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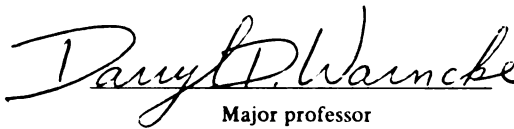
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**STUDIES COMPARING THE POTASSIUM CHEMISTRY
AND CLAY CONTENT OF SOME MICHIGAN, INDIANA,
AND OHIO SOILS**

presented by

James Barrett Sallee

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of the requirements for

M.S. degree in Crop & Soil Sciences


Major professor

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**STUDIES COMPARING THE POTASSIUM CHEMISTRY
AND CLAY CONTENT OF SOME MICHIGAN, INDIANA,
AND OHIO SOILS**

By

James Barrett Sallee

A THESIS

**Submitted to
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ABSTRACT

STUDIES COMPARING THE POTASSIUM CHEMISTRY AND CLAY CONTENT OF SOME MICHIGAN, INDIANA, AND OHIO SOILS

By

James Barrett Sallee

Michigan, Indiana, and Ohio share common soil series. However, few studies have been made comparing the chemistry and clay composition of these soil series with respect to potassium (K) availability. The objective of this study was to determine the degree of similarity in the K chemistry of soils common to this tri-state area. In 1995 and 1996, 54 soils were collected for investigation. Cation exchange capacity (CEC), total K, ammonium acetate (NH_4OAc) and sodium tetraphenylboron (NaBPh_4) extractable K levels, and clay content were determined for all soils. Neubauer experiments with barley (*Hordeum vulgare* cv Bowers) were conducted in a growth chamber to investigate K release during intensive cropping. Four soils having a wide range in total K content were selected for clay mineralogical analysis by x-ray diffraction. Large differences in CEC, total K, and nonexchangeable K were found between major soil series. Exchangeable K levels were not significantly different between soil series. The contribution of exchangeable K to total plant uptake ranged from 17 to 75% between soil series. Soils with high clay content tended to have larger amounts of total K than soils with low clay content. The coarse clay (2-0.2 μm) and fine clay (<0.2 μm) fractions were dominated by 2:1 clays. Illite contents ranged from 10 to 40% in the coarse clay and from 5 to 30% in the fine clay of the soils studied. Although differences in K chemistry and mineralogy exist between soil series, soils in a given series generally exhibit similar K chemistry regardless of geographic location.

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It is my sincere hope that the results from these potassium studies will set the stage for further research on the potassium chemistry of soils in Michigan, Indiana, and Ohio, and that this research will ultimately lead to the improvement of K fertilizer recommendations in the tri-state region.

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INTRODUCTION

Potassium (K) is absorbed by plant roots in larger quantities than any other cation (Barber, 1968). The potassium content of healthy leaf tissue for most plants is in the range of 1 to 4% (Brady and Weil, 1996, p.474). The benefits of K to plant growth have been recognized since the middle of the 17th century when J. R. Glauber in the Netherlands first hypothesized that saltpeter was the “principle” of vegetation (Russell, 1988). He achieved large increases in crop growth when potassium nitrate was added to the soil. In 1840, von Leibig reported that K was an essential plant nutrient (Stewart, 1985). Since that time, the role of K in both soils and plants has been extensively studied. It is now known that K has important roles in many physiological plant processes, including: enzyme activation, protein synthesis, photosynthesis, osmoregulation, cell extension, stomatal movement, light-driven and seismonastic movements, phloem transport, and cation-anion balance (Marschner, 1995).

In nature, plants obtain all of their K directly from the native K reserves of the soil or from K fertilizers that are added to the soil. Whenever nutrients of any form are added to the soil, the soil becomes both a source and a sink for these nutrients. Therefore, it is important to understand the factors that influence the availability of these nutrients to plants. This is especially true for K due to the dynamic nature of K availability in the soil.

Potassium Content, Mineralogy, and Weathering in Soils

Potassium makes up, on the average, 2.6% of the lithosphere. It is the seventh most abundant element and the fourth most abundant plant mineral nutrient in the earth's crust (Schroder, 1978). The K content of mineral soils, expressed as K_2O , ranges from 0.05 to 3.5%. Most agricultural soils in the United States contain from 1 to 2% (10,000 to 20,000 $mg\ kg^{-1}$) K (Jackson, 1964). However, of the total amount of K in soils, approximately 90 to 98% is in the mineral form, 1 to 10% is fixed or nonexchangeable, and only 0.1 to 2% is exchangeable or in the soil solution (Tisdale et al., 1985). Generally, solution K is only a few percent of the exchangeable K (Schroeder, 1974). The soil organic matter usually contains less than 0.1% K while the K in living microorganisms is one order of magnitude lower (Schroeder, 1974). Thus, the contribution of K from the organic fraction of the soil is small.

The total K content of a soil is determined in large measure by the mineralogy of the parent material; although, it can be affected by other factors such as the degree of weathering, K fertilization, and losses due to crop removal, erosion, and leaching. On average, the K composition of igneous (including metamorphic), shale, sandstone, and limestone rocks is 26, 27, 11, and 2.7 $g\ K\ kg^{-1}$ respectively (Bertsch and Thomas, 1985). The composition of the soil mineral fraction is a mixture of both primary and secondary minerals. Primary minerals are minerals formed at high temperatures during the genesis of igneous and metamorphic rocks. Secondary minerals are minerals formed at low temperature and are derived from sedimentary rocks or formed in soils by weathering (Jackson, 1964).

Primary minerals comprise the main portion of the sand (particles ranging from 2.0 to 0.05 mm in diameter) and silt (particles ranging from 0.05 to 0.002 mm in diameter) particles of most soils. In contrast, the clay (particles less than 0.002mm in diameter) particles of most soils are comprised of secondary minerals except for very young soils that have undergone little weathering. One primary mineral group of major importance in soils is the K-feldspars (KAlSi_3O_8). The K-feldspars include sanidine, orthoclase, microcline, and adularia. Feldspars typically constitute 5 to 25% of the mineralogy of sand and silt particles (Jackson, 1964). The structure of the K-feldspars consists of a three dimensional framework of linked SiO_4 and Al_2O_3 tetrahedra which have sufficient space in the framework for K to balance electrostatic charge. Four-membered rings of tetrahedra are the basic units of the framework. These rings are then joined together to form a honeycomb type of arrangement (Sparks, 1987, Sparks and Huang 1985).

As the minerals in soils weather, they release their K and form secondary minerals. Vermiculite, for example, is formed from the weathering of mica (Douglas, 1989). Huang et al. (1968) listed the following common feldspars and micas according to the rate at which they weather and release their K: biotite, muscovite, orthoclase, and microcline. Feldspars weather when protons replace structural cations. Hydrolysis of the Al-O-Si bond destabilizes the mineral structure and results in mobilization of silica (Rasmussen, 1972). This leads to formation of silicic acid which promotes the release of basic cations (Huang, 1989). Humic and fulvic acids also can weather feldspars and micas through complexation and chelation reactions (Tan, 1980).

Micas are the second group of primary minerals with fundamental importance to the K chemistry of soils. Micas are more common in fine-grained sedimentary rocks such as shales and less common in coarse textured rocks such as sandstones (Sparks and Huang, 1985). In contrast to feldspars, the fraction of K in soils from mica tends to increase with decreasing particle size (Sparks, 1987).

Micas are 2:1 layer silicate minerals composed of a sheet of octahedral cations sandwiched between two layers of $(\text{SiO}_4)^{4-}$ tetrahedra. The apical hydroxyls and oxygens of the tetrahedral layer are shared by the octahedral layer. These sheets are held together electrostatically by potassium ions which neutralize the negative charge between adjacent 2:1 sheets. Both dioctahedral and trioctahedral micas exist in nature. Dioctahedral micas contain Al^{3+} as the octahedral cation; whereas trioctahedral micas have Fe or Mg as the octahedral cation (Fanning et al., 1989, Sparks and Huang, 1985). In the dioctahedral micas, such as muscovite, only two octahedral sites are filled by cations. In the trioctahedral micas, all three octahedral sites are filled by cations (Sparks and Huang, 1985).

The layer charge associated with micas and other 2:1 minerals can be attributed to three factors: 1) substitution of Si^{4+} by a lower valence cation in the tetrahedral sheet, 2) substitution of Al^{3+} by a lower valence cation in the tetrahedral sheet, or 3) cation vacancies in the octahedral sites (Sparks and Huang, 1985). The degree of isomorphous substitution and resultant layer charge will have a direct effect upon the cation exchange capacity (CEC) of the soil. Soils containing minerals with more isomorphous substitution will exhibit a higher CEC than soils containing minerals with less isomorphous substitution.

Two mechanisms have commonly been recognized in the weathering of micas. These two mechanisms are edge weathering and layer weathering (Fanning et al., 1989). Jackson et al. (1952) reported that micas weather along preferential planes which result in expansion of the mineral. Huff (1972) observed layer weathering with several illites and a mixed layer illite-montmorillonite. Development of fractures occurred in these samples when the interlayer K was removed by sodium tetraphenylboron (NaBPh_4). Scott (1968) reported that edge weathering was the dominate mechanism of K release in $> 10\mu\text{m}$ muscovite particles. In mica particles $< 2\mu\text{m}$, layer weathering was the dominate mechanism of K release. Scott and Smith (1967) obtained visual evidence of edge weathering in large mica particles weathered with NaBPh_4 solution.

The release of K with weathering of feldspars and micas is of great practical importance to plants, animals, and humans. Although soils may contain large amounts of K, only a small portion of it is available for uptake by the plant at any given time. There are four pools of K in the soil: solution K, exchangeable K, nonexchangeable K, and mineral K (Sparks, 1987). Nonexchangeable K is distinct from mineral K in that it is not bonded covalently within the crystal structure of soil minerals. Instead, it is held between adjacent tetrahedral layers of dioctahedral and trioctahedral micas, vermiculites, and intergrade clay minerals (Martin and Sparks, 1985).

In all soils, there exists a dynamic equilibrium between each of these four forms of K. This equilibrium is controlled by many factors including K composition of the parent material, degree of weathering, amount of K fertilization, and intensity of cropping. The K that is immediately available for plant uptake is the K in the soil solution. As the K in the soil solution is depleted, K on the exchange sites is released into

the soil solution. This release of exchangeable K buffers the concentration of K in solution. As more K is released from the exchange sites, a portion of the nonexchangeable K becomes available for exchange with ions in the soil solution. The rate of this release is highly dependent upon the specific parameters of the individual soil-plant system. Over the years, much effort has gone into the development of chemical extractants that would provide a reliable measure of plant available potassium. While these efforts have met with some success, there is still a need to improve soil K tests and refine soil test interpretations for K.

Contrasting Concepts in Soil Test Interpretation

“The soil testing-fertilizer recommendation process involves several discrete but somewhat interrelated steps including field sampling, sample preparation, chemical analysis, interpretation of analytical results, and development of recommendations based on these results” (Eckert, 1987). Today, there are two major philosophies which guide the practice of soil testing and fertilizer recommendation in the United States. Both of these concepts originated in the 1940’s although the research was conducted in different regions of the country. In order to understand how these different concepts originated and how they affect current practice in the soil testing arena, it is beneficial to investigate each of these concepts in detail.

The basic cation saturation ration (BCSR) concept originated with Bear and co-workers (Bear et al., 1945) in New Jersey from studies with alfalfa on 20 of New Jersey’s most important agricultural soils. They proposed that for an “ideal” soil the exchange complex should contain 65% Ca, 10% Mg, 5% K, and 20% H on an equivalent basis.

These saturations would give cation ratios of 13:1 for Ca:K, 2:1 for Mg:K and 4:1 for H:K. These results were based on eight years of research (Bear and Toth, 1948). In reading through the series of papers by Bear et al., one is able to identify several reasons why these ratios were selected for the New Jersey soils.

Hunter et al. (1943) reported that although alfalfa could grow normally at soil Ca:K ratios from 1:1 to 100:1 the Ca:K ratios within the plant were much narrower. They observed that when the Ca:K ratio on an equivalent basis within the plant was greater than 4:1 the yields of the alfalfa were markedly depressed. A sharp decrease in alfalfa yield occurred when the Ca tissue concentration was greater than 2% or if the K tissue concentration was less than 1%. These values were then established as critical limits for alfalfa (Bear and Toth, 1948). At a soil Ca:K ratio of 32:1 the Ca:K ratio in the alfalfa was 3:1. The K concentration in the shoots was 1.15% (Bear and Prince, 1945). Bear and Toth (1948) reported that during earlier work by Bear et al. (1944), it was found that alfalfa yields were increased in 18 out of 20 soils by adjusting the Ca:K ratio to near the "ideal" 13:1 ratio. During this same period, Prince et al. (1947) showed that when the Mg saturation of the exchange complex was less than 10%, a majority of these same soils responded to applications of Mg in the soluble form.

It had been observed that crops grown on some New Jersey soils expressed symptoms of Mn and other micronutrient deficiencies. Bear and Toth (1948) found that adjusting the soil pH to 6.5 could alleviate these symptoms. At a pH of 6.5 the exchange complex would contain 20% H and 65% Ca. Thus a Ca:K ratio of 13:1 would supply ample K (> 1% K in alfalfa tissue) and yet prevent luxury consumption of K. Bear and Toth (1948) also considered the fact that it was cheaper to apply Ca than K as a fertilizer.

Therefore, since the plant would tolerate a wide range in soil Ca:K ratios, it made economic sense to add sufficient Ca to the soil to limit excessive uptake of K but still maintain healthy plant growth. These findings were used by Bear and his colleagues as the scientific and practical basis for the selection of a specific basic cation saturation ratio for an “ideal” soil. Later, Graham (1959) suggested that the percentage base saturation for soils in Missouri could range from 65-85% for Ca, 6-12% for Mg, and 2-5% for K without affecting the soil’s ability to produce optimum yields.

