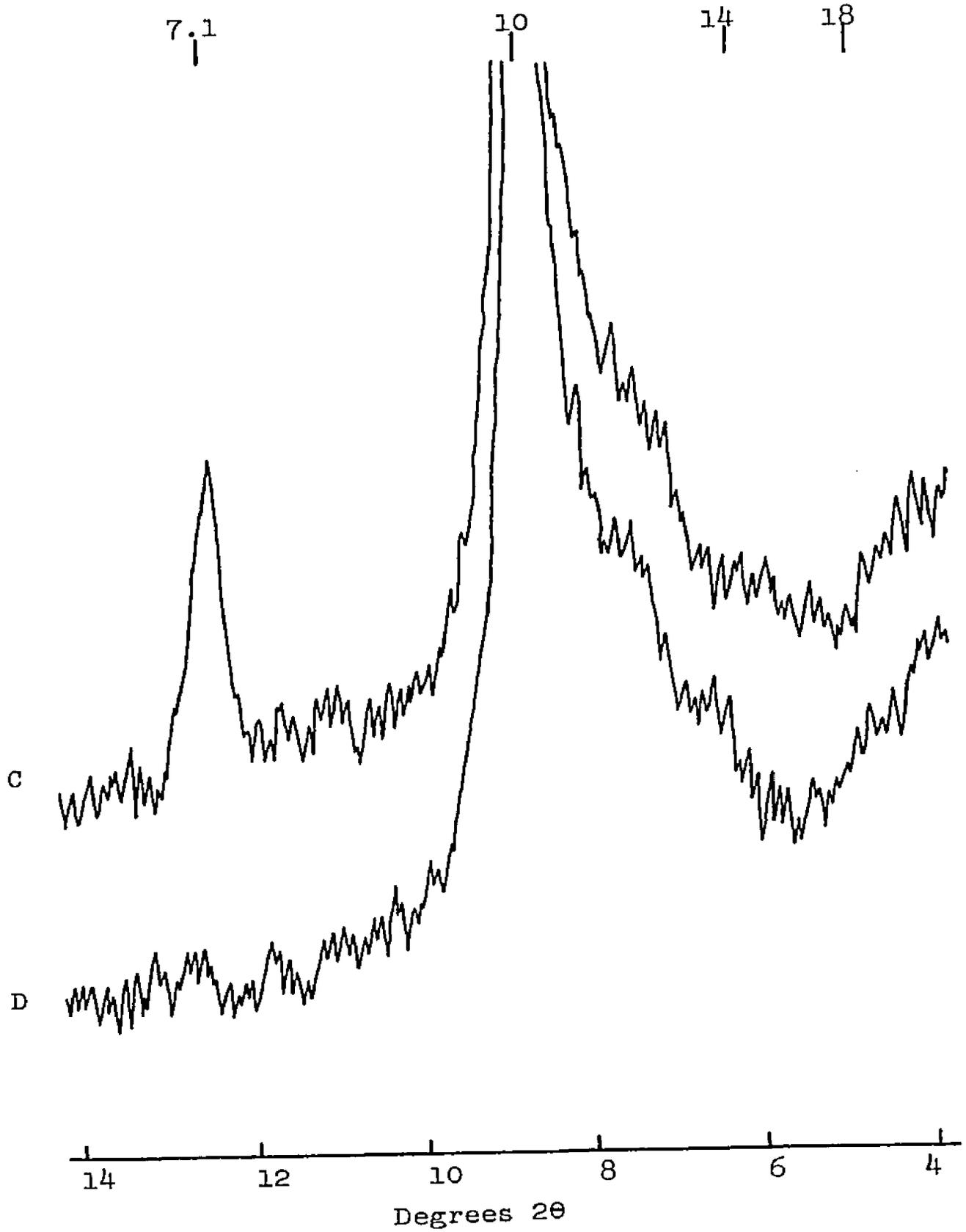
d space ( $\text{\AA}$ )

Figure A40 (cont'd.)