Since the time of Bear’s proposal of an “ideal” basic cation saturation ratio, other researchers have attempted to verify the concept but have found little evidence for the existence of an ideal ratio. Hunter (1949) reported that the yield of alfalfa was not affected by varying Ca:Mg ratios in the soil, although it did have a highly significant effect upon the percentages of Ca and Mg in the alfalfa. In Indiana, Foy and Barber (1958) found no yield reduction with corn even when Mg deficiency was induced by high rates of calcitic lime and potash on two acid soils. However, they reported that lime did produce a significant yield increase on one of the soils. McLean and Carbonell (1972) reported that yields of German millet (*Seteria italica* L. Beauv.) were not affected by varying Ca:Mg ratios. In growth chamber studies with German millet, Eckert and McLean (1981) found no evidence of an ideal ratio for Ca:Mg:K. After an additional six years of field studies with corn, soybeans, wheat, and alfalfa, McLean et al. (1983) concluded that an “ideal” basic cation saturation ratio did not exist. They suggested that the emphasis of fertility programs should be to provide sufficient but not excessive amounts of nutrients rather than to provide an ideal ratio of basic cations.

Although it would seem that the scientific evidence for the existence of an ideal basic cation saturation ratio is tenuous, McLean (1977) reported that there has been an increasing use of this concept for soil testing and fertilizer recommendations. In 1960, 1.25 million soil samples were tested in the North Central Region of the United States. Of these samples, 2/3 were analyzed by university soil testing labs. By the late 1960's, 2 million samples were tested, of which only 1/5 were analyzed by university soil testing labs. The rest of the samples were analyzed by commercial and industrial soil testing labs. Almost all of the commercial and industrial labs used the BCSR concept when making fertility recommendations. Consequently, the total number of soils managed according to the BCSR concept is increasing. Liebhardt (1981) suggested that in Delaware 80 to 90% of the soils are managed using the BCSR concept. Although there appears to be little scientific evidence for the hypothesis that there is an "ideal" ratio of basic cations in the soil, the BCSR concept is still commonly used as the philosophical basis for making fertilizer recommendations.

The second major concept used in soil fertility recommendations is the concept of a sufficiency level of available nutrients (SLAN). In a survey of 43 public universities operating soil testing labs, Eckert (1987) reported that 41 out of 43 of these public universities used the sufficiency level approach for making K fertilizer recommendations. The SLAN concept was developed by Bray (1944, 1945) in Illinois. In research with crops grown in four-year rotation, Bray found a correlation between the level of exchangeable K and crop yield when the level of exchangeable K was expressed as a percentage of K required to produce maximum yield. The maximum yield was taken to be the yield obtained on the experimental plots receiving adequate amounts of K. Bray

called the percentage yield obtained the “percentage sufficiency of the available potassium” (Bray, 1944). Bray observed that each additional unit of exchangeable K gave an increasingly smaller percent yield increase. Based upon his findings, Bray applied the Mitscherlich equation to describe this “law of diminishing returns” response curve and modified the equation into the following form:

$$\text{Log } (A-y) = \text{Log } A - c_1 b_1 \quad [1]$$

where A = yield obtained when K is not deficient, y = yield obtained at any other K soil test level, b_1 = the soil test K level, c_1 = a proportionality constant for the crop. The proportionality constant is determined experimentally and varies by crop. Calculation of the proportionality constant, c_1 , requires values for A, y, and b to be known and involves the following assumptions (Bray, 1944): 1) The yield obtained on the reference plot is the maximum yield obtainable, i.e. no additional yield increase would result from further additions of K, 2) The difference in yield between plots receiving K and plots not receiving K is due entirely to the potash, and 3) The total exchangeable K as measured by the soil test is a measure of the amount of plant available potassium.

Bray (1944) also modified the Mitscherlich equation to account for x, the amount of fertilizer added to the soil. With the addition of this term, the Mitscherlich equation takes the form:

$$\text{Log } (A - y) = \text{Log } A - (c_1 b_1 + cx) \quad [2]$$

where A = yield obtained when K is not deficient, y = yield obtained at any other K soil test level, b_1 = the soil test K level, x = amount of K added, c_1 and c = proportionality constants for the crop and soil respectively. Bray (1945) noted that A is not the theoretical maximum yield when none of the essential plant nutrients are deficient, but

rather it is the yield obtained when the one nutrient under consideration is not deficient. Bray (1945) selected a 98% relative yield as the sufficiency level for the crops he studied. Today, most laboratories use a 95 to 99% relative yield as the sufficiency level (Eckert, 1987).

Different Philosophies Used in Making Fertilizer Recommendations

Three philosophies are commonly used today in the United States for making fertilizer recommendations. These are the basic cation saturation ratio concept, the nutrient sufficiency approach, and the nutrient build-up and maintenance plan. The basic cation saturation approach is used to establish designated or specific ratios among Ca, Mg, and K. Fertilizer recommendations are then made to achieve these ratios of basic cations in the soil. This philosophy is often used when lime recommendations are made and can be of benefit on soils having naturally low Mg levels. In the nutrient sufficiency approach, fertilizer recommendations are made to obtain a desired yield goal at the existing soil test level. This is a conservative strategy because the aim is to apply only the quantity of nutrient needed to achieve a desired yield goal, without attempting to increase the fertility level of the soil. In the nutrient build-up and maintenance program, a critical soil test level is established. The critical soil test level is considered to be that soil test value at which the soil can adequately supply nutrients to support optimum economic growth (Vitosh et al., 1995). Below the critical level, a build-up level of fertilizer is recommended. That is, sufficient fertilizer is recommended to produce the desired yield at the existing soil test level and to raise the existing soil test value to the critical level over a period of several years. After the critical soil test level has been

reached, recommendations are made to compensate for crop removal and maintain the soil test value at or slightly above the critical level. This plan is generally used with three objectives in mind: 1) Increase the soil test value to the critical level and maintain it at that level. 2) “Banking” soil fertility, and 3) Build a margin of safety for protection against differential crop response in poor weather years (Eckert, 1987). Raising soil test values to the maintenance level also helps to safeguard against sampling and analytical variation (Vitosh et al., 1995).

Differences in Potassium Recommendations in the Tri-State Region

Although 1M neutral ammonium acetate is used as a common extractant for K by all the states in the North Central Region (Brown and Warncke, 1988) philosophical differences in soil test interpretation have resulted in markedly different K recommendations by some states. This has been the case in Michigan, Indiana, and Ohio. In the past, Michigan recommended build-up when the soil test K level was low but did not follow with a maintenance recommendation (Christenson et al., 1992). Michigan also never established critical soil test values for K. Ohio’s K guidelines included recommendations for soil buildup and crop removal. In addition, Ohio established a sufficiency level for K based upon the CEC of the soil (Anonymous, 1988). This approach was based upon the work of Fisher (1974) in Missouri. Indiana also has followed a nutrient buildup and maintenance concept and categorized their soils as deficient, adequate, optimum, or excessive according to the soil test K value. Indiana did not, however, use a CEC factor in their K recommendations except to recommend that

not more than 150 lb/A of K_2O be applied to soils having a CEC of less than 6 cmol/kg to prevent excessive losses of K due to leaching (Anonymous, 1992).

One of the biggest differences in K recommendations between the three states has been Ohio's use of the soil CEC to establish the sufficiency level for K. Prior to the mid 1970's, 200 lb/A of exchangeable K was used as the sufficiency level in Ohio for all soils and all crops except alfalfa (McLean, 1976). This was based upon Bray's data (1945) which showed that an exchangeable K value of 200 lb/A gave 95 to 98% maximum yield for corn, clover hay, soybeans, wheat, and oats. During the period from 1961 to 1971, the average level of exchangeable K of soils tested by the Ohio State University Soil Testing Laboratory increased from 165 lb/A to 237 lb/A. This increase was attributed to the fact that additions of K through fertilizers and K released from nonexchangeable forms was greater than K removed by crops or lost through leaching. In the four counties (Defiance, Paulding, Putnam, and Ottawa) in the Lake-Plain region of northwest Ohio, which have an average of 83% of soils that are fine textured, the level of exchangeable K did not increase (326 lb/A versus 328 lb/A) during this 10 year period. However, in the five other counties in the Lake-Plain Region, which have only 51% of soils that are fine textured, the level of exchangeable K increased from 188 lb/A to 240 lb/A. McLean (1976) presented data, based upon the bonding strength of exchangeable K, that for Ohio soils there could be as much as a three-fold difference in the amounts of exchangeable K available to plants on soils with CEC's ranging from 10 to 40 cmol/kg. Earlier work by Conyers and McLean (1968) had shown that in clay separates of Ohio soils weathered with growing roots, the ability of the clay to fix K in the nonexchangeable form was greater than the clay's ability to release K. Based upon these

findings and observations by university agronomists and local farmers, McLean felt that an increase in K fertilizer recommendations would be appropriate; although he admitted that it was not then known how large of an increase should be made in K recommendations or whether increased K recommendations would be suitable for all fine textured soils. In reflection of this philosophical shift, the Ohio State University Soil Testing Laboratory adopted the equation proposed by Fisher (1974) to establish the sufficiency level for K:

$$K_{\text{ sufficiency level (ppm)}} = 110 + 2.5 \times \text{CEC} \quad [3]$$

This formula has been in use in Ohio since the mid-1970's and is still used as the basis for making K recommendations in that state.

Reasons for Tri-State Fertilizer Recommendations

There are at least three important reasons for the effort to develop common fertilizer recommendations for Michigan, Indiana, and Ohio (Vitosh, 1995). The first reason is that for many years, farmers and agribusiness companies that operate near the border areas have been interested in the development of common fertilizer recommendations that would provide for consistent management practices in neighboring areas. A second reason is that a common set of recommendations would provide more credibility for university research. The third reason is that over the past 20 years there has been a steady decline in the number of soil fertility specialists at public universities. Given the present economic and political mood in both the private and public sector, it is likely that this trend will continue. Therefore, it is very important that the scientific basis for fertilizer recommendations be well documented. A fourth reason for common

recommendations is the fact that Michigan, Indiana, and Ohio share common soils. Therefore, these soils should exhibit similar characteristics in K chemistry.

The objective of this research project was to determine the degree of similarity in K chemistry of soils common to the three states. Examination of the K chemistry of soils collected from multiple locations throughout the tri-state area would provide support either for or against the assumptions underlying the tri-state recommendations. This objective was achieved through a combination of biological, chemical, mineralogical, and physical diagnostic approaches. The results of these studies are described in the following two chapters.

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CHAPTER 1

POTASSIUM RELEASE FROM EXCHANGEABLE AND NONEXCHANGEABLE FORMS IN MICHIGAN, INDIANA, AND OHIO SOILS AS MEASURED BY CHEMICAL EXTRACTION AND NEUBAUER TECHNIQUES

ABSTRACT

There are no papers in the literature that compare the potassium (K) chemistry of soil series common to Michigan, Indiana, and Ohio. In 1995 and 1996, 54 soils from this tri-state region were collected for study. The objectives of this investigation were: 1) to determine the degree of similarity in the K chemistry of soils common to the three states; 2) to determine the nature of K release during intensive cropping; and 3) to determine whether ammonium acetate (NH_4OAc) or sodium tetraphenylboron (NaBPh_4) would better predict plant available K for soils of the tri-state area. Cation exchange capacity (CEC), total K, NH_4OAc and NaBPh_4 extractable K levels were determined for all soils. Neubauer experiments with barley (*Hordeum vulgare* cv. Bowers) were conducted in a growth chamber to investigate K release during intensive cropping. Large differences in CEC, total K, and nonexchangeable K release were found between soil series. The finest textured soils had higher levels of total K, and released more nonexchangeable K than soils having less clay. Exchangeable K values were much lower than nonexchangeable K values and were not significantly different between soil series regardless of texture. The contribution of exchangeable K to total plant uptake ranged from 17 to 75% between soil

series. Regression analysis did not show NaBPh_4 to be a better index of plant available K than NH_4OAc . Although large differences in K chemistry exist between soil series, individual soils in a given series will generally exhibit similar K chemistry regardless of geographic location. These findings suggest that regional K fertilizer recommendations can be made for common soil series in the tri-state area.

INTRODUCTION

The improvement of analytical methodologies to accurately measure the bioavailability of soil nutrients is an important objective for soil fertility specialists and soil testing laboratories throughout the U.S. and the world. Accurate measurements of plant available potassium (K) in soils are complicated by the fact that K equilibria in soils are dynamic. Potassium can be released and fixed by soil minerals (Mortland et al., 1957; Ross et al., 1989). Potassium exists in four phases in the soil: solution, exchangeable, nonexchangeable, and mineral (Sparks, 1987). Although soils may contain large amounts of K, only a small portion is immediately available to the plant. Typically, solution and exchangeable K are only 0.1 to 2% of total K (Tisdale et al., 1985). Under field conditions, the roots of annual crops occupy a volume that is only 0.4 to 2% of the soil volume in the A horizon (Barber, 1968). Therefore, if a chemical extractant is to provide a reliable index of plant available K, it must extract a quantity of K that will correlate well with the amount of K taken up by the crop.

Ammonium acetate, NH_4OAc , which measures exchangeable K levels, has traditionally been used to estimate plant available K. However, plants also utilize a portion of the nonexchangeable K released from 2:1 clay minerals (Mengel and

Rahmatullah, 1994). In the past, various extractants have been used to estimate plant available nonexchangeable K. These have included, among others: boiling HCl and HNO₃, sodium tetraphenylboron (NaBPh₄), and Ca-saturated and H-saturated cation exchange resins (Sparks, 1985).

Sodium tetraphenylboron was chosen in this study because it mimics the action of plant roots by lowering the concentration of K in solution. The NaBPh₄ procedure was developed by Scott and co-workers at Iowa state during the late 1950's and 1960's. In their pioneering work, they used NaBPh₄ to extract K from soil and pure mineral systems (Reed and Scott, 1966; Scott and Reed, 1962a,b; Scott and Welch; 1961, Scott et al., 1960, Smith and Scott, 1966). Sodium tetraphenylboron lowers the solution K concentration by precipitating K in solution with the BPh₄⁻ anion to form KBPh₄ while the Na acts as an exchanger for K. The excess NH₄ in the quenching solution terminates the reaction by saturating the exchange sites with NH₄, thereby inhibiting further release of K. Potassium is released into solution by dissolution of the KBPh₄ precipitate by boiling, and Hg or Cu is used to destroy the BPh₄⁻ anion.

Although common soil testing procedures for K are used throughout the North Central region of the U.S. (Brown and Warncke, 1988), philosophical differences in soil test interpretations have caused some states to recommend greatly different rates of K fertilizers. Historically, this has been the case in Michigan, Indiana, and Ohio, but in the past several years, soil fertility specialists from Michigan State, Purdue, and Ohio State Universities have worked together to produce a common set of fertilizer recommendations for the tri-state region. The result of this collaborative effort has been the recent publication of an extension bulletin entitled "Tri-state fertilizer

recommendations for corn, soybeans, wheat and alfalfa" (Vitosh et al., 1995). As the new tri-state fertilizer recommendations were developed, it was decided that additional work would be needed to determine the adequacy of the new recommendations. This work, then, is a part of the ongoing effort to provide the research data necessary to evaluate the new regional approach to K fertilizer recommendations in the tri-state area.

The objectives of this study were: 1) to determine the degree of similarity in K chemistry of similar soil series from the tri-state region; 2) to determine the nature of K release of these soils during intensive cropping; and 3) to determine if NH_4OAc or NaBPh_4 provides a better index of plant available K.

MATERIALS AND METHODS

Soil Selection, Collection, and Preparation

Soils were collected from sites throughout Michigan, Indiana, and Ohio in 1995 and 1996. Sites were selected by first using a generalized state soil association map to identify those counties within each state where the soil associations of interest were extensive. Individual sites were then chosen based upon the more detailed information in the respective county soil survey reports. The counties from which soil samples were collected are shown in Figure 1.1. The location of individual soils and their soil family classification are listed in appendix A. Samples were taken from locations as close as possible to the site of the representative pedon to minimize potential differences in soil characteristics. The soils in this study were chosen based upon the extensiveness of their distribution throughout Michigan, Indiana, and Ohio and their agricultural importance. At the center of the study are two soil association groups; the Miami, Conover, Brookston

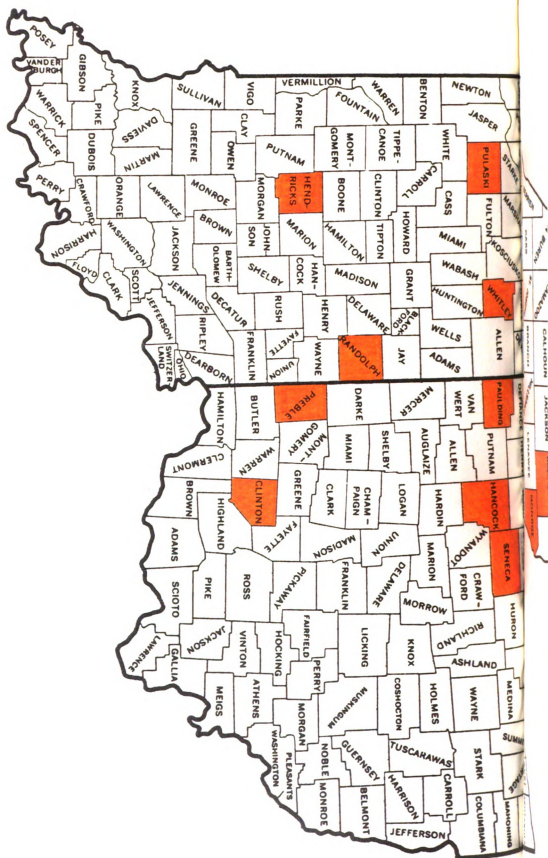
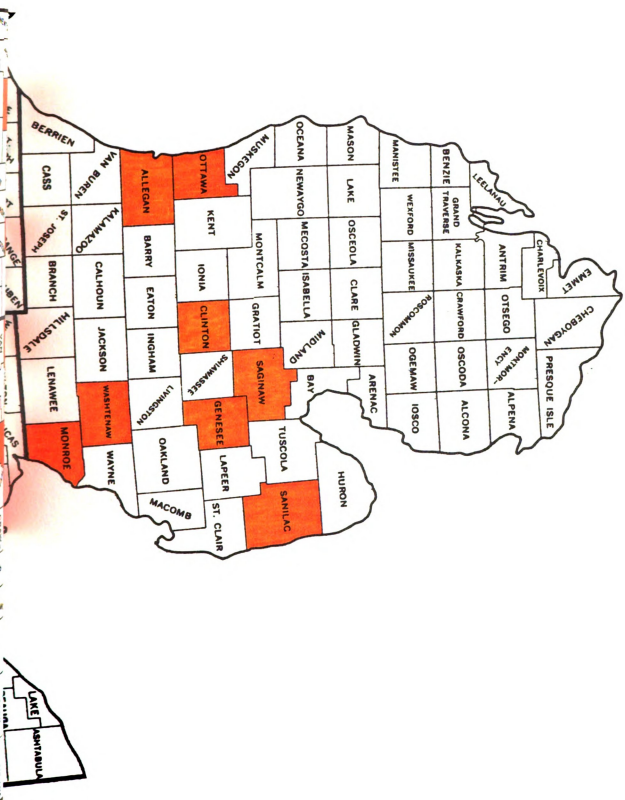


Figure 1.1. Tri-state map of Michigan, Indiana, and Ohio. Counties from which soil samples were collected are shown in color.



soil association group and the Morley, Blount, Pewamo soil association group. These two soil groups form two toposequences, meaning that they are associated with each other in the landscape and were formed in the same parent material. Their main differences are topography and drainage class. The Miami and Morley soils are well drained, the Conover and Blount soils are somewhat poorly drained, and the Brookston and Pewamo soils are poorly drained. The Miami, Conover, and Brookston soils were formed in loam glacial till whereas the Morley, Blount, and Pewamo soils were formed in clay loam or silty clay loam glacial till (Smeck et al., 1968). The Morley, Blount, Pewamo soil association is the largest soil association in Ohio (Dr. George Hall, personal communication).

The Marlette, Capac, Parkhill soil association group, which is found only in Michigan, was selected because it occupies extensive portions of central and southern Michigan where intensive agriculture is prevalent. The Hoytville, Misteguay, and Paulding soils, although not found in all three states, were selected because of their fine texture and high K contents.

A representative sample from the Ap horizon of each soil was collected in 5 gallon buckets and transported to Michigan State. Bulk samples were air dried and sieved through a 1/4" wire mesh screen prior to mixing of the soil. Bulk samples were transferred to a cement mixer and mixed for 10 minutes. A representative subsample was then taken and dried at 35° C for 24 hours. After drying, samples were ground with a flail grinder to pass a 10 mesh (<2 mm) sieve. The <2mm fraction was mixed for 10 minutes in a twin shell dry blender to ensure complete homogenization of the soil. After

mixing, the samples were placed in waxed cardboard cartons and stored until chemical analyses were performed.

Chemical Analyses

Exchangeable K (Brown and Warncke, 1988) was determined with 2 gram samples of soil weighed in duplicate and placed into 125 mL erlenmeyer flasks. Twenty mL of 1 *M* neutral NH_4OAc were added and samples were shaken for 5 minutes on a reciprocating shaker at 200 oscillations per minute. After extraction, samples were filtered through No. 2 Whatman filter paper. The K concentration in the extract solution was determined with a Technicon autoanalyzer flame photometer.

Exchangeable plus nonexchangeable K was measured using a modified NaBPh_4 procedure based upon Cox et al. (1996). One-half gram samples were weighed in duplicate and placed into 50 mL folin wu tubes. Three mL of a solution containing 1.7 *M* NaCl , 0.167 *M* NaBPh_4 , 0.01 *M* EDTA were added to the samples. The samples were swirled gently and allowed to sit for the desired extraction period (five minutes or seven days). After extraction, 25 mL of a quenching solution containing 0.5 *M* NH_4Cl plus 0.11 *M* CuCl_2 was added to terminate the release of K. Samples were then placed on a digestion block and allowed to boil gently at 150° C for 30 to 45 minutes or until the KBPh_4 precipitate was dissolved. After boiling, 15 drops of 6 *M* HCl were added to the samples to prevent precipitation of Cu and brought to a 50 mL volume with deionized water. A 20 mL aliquot was taken after the samples had clarified sufficiently for analysis. The K concentration in solution was determined with a model 51Ca Perkin Elmer flame photometer.

Finely ground (<100 mesh) 0.1 gram samples were weighed in duplicate and analyzed for total K using the $\text{HClO}_4\text{:HF}$ double acid digestion procedure as described by Knudsen et al. (1982). Percent organic matter was determined colorimetrically with duplicate 1 gram samples by heat of dilution with concentrated H_2SO_4 (Schulte, 1988). Duplicate 5 gram samples were used to determine soil pH using a 1:1 soil to water ratio (Eckert, 1988). Cation exchange capacity (CEC) was determined by a centrifugation method with duplicate 2 gram samples (Warncke, 1997). Twenty mL of 1 M neutral NH_4OAc were added to the soils. The samples were mixed with a vortex mixer and centrifuged for five minutes. After centrifugation, the supernatant was discarded. This was done three times. Samples were washed free of excess NH_4^+ by adding 15 mL of 95% ethyl alcohol, then mixing and centrifuging the samples. The supernatant from the alcohol washings was discarded. This was done three times. The NH_4^+ was displaced by adding 10 mL of a 10% acidified NaCl solution and 5 mL of deionized water. The samples were mixed, centrifuged, and the supernatant transferred to a 50 mL volumetric flask. This was done three times. The samples were then brought to volume. The displaced NH_4^+ in the extract was measured with the LaChat system.

Neubauer Studies

A Neubauer method modified from that of McGeorge (1946) was utilized to study the K release characteristics of the soils during intensive cropping. One hundred grams of oven dry soil were placed into four-inch clear vinyl saucers and seeded with 110 spring barley (*Hordeum vulgare* cv. Bowers) seeds obtained from Michigan Foundation Seed, Lansing, Michigan. The barley seeds were wrapped in moist paper towel for 12

hours prior to seeding to imbibe water and speed germination of the seeds. Eighty-five grams of soil were placed below the seed and 15 grams of soil were placed on top of the seed to promote better contact between the soil and the seed. Twenty-eight mL of water were added to the saucers. The soil surface was then covered with 45 to 50 grams of polypropylene plastic beads to reduce evaporative losses from the soil surface and to bring all pots to a uniform weight. Each soil was replicated four times. Pots were watered twice a day with a nutrient solution containing $100 \mu\text{g ml}^{-1}$ nitrogen as NH_4NO_3 and $20 \mu\text{g ml}^{-1}$ phosphorus as $\text{Ca}(\text{H}_2\text{PO}_4)_2$ to maintain optimum soil moisture content. Plants were grown in a controlled environment growth chamber for 22 days after seeding. The daylength was 16 hours with 85% relative humidity. The daytime temperature was 73°F with a nighttime temperature of 68°F . The average photon flux during the experiments ranged from 364 to $389 \mu\text{mol m}^{-2} \text{s}^{-1}$. After 22 days the plants were harvested by clipping the shoots at the soil level. The moist soil was separated from the roots as efficiently as possible. The roots were then placed on a 60-mesh sieve and washed free of adhering soil under a stream of running tap water. The shoot and root tissue samples were placed in labeled brown paper bags and dried at 60°C for 48 hours. After drying, shoot and root tissue samples were ground using a cyclone grinder. One-half gram tissue samples were weighed into crucibles and ashed in a muffle furnace at 500°C for 5 hours. After ashing, the samples were taken up in 25 mL of 3 M HNO_3 , filtered, diluted, and K was determined by flame photometry. Potassium uptake was calculated according to the following formula: $[(\text{shoot dry weight} * \text{shoot K concentration}) + (\text{root dry weight} * \text{root K concentration})] - \text{K content of the seed (15.49 mg K per seed lot)}$. This value was then multiplied by 10 to convert the K uptake per 100

mg soil to K uptake per kg soil. The recovered soil from the pots was dried at 35° C, mixed, and subsamples taken to determine NH_4OAc and NaBPh_4 extractable K levels after cropping.

Mean separation and regression analysis of the data was done using the Statistix software program (Analytical Software, 1996).

RESULTS AND DISCUSSION

Chemical Analyses

A summary comparison of the amounts of K extracted by NaBPh_4 and NH_4OAc for all 54 soils is presented in Table 1.1. As expected, NaBPh_4 extracted more K. The

Table 1.1. Comparison of the amounts of K extracted by NaBPh_4 and NH_4OAc in 54 soils from the tri-state area.†

	K Extractable by NaBPh_4 in 7 days	K Extractable by NaBPh_4 in 5 minutes	K Extractable by NH_4OAc in 5 minutes	7 Day:5 Minute NaBPh_4 Extractable K	5 Minute NaBPh_4 : NH_4OAc Extractable K
	% of total K			Ratio	
low	10	1.5	0.4	7.6:1	2.1:1
high	55	8.6	2.5	74.8:1	8.3:1
average	29	4.6	1.1	30.8:1	4.6:1

†Values listed in table are based on extractable K levels prior to initiation of Neubauer growth studies.

amount of K extractable with NaBPh_4 in seven days ranged from 10 to 55% of the total K. These values are similar to those reported by Smith et al. (1968). In their study, 20 to 47% of the total K was extracted by NaBPh_4 . Data by Cox et al. (1996) showed that a seven-day extraction period was sufficient to release nearly all of the K extractable by NaBPh_4 . These data are important because they demonstrate the strong K extracting

ability of this reagent, and they measure the long-term available K reserves of representative soils of the tri-state area. The five-minute NaBPh_4 extractable K is useful from a soil fertility standpoint because it more closely measures that portion of the nonexchangeable K that would be readily plant available. With a five-minute extraction, the values are much lower, ranging from 1.5 to 8.6% of the total K. The average value across all soils was 4.6%. The exchangeable K was even less, ranging from 0.4 to 2.5% and averaging only 1% of total K. The ratio of the seven-day to five-minute NaBPh_4 extractable K is interesting because it indicates the relative proportions of K released in a short time versus the amount of K released over a longer time. This ratio provides a comparative measure of the quantity of nonexchangeable K that would be more readily plant available versus the amount of nonexchangeable K that might become available over the long-term through weathering. Presumably, the lower the ratio, the greater the percentage of nonexchangeable K that would be readily plant available. It is interesting to note that although the average ratio is 30.8:1, there is nearly a 10-fold difference in this ratio between the highest and lowest soils. From a soil fertility standpoint, it is also important to compare the ratio of the five-minute $\text{NaBPh}_4\text{:NH}_4\text{OAc}$ extractable K. On the average, NaBPh_4 extracted 4.6 times as much K as NH_4OAc in five minutes. Once again, this difference demonstrates the ability of NaBPh_4 to extract large quantities of nonexchangeable K from the soil.

An important objective of this study was to determine the degree of similarity in the K chemistry of soils in the tri-state area. Differences in total K content are quite evident when all soil groups are compared (Table 1.2). The Paulding type soils contain the greatest amount of total K, 28,700 mg K kg^{-1} , whereas the Miami soils contain the

Table 1.2. Mean values of CEC, total K, nonexchangeable K, and exchangeable K for all soil groups before Neubauer growth studies.

Soil Group	Number of Soils	CEC		Total K		Seven-Day Nek‡		Five-Minute Nek§		Exk¶	
		Mean	SE†	Mean	SE	Mean	SE	Mean	SE	Mean	SE
		cmol _c kg ⁻¹		mg K kg ⁻¹							
Paulding#	2	28.8a*	1.6	28,700a	800	12,300a	3,600	1,560a	425	270a	5
Hoytville	2	20.3b	4.0	21,000b	3,400	7,780b	2,700	1,150a	410	180a	45
Pewamo	6	21.0b	2.9	19,800b	1,020	6,110bc	594	910ab	63	260a	45
Morley††	7	12.6c	1.5	18,400bc	1,140	5,650c	915	710ab	141	200a	48
Blount	7	15.4bc	1.1	18,400bc	352	5,110c	413	620ab	75	210a	18
Capac	3	12.4c	1.1	18,300bc	1,200	5,210c	456	550ab	136	160a	72
Parkhill	2	15.0bc	1.9	17,800bc	1,650	5,580c	165	540ab	165	190a	80
Marlette	3	13.5bc	1.9	17,700bc	639	4,850c	169	510b	54	140a	41
Conover‡‡	8	14.3bc	1.8	16,600c	1,238	4,400c	1,040	530b	146	140a	13
Brookston§§	7	19.7b	2.3	16,200c	498	4,270cd	522	630ab	67	220a	24
Miami¶¶	7	11.3c	1.4	15,900c	922	3,430d	792	450b	172	200a	45

*Means followed by the same letter are not significantly different at the 0.05 probability level.

†SE = Standard error of the mean.

‡Seven-Day Nek = Seven-Day NaBPh₄ extractable K minus the exchangeable K.

§Five-Minute Nek = Five-Minute NaBPh₄ extractable K minus the exchangeable K.

¶ExK = Exchangeable K (Five-Minute 1M neutral NH₄OAc extractable K).

#Paulding includes Paulding and Mistegway soils.

††Morley includes Glynwood soils.

‡‡Conover includes Crosby and Celina soils.

§§Brookston includes Kokomo soils.

¶¶Miami includes Miamian soils.

least amount of total K, 15,900 mg K kg⁻¹. The soils follow a definite trend with the finer textured soils containing more total K. This suggests that soils with a higher clay content will contain more total K than soils with a lower clay content. The cation exchange capacity does not follow such a clear trend for the soils in the middle although the soils at the extremes, the Paulding and Miami soils do show distinct differences in CEC. Cation exchange capacity, total K, seven-day and five-minute nonexchangeable K, and exchangeable K data for individual soils are presented in appendix B.

The seven-day nonexchangeable K follows a pattern very similar to that exhibited by total K. There is a very consistent trend for the soils high in total K to release large amounts of nonexchangeable K to NaBPh₄ extraction. This would be expected since NaBPh₄ is very effective in removing K from the interlayers of the 2:1 clay minerals. There is more than a three-fold difference in seven-day nonexchangeable K release between the Miami and Paulding soil groups. This indicates that the long-term K supplying power is less for the Miami soils and that these soils would require more frequent K fertilization to maintain high levels of fertility. The five-minute nonexchangeable K also exhibits a pattern similar to that for the seven-day nonexchangeable K. These trends suggest that NaBPh₄-K levels could be a reliable index of the K supplying power of these soils.

The exchangeable K levels of these soils show no significant differences between any of the soil groups. The soils with low nonexchangeable K values have exchangeable K values comparable to the exchangeable K values of the soils high in nonexchangeable K. These results emphasize the fact that exchangeable K values alone give little

indication of the ability of these soils to release nonexchangeable K nor does it provide any information on the rate of nonexchangeable K release.

After consideration of the data from all the soils in the tri-state study, the second important issue is to determine what differences are present between the six soil series common to the three states. These data are presented in Table 1.3. The finer textured Morley, Blount, and Pewamo soils are higher in total K than the Miami, Conover, and Brookston soils. The CEC for these soils does not follow any clear pattern analogous to total K. However, the finer textured soils do have a slightly higher average CEC than their coarser textured counterparts. There is nearly a two-fold difference in the mean CEC, 21.0 versus 11.3 $\text{cmol}_\text{c} \text{ kg}^{-1}$, between the Pewamo and Miami soil groups respectively. It is worthwhile to mention that the poorly drained Pewamo (4.0% average organic matter content) and Brookston soils (4.3% average organic matter content) have the highest CEC and the highest organic matter content of any of the soil groups. However, one would expect these soils to contain more smectite which would also increase the CEC. The relative importance of both the organic and inorganic contribution to total CEC is investigated in more detail in chapter two.

Differences in seven-day nonexchangeable K were not statistically significant among the six soil series; although there is almost a 1.8 times difference between the highest and lowest values. This lack of significance is due to the large variability present within the soils of some groups. This is reflected in the large standard error values. This is particularly true for the Conover group where the standard error is nearly 1/4 the value of the mean. The five-minute nonexchangeable K values also do not show significant differences when only the six soil groups are considered. It is to be expected however

Table 1.3. Mean values of CEC, total K, nonexchangeable K, and exchangeable K before Neubauer growth studies for the six soil series common to the tri-state area. Soils are grouped by major soil series.

Soil Group	Number of Soils	CEC		Total K		Seven-Day Nek†		Five-Minute Nek§		Exk¶	
		Mean	SE†	Mean	SE	Mean	SE	Mean	SE	Mean	SE
		cmol _c kg ⁻¹		mg K kg ⁻¹		mg K kg ⁻¹		mg K kg ⁻¹		mg K kg ⁻¹	
Pewamo	6	21.0a*	2.9	19,800a	1,020	6,110a	594	910a	63	260a	45
Morley#	7	12.6c	1.5	18,400ab	1,140	5,650a	915	710a	141	200a	48
Blount	7	15.4bc	1.1	18,400ab	352	5,110a	413	620a	75	210a	18
Conover††	8	14.3c	1.8	16,600b	1,238	4,400a	1,040	530a	146	140a	13
Brookston‡‡	7	19.7ab	2.3	16,200b	498	4,270a	522	630a	67	220a	24
Miami§§	7	11.3c	1.4	15,900b	922	3,430a	792	450a	172	200a	45

*Means followed by the same letter are not significantly different at the 0.05 probability level.

†SE = Standard error of the mean.

‡Seven-Day Nek = Seven-Day NaBPh₄ extractable K minus the exchangeable K.

§Five-Minute Nek = Five-Minute NaBPh₄ extractable K minus the exchangeable K.

¶ExK = Exchangeable K (Five-Minute 1M neutral NH₄OAc extractable K).

Morley includes Glynwood soils.

†† Conover includes Crosby and Celina soils.

‡‡ Brookston includes Kokomo soils.

§§ Miami includes Miamian soils.

that the differences between the soil groups would be less when the groups with the highest values for total K and seven-day and five-minute nonexchangeable K (e.g. Paulding and Hoytville) are not considered. Although the seven-day and five-minute nonexchangeable K values do not show statistically significant differences, they do follow the same pattern as the total K values. The Pewamo soils that are highest in total K have greater amounts of nonexchangeable K. The exchangeable K values show no statistically significant differences when only the six soil groups are considered.

Comparing the six common soil series across the three states addresses the question of whether the soils of Michigan are different from the soils of Indiana or Ohio. In Table 1.4, all soils from the six common soil series are compared by state. Table 1.4 shows that there are no statistically significant differences by state in the mean values for CEC, total K, seven-day and five-minute nonexchangeable K, or exchangeable K when the six common soil series are grouped together. To further address the question of whether the soils are similar, the common soil series were individually compared across states. These data are presented in Tables 1.5 to 1.9. There were no significant differences in CEC, total K, seven-day and five-minute nonexchangeable K, or exchangeable K values between the three states for any of the individual common soil series. These data support the philosophy that there is a sound basis for a regional approach to the development and utilization of tri-state fertilizer recommendations.

Another issue of interest is the question of whether the soils in Michigan would exhibit differences in K chemistry based upon their location in the state. To address this question, seven soil series common to the Michigan, Saginaw, and Huron-Erie glacial lobes were selected. The bedrock of Michigan is shaped like a bowl. Therefore, our

Table 1.4. Mean values of CEC, total K, nonexchangeable K, and exchangeable K before Neubauer growth studies for the six soil series common to the tri-state area. Soils are grouped by state.

State	Number of Soils	CEC		Total K		Seven-Day Nek†		Five-Minute Nek§		ExK¶	
		Mean	SE†	Mean	SE	Mean	SE	Mean	SE	Mean	SE
		cmol _c kg ⁻¹		mg K kg ⁻¹							
Michigan	17	13.9	1.5	17,500	815	4,840	555	630	85	200	23
Indiana	12	17.2	1.4	16,500	690	4,000	620	560	89	210	30
Ohio	13	16.2 _{ns}	1.6	18,200 _{ns}	505	5,440 _{ns}	485	700 _{ns}	99	200 _{ns}	23

ns = Means in the same column are not significantly different at the 0.05 probability level.

†SE = Standard error of the mean.

†Seven-Day Nek = Seven-Day NaBPh₄ extractable K minus the exchangeable K.

§Five-Minute Nek = Five-Minute NaBPh₄ extractable K minus the exchangeable K.

¶ExK = Exchangeable K (Five-Minute 1M neutral NH₄OAc extractable K).

Table 1.5. Cation exchange capacity of the six soil series common to Michigan, Indiana, and Ohio. Individual series are compared across states, not between series.

Soil Group	Number of Soils	CEC					
		Michigan		Indiana		Ohio	
		Mean	SE†	Mean	SE	Mean	SE
cmol _c kg ⁻¹							
Miami‡	7	8.2	0.6	12.8	1.9	14.6ns	2.8
Conover§	8	15.0	5.0	12.9	0.5	14.6ns	2.0
Brookston¶	7	15.7	2.4	19.1	0.2	26.1ns	5.0
Morley#	7	10.9	1.2	15.9	2.7	11.8ns	4.4
Blount	7	15.4	2.1	17.5	0.9	13.5ns	2.3
Pewamo	6	20.7	9.3	25.0	2.5	17.3ns	1.1

ns = Means in the same row are not significantly different at the 0.05 probability level.

SE = Standard error of the mean.

‡Miami includes Miamian soils.

§Conover includes Crosby and Celina soils.

¶Brookston includes Kokomo soils.

#Morley includes Glynwood soils.

Table 1.6. Total K content of the six soil series common to Michigan, Indiana, and Ohio. Individual series are compared across states, not between series.

Soil Group	Number of Soils	Total K					
		Michigan		Indiana		Ohio	
		Mean	SE†	Mean	SE	Mean	SE
mg K kg ⁻¹							
Miami‡	7	15,700	406	13,900	500	18,300ns	2,750
Conover§	8	17,700	3,490	14,800	950	16,600ns	353
Brookston¶	7	16,000	666	15,100	700	17,700ns	150
Morley#	7	18,000	2,730	18,000	950	19,500ns	1,600
Blount	7	18,800	296	17,700	350	18,500ns	1,200
Pewamo	6	19,900	3,600	19,900	1,400	19,500ns	700

ns = Means in the same row are not significantly different at the 0.05 probability level.

SE = Standard error of the mean.

‡Miami includes Miamian soils.

§Conover includes Crosby and Celina soils.

¶Brookston includes Kokomo soils.

#Morley includes Glynwood soils.

Table 1.7. Seven-day nonexchangeable K content of the six soil series common to Michigan, Indiana, and Ohio. Individual series are compared across states, not between series.

Soil Group	Number of Soils	Seven-Day Nonexchangeable K					
		Michigan		Indiana		Ohio	
		Mean	SE†	Mean	SE	Mean	SE
mg K kg ⁻¹							
Miami‡	7	2,890	757	2,030	210	5,640ns	2,030
Conover§	8	6,080	2,480	1,860	390	4,410ns	640
Brookston¶	7	4,470	580	2,660	310	5,600ns	440
Morley#	7	5,020	1,590	6,390	1,280	5,860ns	2,680
Blount	7	5,370	108	4,590	625	5,260ns	1,660
Pewamo	6	5,430	1,990	6,490	730	6,420ns	320

ns = Means in the same row are not significantly different at the 0.05 probability level.

SE = Standard error of the mean.

‡Miami includes Miamian soils.

§Conover includes Crosby and Celina soils.

¶Brookston includes Kokomo soils.

#Morley includes Glynwood soils.

Table 1.8. Five-minute nonexchangeable K content of the six soil series common to Michigan, Indiana, and Ohio. Individual series are compared across states, not between series.

Soil Group	Number of Soils	Five-Minute Nonexchangeable K					
		Michigan		Indiana		Ohio	
		Mean	SE†	Mean	SE	Mean	SE
mg K kg ⁻¹							
Miami‡	7	270	72	290	145	880ns	570
Conover§	8	710	373	230	10	540ns	110
Brookston¶	7	680	106	440	75	740ns	50
Morley#	7	550	208	890	45	760ns	465
Blount	7	720	104	550	5	550ns	245
Pewamo	6	920	180	970	145	860ns	5

ns = Means in the same row are not significantly different at the 0.05 probability level.

SE = Standard error of the mean.

‡Miami includes Miamian soils.

§Conover includes Crosby and Celina soils.

¶Brookston includes Kokomo soils.

#Morley includes Glynwood soils.

Table 1.9. Exchangeable K content of the six soil series common to Michigan, Indiana, and Ohio. Individual series are compared across states, not between series.

Soil Group	Number of Soils	Exchangeable K					
		Michigan		Indiana		Ohio	
		Mean	SE†	Mean	SE	Mean	SE
mg K kg ⁻¹							
Miami‡	7	180	50	210	130	240ns	125
Conover§	8	130	33	120	0	150ns	15
Brookston¶	7	230	63	210	0	230ns	15
Morley#	7	220	107	200	60	170ns	90
Blount	7	240	33	200	5	180ns	40
Pewamo	6	200	20	320	140	270ns	55

ns = Means in the same row are not significantly different at the 0.05 probability level.

SE = Standard error of the mean.

‡Miami includes Miamian soils.

§Conover includes Crosby and Celina soils.

¶Brookston includes Kokomo soils.

#Morley includes Glynwood soils.

Table 1.10. Mean values of CEC, total K, nonexchangeable K, and exchangeable K before Neubauer growth studies for the seven soil series common to the three glacial lobes of Michigan.†

Glacial Lobe	Number of Soils	CEC		Total K		Seven-Day Nek§		Five-Minute Nek¶		Exk#	
		Mean	SE‡	Mean	SE	Mean	SE	Mean	SE	Mean	SE
		cmol _c kg ⁻¹		mg K kg ⁻¹							
Michigan	7	14.3a*	2.0	19,800a	1,180	5,800a	1,160	680a	156	210a	35
Saginaw	7	12.2a	1.3	16,400b	882	4,340a	411	490a	95	170a	28
Huron-Erie	7	12.5a	1.7	16,200b	450	4,380a	286	550a	84	190a	50

*Means followed by the same letter are not significantly different at the 0.05 probability level.

†Soil series are Marlette, Capac, Miami, Conover, Brookston, Glynwood or Morley, and Blount.

‡SE = Standard error of the mean.

§Seven-Day Nek = Seven-Day NaBPh₄ extractable K minus the exchangeable K.

¶Five-Minute Nek = Five-Minute NaBPh₄ extractable K minus the exchangeable K.

#ExK = Exchangeable K (Five-Minute 1M neutral NH₄OAc extractable K).

hypothesis was that the soils in the Michigan and Huron-Erie glacial lobes are similar because the Wisconsin glacier passed over the same layers of bedrock in the western and eastern parts of the state. Differences, if any, would be expected in the Saginaw lobe because younger bedrock layers are present.

The data in Table 1.10 reveal that for the seven soil series selected from each lobe the only statistically significant difference was in the mean total K content of the soils. The soils from the Michigan lobe had a higher total K content than the soils from the Saginaw and Huron-Erie glacial lobes. Although the differences were not statistically significant, the soils in the Michigan lobe also had higher CEC, seven-day and five-minute nonexchangeable K, and exchangeable K values.

Neubauer Studies

The second objective of this study was to determine the nature of K release during intensive cropping. Many researchers have conducted intensive cropping experiments to measure the capability of soils to release K (Addiscott and Johnston, 1975; Mutscher and Tu, 1988; Pratt, 1951; Singh and Ghosh, 1984; Tabatabai and Hanway, 1969). Traditionally, these studies have often used large quantities of soil which require long cropping periods, months or years, in order to lower the soil K levels through plant uptake. The advantages of the Neubauer procedure are that it greatly reduces the length of time needed to conduct a study by eliminating the necessity of multiple harvests to achieve high rates of nutrient removal, and it does not require large quantities of soil. The Neubauer method has been used in Indiana (Thorton, 1931; Thorton, 1935) and in Ohio (Olsen and Shaw, 1943) to evaluate the fertility status of soils. However, these

studies were conducted over 50 years ago. Except for the work of Binnie and Barber (1964) there are few, if any, more recent reports in the literature on utilization of the Neubauer technique for studying the nutrient supplying capabilities of soils in this tri-state area. In light of the fact that many agronomic practices have changed in the intervening half-century, it is obvious that there is a need to reevaluate the fertility status of common soil series in this tri-state region.

Table 1.11 presents summary data of the amounts and percentage of uptake from exchangeable and nonexchangeable K by barley plants during the Neubauer growth

Table 1.11. Amount of K taken up from the exchangeable and nonexchangeable soil K fractions by barley plants during Neubauer growth studies.

	Exchangeable K uptake†	Nonexchangeable K uptake‡	Uptake from Exchangeable K§	Uptake from Nonexchangeable K¶
	mg K kg ⁻¹		%	
low	20	6	11	10
high	350	387	90	89
average	111	116	53	47

†Exchangeable K uptake = Difference between NH₄OAc-K before and after Neubauer growth study (Delta NH₄OAc-K).

‡Nonexchangeable K uptake = Plant uptake K minus delta NH₄OAc-K.

§Uptake from exchangeable K = (Delta NH₄OAc-K divided by plant uptake K) x 100.

¶Uptake from nonexchangeable K = (Nonexchangeable K uptake divided by plant uptake K) x 100.

studies. Values for individual soils are listed in Appendix B. Although there was a wide range in uptake values from the exchangeable K, 11 to 90%, and nonexchangeable K, 10 to 89%, respectively, the magnitude of the differences were similar and the average values were nearly identical. On the average, the barley plants utilized the exchangeable and nonexchangeable K in nearly equal proportions, 53% versus 47% respectively. The high and low values from this study cover the range of percent nonexchangeable uptake

reported in the literature. Niebes et al. (1993) reported that nonexchangeable K accounted for 65 to 80% of total uptake by rape. Menon et al. (1988) found that nonexchangeable K accounted for 22 to 79% of total uptake by the end of four harvests for grass, legume, and cereal crops grown in the greenhouse. Tarfadar and Mukhopadhyay (1989) indicated that in 19 soils from West Bengal nonexchangeable uptake averaged 63%. Tening et al. (1995) reported that in the Nigerian soils they studied stylo (*Stylosanthes hamata* cv. Verano) plants received 23 to 84% of their K from the nonexchangeable forms during exhaustive cropping.

In Table 1.12, the average dry weight, percent K, and total K uptake of the barley shoot and root tissue are reported. The root dry weights are slightly lower than the actual amounts due to incomplete (approximately 85%) recovery of all the roots. In these studies, the K shoot concentrations ranged from 0.72 to 2.77% and averaged 1.61%. The K root concentrations were more constant, ranging from 0.25 to 0.55% with an average value of 0.39%. Warncke and Barber (1974) reported that the proportion of K in corn roots grown in nutrient solution was 11% of the total at 18 to 25 days. Since most of the roots were recovered and because the K concentration in the roots is very low, the K uptake values reported are probably less than 5% below the actual uptake values. In Table 1.13, mean plant uptake values and the percent of uptake from exchangeable K for all the soil groups are presented. The percent of uptake from exchangeable K was calculated as the difference in the exchangeable K level before and after the Neubauer growth study, divided by the total plant uptake.

The Paulding soil group had the highest plant uptake, 371 mg K kg⁻¹ soil. The Conover soil group had the lowest plant uptake, 139 mg K kg⁻¹ soil. Although there were

Table 1.12. Average dry weight, percent K, and total K uptake of harvested barley shoot and root tissue from the 54 soils used in the Neubauer growth studies.

Soil	County	State	Shoot	Root	Shoot	Root	Plant
			Dry Wt†	Dry Wt	K Conc.‡	K Conc.	Uptake §
			grams		%		mg K kg ⁻¹
Marlette	Allegan	MI	1.80	2.67	1.64	0.40	247
Marlette	Clinton	MI	1.80	2.54	1.23	0.32	147
Marlette	Sanilac	MI	1.70	2.56	1.07	0.30	105
Capac	Allegan	MI	1.89	2.46	1.23	0.30	150
Capac	Clinton	MI	1.81	2.56	2.17	0.53	374
Capac	Sanilac	MI	1.54	2.57	0.72	0.32	38
Parkhill	Clinton	MI	1.68	2.66	1.94	0.47	295
Parkhill	Sanilac	MI	1.80	2.50	1.09	0.28	112
Miami	Ottawa	MI	1.66	2.31	1.03	0.32	91
Miami	Genesee	MI	1.64	2.60	1.40	0.32	158
Miami	Washtenaw	MI	1.82	2.82	1.57	0.43	250
Miami	Pulaski	IN	1.76	2.56	2.10	0.45	331
Miami	Hendricks	IN	1.50	2.28	0.77	0.29	26
Miamian	Preble	OH	2.08	2.47	2.63	0.50	517
Miamian	Clinton	OH	1.63	2.59	0.87	0.31	67
Conover	Ottawa	MI	1.68	2.35	1.88	0.36	244
Conover	Genesee	MI	1.73	2.59	0.91	0.28	74
Conover	Washtenaw	MI	1.91	2.40	1.29	0.29	159
Crosby	Pulaski	IN	1.74	2.36	1.08	0.32	108
Crosby	Hendricks	IN	1.57	2.24	1.04	0.28	71
Celina	Preble	OH	2.09	2.34	1.18	0.34	171
Crosby	Preble	OH	1.83	2.61	1.16	0.37	154
Crosby	Clinton	OH	1.64	2.42	1.24	0.35	134
Brookston	Allegan	MI	2.01	2.55	2.16	0.53	412
Brookston	Genesee	MI	1.77	2.40	1.56	0.39	215
Brookston	Washtenaw	MI	1.80	2.56	1.68	0.42	254
Brookston	Pulaski	IN	1.71	2.52	1.83	0.41	260
Brookston	Hendricks	IN	1.65	2.59	1.22	0.39	148
Kokomo	Preble	OH	1.85	2.77	1.88	0.47	324
Kokomo	Clinton	OH	1.47	2.25	1.39	0.34	125

Table 1.12. (cont'd)

Soil	County	State	Shoot Dry Wt†	Root Dry Wt	Shoot K Conc.‡	Root K Conc.	Plant Uptake§
			— grams —		— % —		mg K kg ⁻¹
Glynwood	Allegan	MI	1.84	2.54	1.58	0.34	220
Morley	Genesee	MI	1.59	2.42	0.81	0.30	47
Morley	Washtenaw	MI	2.02	2.59	2.44	0.52	474
Morley	Whitley	MI	1.86	2.75	2.48	0.52	447
Morley	Randolph	MI	1.77	2.59	1.77	0.47	281
Glynwood	Hancock	OH	1.99	2.47	0.81	0.25	69
Glynwood	Seneca	OH	2.00	2.31	1.98	0.41	334
Blount	Allegan	MI	1.96	2.46	2.21	0.46	390
Blount	Clinton	OH	1.71	2.45	1.61	0.39	217
Blount	Monroe	MI	1.74	2.62	1.80	0.43	271
Blount	Whitley	IN	1.64	2.32	1.34	0.35	146
Blount	Randolph	IN	1.60	2.58	1.57	0.49	224
Blount	Hancock	OH	1.72	2.40	1.14	0.32	118
Blount	Seneca	OH	1.75	2.32	1.83	0.37	253
Pewamo	Allegan	MI	1.44	2.32	2.28	0.51	290
Pewamo	Monroe	MI	2.06	2.38	1.75	0.34	286
Pewamo	Whitley	IN	1.60	2.28	1.80	0.42	228
Pewamo	Randolph	IN	1.77	2.31	2.77	0.55	462
Pewamo	Hancock	OH	1.64	2.46	1.61	0.38	203
Pewamo	Seneca	OH	1.84	2.45	2.22	0.41	353
Hoytville	Monroe	MI	1.78	2.33	1.51	0.38	201
Hoytville	Paulding	OH	1.57	2.30	1.97	0.36	236
Paulding	Paulding	OH	1.92	2.20	2.27	0.43	372
Misteguay	Saginaw	MI	1.85	2.64	2.20	0.44	370

†The dry weight of shoot and root tissue listed in the table is the average of the four replications for each soil.

‡The K concentration in shoot and root tissue listed in the table is the average of the four replications for each soil.

§Plant Uptake = [(shoot dry weight * shoot K conc.) + (root dry weight * root Kconc.)] - {K content of seed (15.49 mg K)} x 10 (to convert from 100 mg soil to 1 kg soil).

Table 1.13. Mean values of plant uptake K and the percent of uptake from exchangeable K for all soil groups.

Soil Group	Number of Soils	Plant Uptake		Uptake from Exchangeable K	
		Mean	SE†	Mean	SE
		— mg K kg ⁻¹ —		— % —	
Paulding‡	2	371a*	1	17b	6
Pewamo	6	304a	38	47ab	7
Morley§	7	267a	64	51ab	10
Brookston¶	7	248a	38	57a	8
Blount	7	231a	34	59a	6
Hoytville	2	219a	18	27ab	7
Miami#	7	206a	66	75a	7
Parkhill	2	204a	92	50ab	5
Capac	3	187a	99	44ab	9
Marlette	3	166a	42	44ab	13
Conover††	8	139a	20	51ab	8

*Means followed by the same letter are not significantly different at the 0.05 probability level.

†SE = Standard error of the mean.

‡Paulding includes Paulding and Misteguay soils.

§Morley includes Morley and Glynwood soils.

¶Brookston includes Kokomo soils.

Miami includes Miamian soils.

†† Conover includes Crosby and Celina soils.

Table 1.14. Mean values of plant uptake K and the percent of uptake from exchangeable K for the six soil series common to the tri-state area. Soils are grouped by major soil series.

Soil Group	Number of Soils	Plant Uptake		Uptake from Exchangeable K	
		Mean	SE†	Mean	SE
		— mg K kg ⁻¹ —		— % —	
Pewamo	6	304	38	47	7
Morley‡	7	267	64	51	10
Brookston§	7	248	38	57	8
Blount	7	231	34	59	6
Miami¶	7	206	66	75	7
Conover#	8	139ns	20	51ns	8

ns = Means in the same column are not significantly different at the 0.05 probability level.

†SE = Standard error of the mean.

‡ Morley includes Morley and Glynwood soils.

§ Brookston includes Kokomo soils.

¶ Miami includes Miamian soils.

Conover includes Crosby and Celina soils.

large differences in uptake between the group means, the differences were not statistically significant because of the high degree of variability within the soils of some groups. However, significant differences do exist in the percent of uptake from exchangeable and nonexchangeable K. The Paulding soil group with 17% of uptake from exchangeable K and the Miami soil group with 75% of uptake from exchangeable K were at the low and high end of the range of exchangeable K uptake values. The difference in the percent of uptake from exchangeable K between these two soil groups is what would be expected. Recall that in Table 1.2 the nonexchangeable K values for the Paulding soils were very high while the nonexchangeable K values for the Miami soils were low. The high percentage of uptake from exchangeable K for the Miami soils is a reflection of the fact that there is little K supplied from nonexchangeable forms. Therefore, the exchangeable K values are much more important in predicting the fertility status of these soils. When exchangeable K levels are reduced by cropping, there will be a relatively smaller amount of replenishment from the nonexchangeable forms. As a result, crop yields are likely to decline more rapidly on these soils. Consequently, careful fertility management would be very important on these soils if maximum productivity is to be sustained. This condition is in contrast to the situation found with the Paulding soils. In these soils, the plants obtained 3/4 of their K from the nonexchangeable forms. This demonstrates that these soils have a large reserve of nonexchangeable K that can replenish the exchangeable K. Therefore, the fertility level of these soils is not likely to decline as quickly. Exchangeable K levels, therefore, may not give an accurate picture of the fertility status of these fine textured soils. On the majority of the soils, however, exchangeable K accounted for 40 to 60% of total uptake.

Table 1.14 shows the K uptake data for the six series common to the tri-state area. Although there is more than a two-fold difference in uptake between the Pewamo and Conover soils, the difference is not statistically significant because of the variability within the soil groups. Also, the percent of plant uptake from exchangeable K does not show statistically significant differences when only the six soil groups are considered. Potassium uptake by barley plants on the Pewamo soils averaged 304 mg K kg^{-1} soil with 47% of uptake coming from exchangeable K. On the Conover soils, K uptake averaged 139 mg K kg^{-1} soil with 51% of uptake attributed to exchangeable K. Although the mean percent uptake from exchangeable K was similar for the two groups of soils, the absolute amount of K removal from the Pewamo soils was more than twice the K uptake on the Conover soils.

Table 1.15 compares the average plant uptake and percent of uptake from exchangeable K for the six common soil series when grouped together by state. In Tables 1.16 and 1.17, the plant uptake and percent of uptake from exchangeable K of the individual soil series are compared across states. No statistically significant differences in plant uptake or percent of uptake from exchangeable K were found between states when all soils were considered or if the six soil series were considered individually. These similarities would further suggest that there is a good basis for a regional approach to fertility recommendations.

Data from the soils of the three glacial lobes in Michigan are presented in Table 1.18. Soils from the Saginaw lobe have a lower mean K uptake value than soils in the Michigan and Huron-Erie glacial lobes, but the difference is not statistically significant. Although not statistically significant, the soils in the Saginaw lobe obtained a higher

Table 1.15. Mean values of plant uptake K and the percent of uptake from exchangeable K for the six soil series common to the tri-state area. Soils are grouped by state.

Soil Group	Number of Soils	Plant Uptake		Uptake from Exchangeable K	
		Mean	SE†	Mean	SE
		— mg K kg ⁻¹ —		— % —	
Michigan	17	238	28	52	6
Indiana	12	228	40	63	6
Ohio	13	217ns	37	58ns	5

ns = Means in the same column are not significantly different at the 0.05 probability level.

†SE = Standard error of the mean.

Table 1.16. Plant uptake of the six soil series common to Michigan, Indiana, and Ohio. Individual series are compared across states, not between series.

Soil Group	Number of Soils	Plant Uptake					
		Michigan		Indiana		Ohio	
		Mean	SE†	Mean	SE	Mean	SE
		— mg K kg ⁻¹ —					
Miami‡	7	166	46	179	153	292ns	225
Conover§	8	159	49	90	19	153ns	11
Brookston¶	7	294	60	204	56	225ns	99
Morley#	7	247	124	364	83	202ns	132
Blount	7	293	51	185	39	186ns	67
Pewamo	6	288	2	345	117	278ns	75

ns = Means in the same row are not significantly different at the 0.05 probability level.

SE = Standard error of the mean

‡Miami includes Miamian soils

§Conover includes Crosby and Celina soils

¶Brookston includes Kokomo soils

#Morley includes Glynwood soils

Table 1.17. Exchangeable K uptake of the six soil series common to Michigan, Indiana, and Ohio. Individual series are compared across states, not between series.

Soil Group	Number of Soils	Uptake from Exchangeable K					
		Michigan		Indiana		Ohio	
		Mean	SE†	Mean	SE	Mean	SE
%							
Miami‡	7	78	10	80	3	66ns	25
Conover§	8	39	14	72	2	49ns	11
Brookston¶	7	44	12	68	14	67ns	21
Morley#	7	61	19	35	22	53ns	5
Blount	7	53	8	69	20	60ns	9
Pewamo	6	30	13	53	14	59ns	0

ns = Means in the same row are not significantly different at the 0.05 probability level.

SE = Standard error of the mean

‡Miami includes Miamian soils

§Conover includes Crosby and Celina soils

¶Brookston includes Kokomo soils

#Morley includes Glynwood soils

Table 1.18. Mean values of plant uptake K and the percent of uptake from exchangeable K for the seven soil series common to the three glacial lobes of Michigan.†

Glacial Lobe	Number of Soils	Plant Uptake		Uptake from Exchangeable K	
		Mean	SE‡	Mean	SE
		—— mg K kg ⁻¹ ——		———— % ————	
Michigan	7	251	44	48	9
Huron-Erie	7	222	53	46	10
Saginaw	7	176ns	41	61ns	6

ns = Means in the same column are not significantly different at the 0.05 probability level.

†Soil Series are Marlette, Capac, Miami, Conover, Brookston, Glynwood or Morley, and Blount.

‡SE = Standard error of the mean.

percentage of their uptake from exchangeable K than the soils in the Michigan and Huron-Erie glacial lobes.

Factors Affecting Potassium Uptake

The amount of K in the shoot and root tissue of the barley plants is a direct function of the quantity of K taken up by the roots. Nutrient absorption is a multiple step process. Barber (1962) considered nutrient absorption by roots to occur in three phases: 1) movement of the nutrient from the soil to the root surface; 2) movement of the ion from the exterior of the root to the interior of the root; and 3) translocation of the nutrients from the root to the shoot. Barber (1968) indicated that root interception, mass-flow, and diffusion were the three mechanisms by which plant roots obtain nutrients from the soil. Root interception is a process of ion absorption resulting from direct physical contact and displacement of ions as the root grows through the soil. Mass flow is the movement of ions through the soil solution to the plant root as a result of water uptake by the root. Diffusion occurs when the plant root removes ions from the soil solution more quickly than the stream of water moving toward the root can replenish them. In this case, a concentration gradient is established and ions will then move by diffusion toward the root where the ion concentration is lowest. Barber (1968) indicated that root interception and mass flow may supply 15% or less of the K requirement of plants in humid region soils. Diffusion then is the major mechanism of K supply to the root. Barber (1985) stated that "the proportion of K that is supplied by each mechanism will depend on the surface area and mean radius of the root system, the K absorption characteristics of the root, the rate of water absorption by the root, the rate of K diffusion, and the levels of

adsorbed K and solution K within the soil.” Soil solution K concentrations range from 20 to 1,000 μM with a concentration of 100 μM being representative for humid region soils (Barber et al., 1963). Although saturation extracts were not measured on the soils used in this study, it is probable that the values reported by Barber et al. (1963) cover the range of soil solution K concentrations actually present in these soils.

One of the major reasons for the high uptake values obtainable via the Neubauer technique is the high root density achieved when a large number of plants are grown on a small quantity of soil. Heming and Rowell (1985) reported that the root density of cereal crops in soil typically ranges from 0.9 to 3.5 cm cm^{-3} . They suggested that at a root density of 0.9 cm cm^{-3} about 50% of the exchangeable K may be unavailable to the root. They stated that if the root density was at least 3.5 cm cm^{-3} diffusion alone should not limit plant growth. Root density in the Neubauer studies was greater than 3.5 cm cm^{-3} . The primary factor limiting the supply of K to the root was probably related to the release of K from nonexchangeable or slowly available forms.

Actively feeding roots cause steep K concentration gradients in the rhizosphere. Jungk et al. (1982) reported steep gradients in a radius of approximately 3 mm around the roots of young maize and rape plants. They reported that solution K concentrations were depleted to around 2 μM . Within a few days the amount of K released in the rhizosphere was twice the amount initially exchangeable. Rao and Takkar (1996) reported lower K concentrations in the rhizosphere of corn roots in smectitic soils. Kuchenbuch (1987) reported that nearly all the nonexchangeable K uptake occurs within 2 mm of the root surface while exchangeable K and nonexchangeable K is desorbed and transported further through the soil. Root hairs greatly increase the nutrient absorbing capability of

roots. Drew and Nye (1969) found that root hairs increased the absorption of K by up to 77% over roots grown in solution culture, which lacked root hairs. They also stated that when root demand was high, diffusion appeared to limit K uptake. Because of the high root density and abundance of root hairs present in the soils during the Neubauer studies, it is probable that the rate of K uptake by the barley plants was limited by diffusion. Asher and Ozanne (1967) reported that for 14 plant species grown in solution culture at 1 μM K all species were K deficient. Eight species achieved maximum yield at 24 μM while the other six species achieved maximum yield at 95 μM . If we assume that the K concentration of 2 μM reported by Jungk et al. (1982) in the depleted rhizosphere zone around the young maize and rape roots is representative of the concentration of K in the rhizosphere of the barley plants in the Neubauer studies, and if we assume an initial soil solution K concentration of 100 μM to be representative of the solution K concentrations in these soils (Barber, 1968) then this would represent a 50 fold decrease in K concentration in the rhizosphere of the actively feeding roots. This estimate gives us an approximate idea of the magnitude of the concentration gradient imposed by the roots.

When considering the reliability of extrapolating results from the Neubauer studies to field conditions, it is necessary to consider differences in K uptake between species. Differences in K uptake characteristics are present within species and between species. McGeorge (1946) showed that rye removed more K than barley in Neubauer experiments. Glass et al. (1981) and Glass and Perley (1980) reported differences in K uptake between barley varieties. Cultivars that had high K influx rates at the seedling stage tended to have higher tissue K content at later stages of development and higher K levels in the seed. Schenk and Barber (1980) reported that C_{\min} , the soil solution

concentration below which no net influx occurs, ranged from 2.7 to 7.3 μM for three corn genotypes. Baligar and Barber (1979) found small differences in average net influx values for P and K between corn varieties grown in Indiana and Florida. Barber (1978) reported that net flux of K was lower for soybeans than corn early in the growing season but greater than corn later in the growing season. Peterson and Barber (1981) discovered that root morphology affected K influx in soybean roots. Dunlop et al. (1979) indicated that under conditions of low K concentration in the soil solution ryegrass has a greater K influx rate than white clover. Plant age also affects K uptake. Mengel and Barber (1974) found that nutrient flux in field corn was higher in plants sampled at 20 days than in plants sampled at 70 days.

These reports emphasize the fact that the results obtained with barley may not be strictly comparable to results obtained with other species. However, because all soils were treated the same, the Neubauer experiments can provide an initial reference point for making comparisons between the soils and these experiments have set the stage for further studies in the field with other crops.

In addition to biological factors that may have influenced the results of the Neubauer studies, it is important to consider soil environmental factors that may affect K uptake (Barber, 1995). Soil moisture affects the rate of K uptake. Danielson and Russell (1957) reported a linear relationship between Rb^{86} uptake and soil moisture. Similar results were reported by Place and Barber (1964). Soil aeration is also a factor in ion uptake by roots. If oxygen concentrations fall below 10% in soils, ion uptake will be reduced (Danielson and Russell, 1957). Oxygen levels do not generally approach 10% in soils unless they become saturated. Soil temperature can influence ion uptake by roots.

Ching and Barber (1979) found that K influx in corn roots was doubled when soil temperatures were increased from 15 and 29° C. Soil pH may also affect K availability in soils although it is not of primary importance if pH is maintained above 5 to 5.5 so that soluble and exchangeable Al become negligible (Nemeth and Grimme, 1972). For the soils used in this study, pH values ranged from 5.6 to 7.9. Therefore, it is unlikely that K availability was influenced by soluble aluminum. For experimental results to be reliable and meaningful, it is essential to minimize the potential differences in biological and environmental factors affecting nutrient uptake as much as possible.

Correlations between Plant Uptake and Extractable Potassium

The third objective of this study was to determine whether NH_4OAc or NaBPh_4 would be a better index of plant available K. The release of nonexchangeable K is a diffusion controlled process (Cox and Joern, 1997; Mortland and Ellis, 1959; Reed and Scott, 1962; Martin and Sparks, 1985). The rate of this release will depend on the concentration of K in the soil solution, the quantity of exchangeable K initially present, the rate of K removal by plant uptake and leaching, and the types of minerals present in the soil. Since NaBPh_4 extracts both exchangeable K and nonexchangeable K from the interlayers of the 2:1 clay minerals, it may be a better predictor of plant available K in soils containing large amounts of 2:1 clay minerals. Wentworth and Rossi (1972) reported that K uptake by barley and NaBPh_4 extraction from several clay minerals was in the following order: vermiculite > illite > biotite > phlogopite > muscovite. Schulte and Corey (1965) found that NaBPh_4 gave a better estimate of K uptake by oats and ryegrass during cropping studies in the greenhouse than did NH_4OAc for four Wisconsin soils and one soil from

Iowa. Husin et al. (1986) found that for 30 Louisiana soils there was a higher correlation between NH_4OAc and K uptake by sorghum-sudan grass for the first two harvests in their study, but that NaBPh_4 gave a better correlation for the third and fourth harvests when the exchangeable K had been depleted to a low level. Jackson (1985) reported that NaBPh_4 generally gave higher correlations with dry matter yield, total K uptake, and percent K in ryegrass than did barium acetate, nitric acid, and ammonium nitrate for 13 soils of differing K levels when the soils were cropped to exhaustion.

The relationship between initial NH_4OAc -K and plant uptake for all 54 soils is shown in Figure 1.2. The coefficient of simple determination is $r^2 = 0.730$. Figure 1.3 shows that the change in NH_4OAc -K was not as well correlated with plant uptake, $r^2=0.500$, as was the initial exchangeable K level. Considerably more scatter can be seen in Figure 1.4 which shows the relationship between initial NaBPh_4 -K and plant uptake, $r^2=0.536$, for all soils. This higher variability would suggest that initial NaBPh_4 -K does not give as good a correlation with plant uptake as initial NH_4OAc -K. Interestingly, though, the relationship between the change in NaBPh_4 -K has a better correlation with plant uptake, $r^2=0.722$, than does the change in exchangeable K (Figure 1.5).

When these trends were discovered, it prompted further investigation to see if these same findings would hold true for the two major soil association groups in the tri-state area. The correlations for the Miami, Conover, Brookston soil association group are shown in Figures 1.6 to 1.9. The correlations for the Morley, Blount, Pewamo soil association group are shown in Figures 1.10 to 1.13. The correlation trends found for all soils also holds true for soils of the two major soil association groups. A summary of the coefficients of determination is presented in Table 1.19.

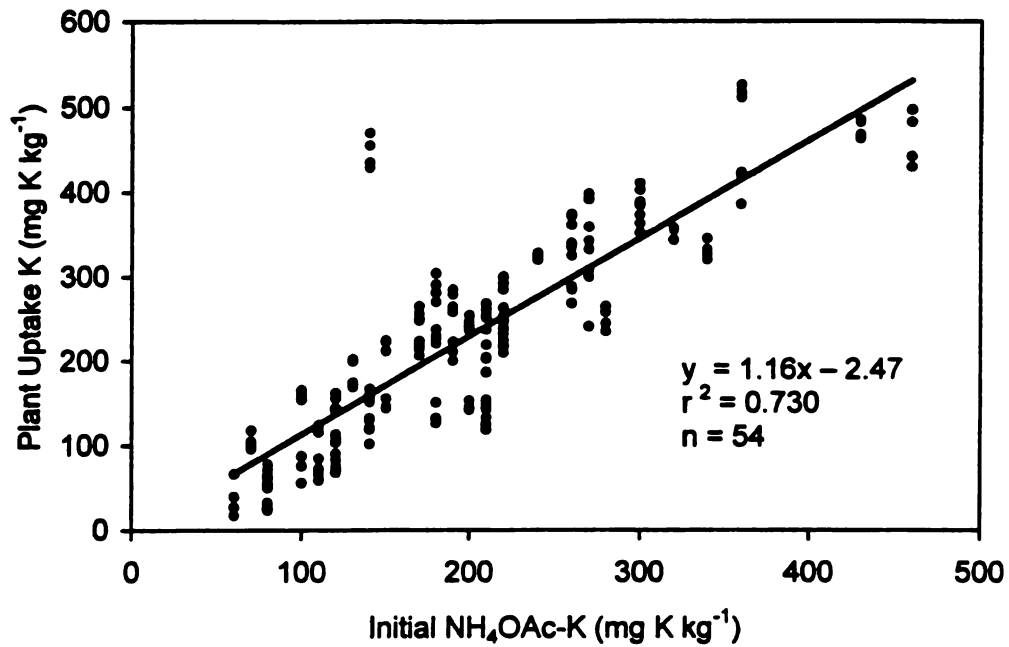


Figure 1.2. Relationship between initial $\text{NH}_4\text{OAc-K}$ and plant uptake K for all soils.

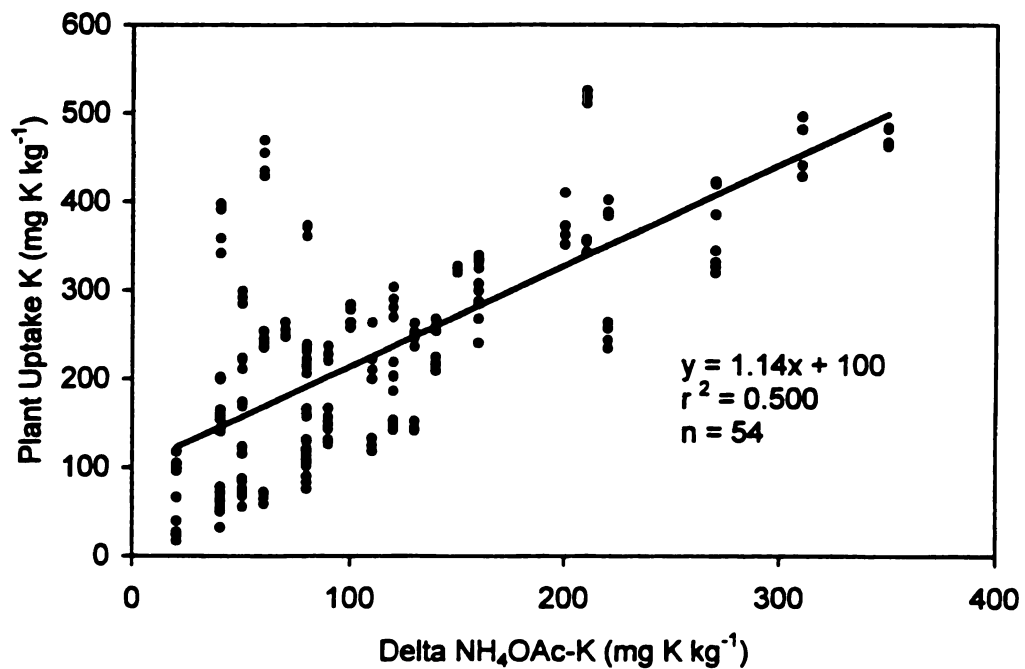


Figure 1.3. Relationship between delta $\text{NH}_4\text{OAc-K}$ and plant uptake K for all soils.

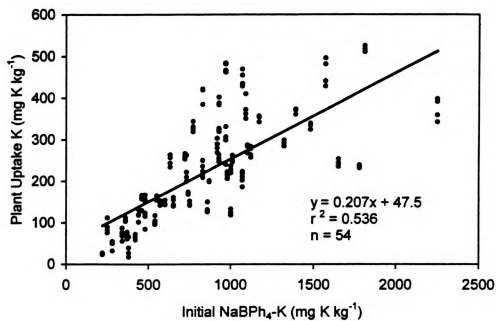


Figure 1.4. Relationship between initial five-minute NaBPh₄-K and plant uptake K for all soils.

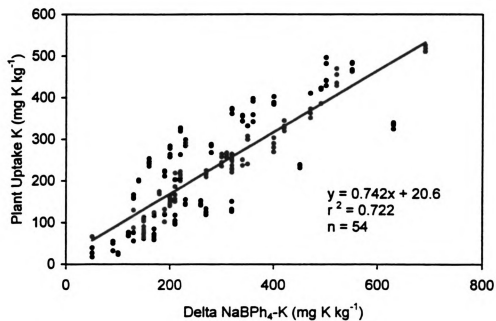


Figure 1.5. Relationship between delta five-minute NaBPh₄-K and plant uptake K for all soils.

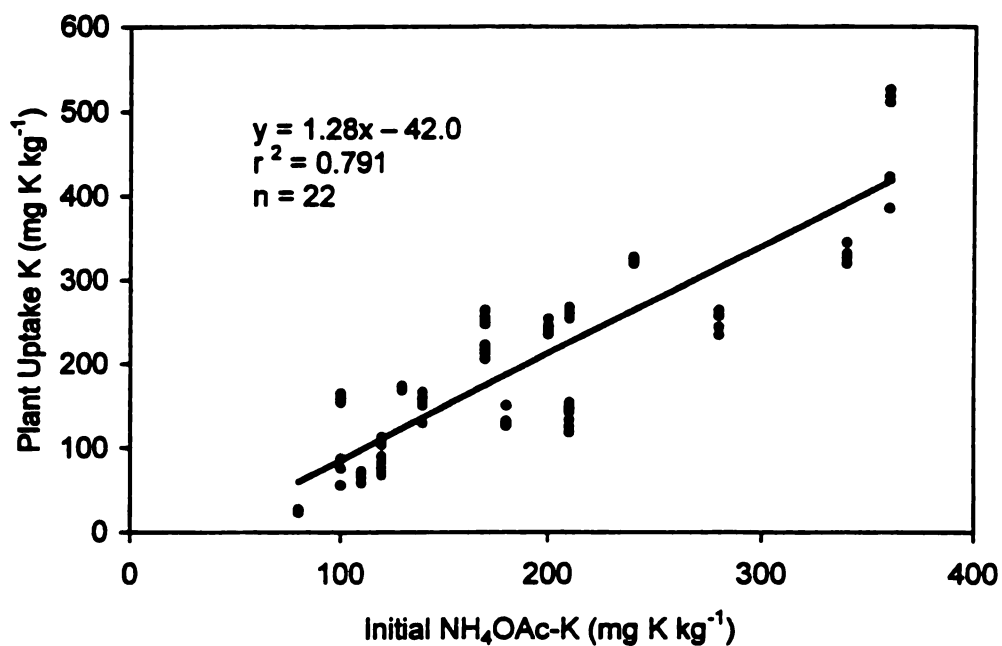


Figure 1.6. Relationship between initial $\text{NH}_4\text{OAc-K}$ and plant uptake K for the Miami, Conover, Brookston soil association group.

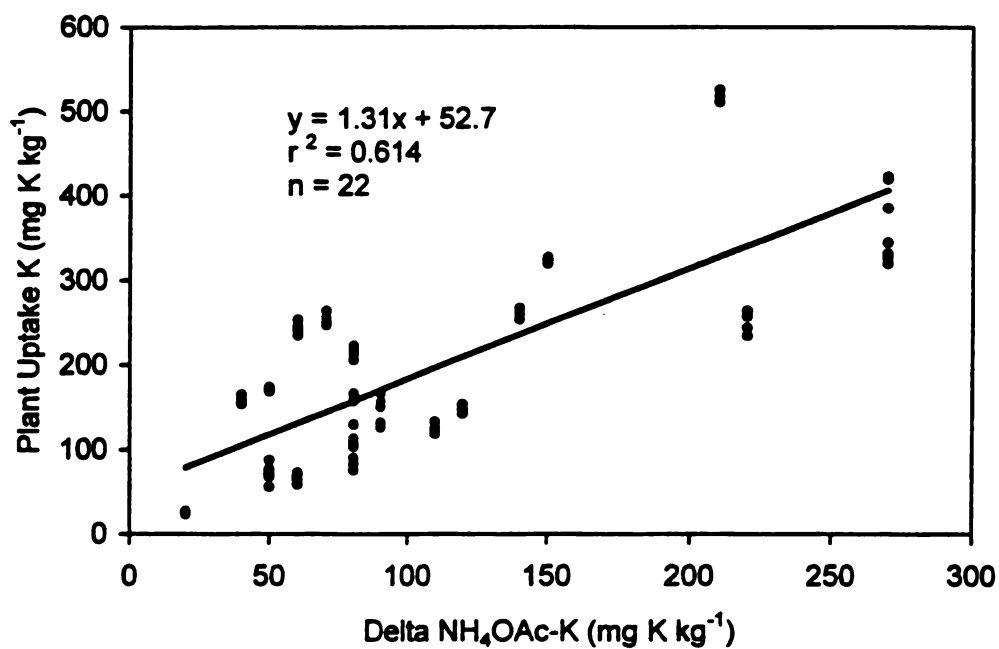


Figure 1.7. Relationship between delta $\text{NH}_4\text{OAc-K}$ and plant uptake K for the Miami, Conover, Brookston soil association group.

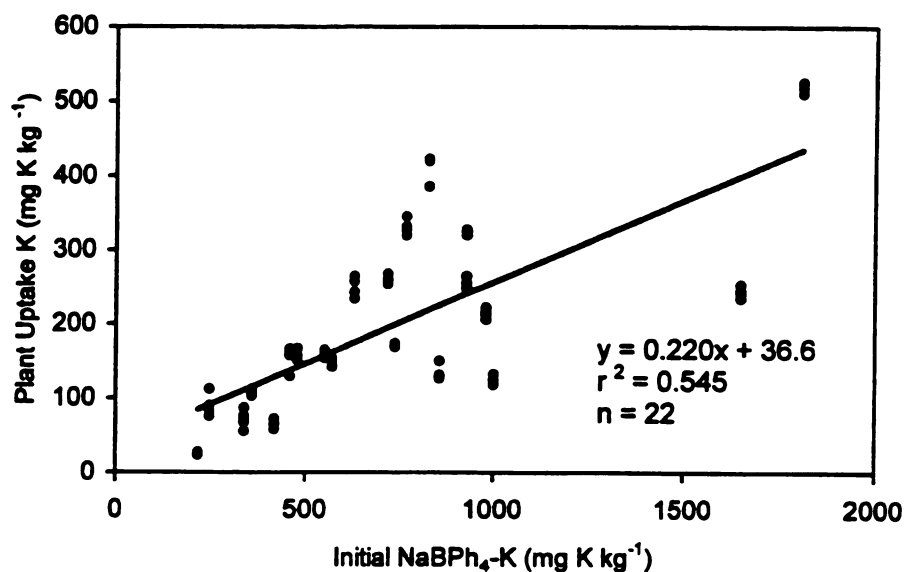


Figure 1.8. Relationship between initial five-minute $\text{NaBPh}_4\text{-K}$ and plant uptake K for the Miami, Conover, Brookston soil association group.

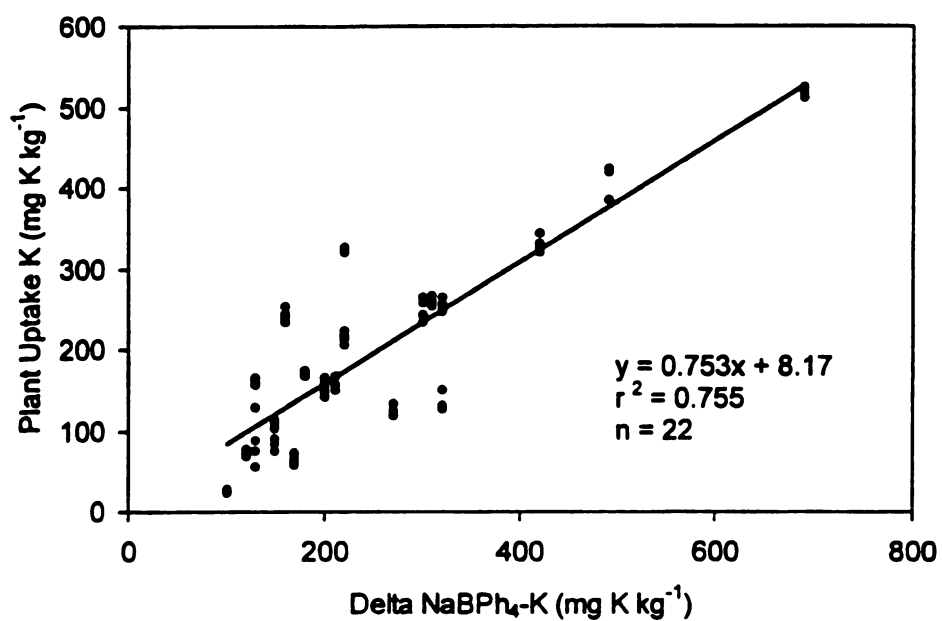


Figure 1.9. Relationship between delta five-minute $\text{NaBPh}_4\text{-K}$ and plant uptake K for the Miami, Conover, Brookston soil association group.

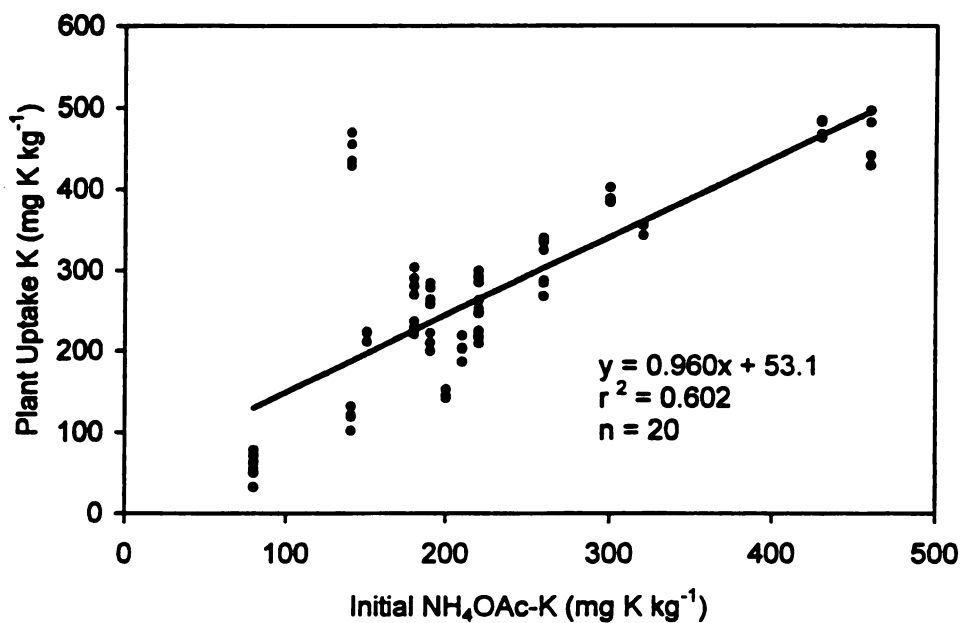


Figure 1.10. Relationship between initial $\text{NH}_4\text{OAc-K}$ and plant uptake K for the Morley, Blount, Pewamo soil association group.

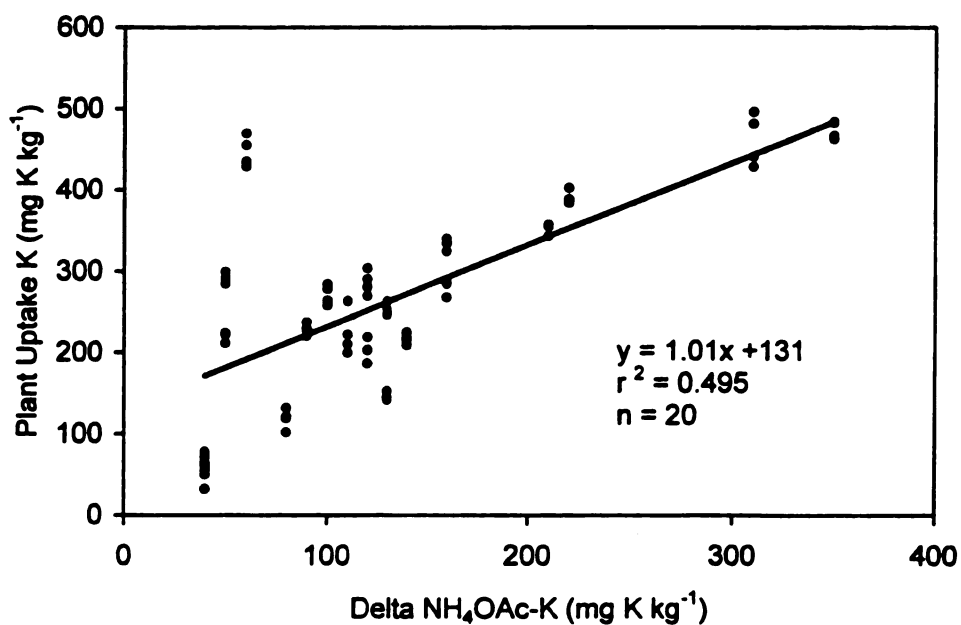


Figure 1.11. Relationship between delta $\text{NH}_4\text{OAc-K}$ and plant uptake K for the Morley, Blount, Pewamo soil association group.

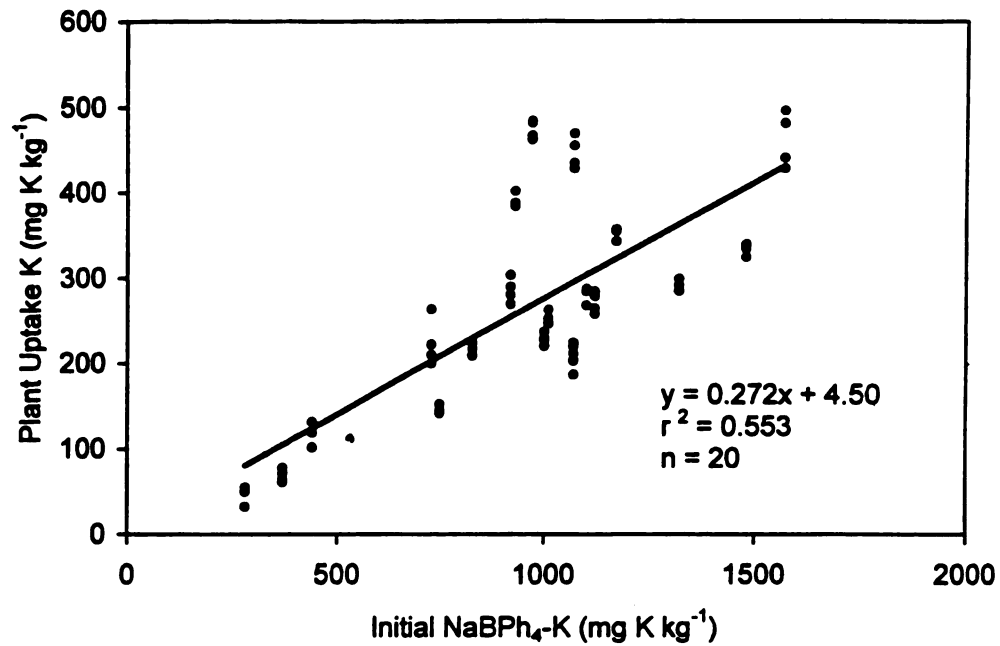


Figure 1.12. Relationship between initial five-minute $\text{NaBPh}_4\text{-K}$ and plant uptake K for the Morley, Blount, Pewamo soil association group.

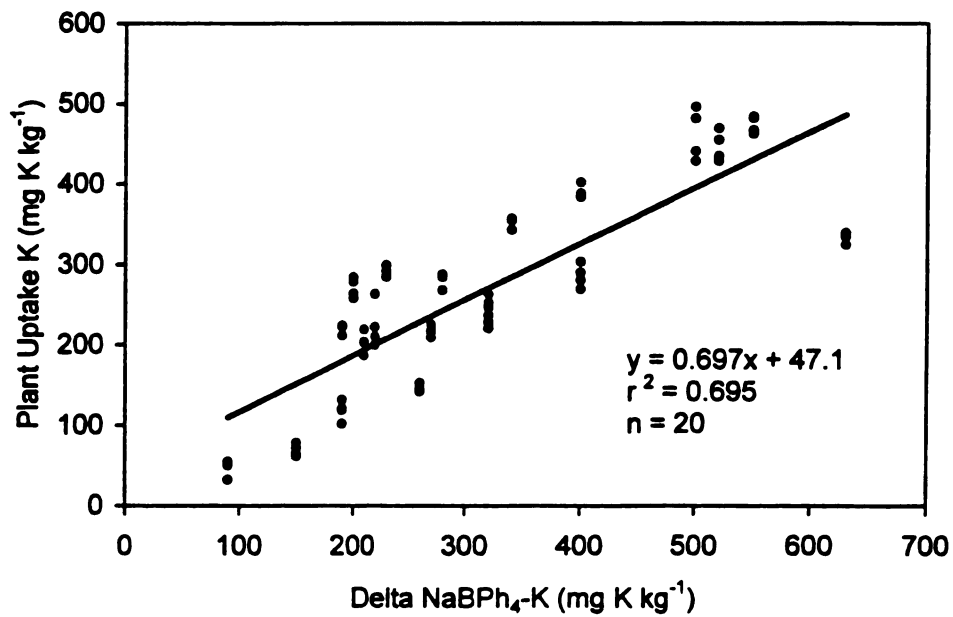


Figure 1.13. Relationship between delta five-minute $\text{NaBPh}_4\text{-K}$ and plant uptake K for the Morley, Blount, Pewamo soil association group.

Table 1.19. Summary of coefficients of determination from regression analysis of $\text{NH}_4\text{OAc-K}$ and $\text{NaBPh}_4\text{-K}$ versus plant uptake K.

	Initial $\text{NH}_4\text{OAc-K}$	Delta $\text{NH}_4\text{OAc-K}$	Initial $\text{NaBPh}_4\text{-K}$	Delta $\text{NaBPh}_4\text{-K}$
	<hr/> r^2 <hr/>			
All soils	0.730***	0.500***	0.536***	0.722***
Miami catena	0.791***	0.614***	0.545***	0.755***
Morley catena	0.602***	0.495***	0.553***	0.695***

*** Significant at the 0.001 probability level.

In all of these comparisons, the initial $\text{NH}_4\text{OAc-K}$ values give a higher correlation than the initial $\text{NaBPh}_4\text{-K}$ values, but the delta $\text{NH}_4\text{OAc-K}$ values are lower than the delta $\text{NaBPh}_4\text{-K}$ values. These findings are in contrast to the results reported by other investigators (Schulte and Corey, 1985; Jackson, 1985), but a thoughtful consideration of the problem and an investigation of reports from the 1950's may provide an explanation for the results.

Conflicting reports on the suitability of exchangeable K as a predictive measure of K availability appeared in several papers from the late 1940's to the early 1960's. A series of field and greenhouse studies conducted in the mid to late 1950's with alfalfa (Hanway et al., 1961), millet (Barber et al., 1961) and corn (Hanway et al., 1962) in the North Central Region generally found exchangeable K, measured with field moist samples, was a suitable index of plant available K. Breland et al. (1950) in a study of 23 Indiana soils did not find a significant relationship between the initial level of exchangeable K and K uptake by ladino clover during a greenhouse cropping experiment. Pratt (1951), however, stated that exchangeable K was the single best measure of K availability for Iowa soils compared to K extractable with boiling 1M HNO_3 and Dowex

50 exchange resin. Schmitz and Pratt (1953) reported that in 18 soils from Ohio, 1M HNO_3 was a better index than exchangeable K in predicting crop response to fertilization. Rouse and Bertramson (1949) with the same 23 Indiana soils studied by Breland et al. (1950) reported that exchangeable K was not related to the quantity of nonexchangeable K released to HNO_3 - a term they called the "potassium supplying power" of the soil. In 1954, Pratt and Morse published the results of a study on 46 soil series from Ohio in which they reported that the correlation between exchangeable K and K release ($\text{HNO}_3\text{-K} - \text{NH}_4\text{OAc-K}$) was not high. They found the K release value to be more characteristic of soil type and soil area than exchangeable K. In this study, they grouped the soils of Ohio according to the major soil regions in the state. The soils were ranked according to their ability to release nonexchangeable K in the following order from least to greatest: 1) sandy soils of the lakebed; 2) soils on Illinoian till; 3) soils formed in low-lime Wisconsin till; 4) soils formed in high-lime Wisconsin till; 5) fine textured soils of the lakebed. In 1958, McLean and Simon reported the results of their study on K release and fixation in 13 representative soils from Ohio. They reported a highly significant correlation between exchangeable K and the response of alfalfa to applied K

The best explanation for these conflicting results perhaps can be found in the paper by Schmitz and Pratt (1953). They speculated that the reliability of exchangeable K as an index to K uptake by plants would vary with the release rates of K from nonexchangeable forms. They considered this release to occur at three rates. At the lowest rate, the release rate of K from nonexchangeable forms was considered to be too small to be of importance in supplying K to plants. At the highest rate, the K release rate was assumed to be high enough to maintain high levels of exchangeable K that would be

highly correlated with the rate of K release from nonexchangeable forms. At an intermediate release rate, the rate of release would not be fast enough to maintain high levels of exchangeable K but yet would be important in supplying K to the plants. At intermediate release rates, it was assumed that there would be a low correlation between levels of exchangeable K and rates of K release from nonexchangeable forms. Mitosis and Rowell (1987) reported that the critical K concentration in soil solution ranged from 33 to 85 μM before release of nonexchangeable K occurred.

Tabatabai and Hanway (1969) found that in Iowa soils plant uptake was highly correlated with the minimum level of exchangeable K. This would correspond to the low release rate suggested by Schmitz and Pratt (1953). Richards et al. (1988) reported large differences in nonexchangeable K uptake from soils that had similar exchangeable K levels. This situation would suggest intermediate rates of nonexchangeable K release. The results of Rao and Khera (1994) would support the idea of high release rates. They found higher minimal K levels in soils initially high in K. They reported a high correlation between K replenishment rate and minimum exchangeable K level. Replenishment rates varied from 0.25 to 0.67 mg K kg^{-1} soil after reaching minimum K levels. Soils with higher illite content had a higher replenishment rate.

Since the late 1950's, exchangeable K has been considered to be a satisfactory index for predicting plant availability of K. This can perhaps be explained by considering the fact that during the 1940's and 1950's crop yields were much lower than yields attainable today. As a result, these soils were not fertilized as heavily 40 to 50 years ago. If the exchangeable K levels were generally less than present levels, then the majority of these soils probably had intermediate rates of K replenishment and would not

have given consistently good correlations between exchangeable K and K uptake. As agronomic practices changed, fertility levels increased and these soils gradually shifted from intermediate to high rates of K release and are now capable of maintaining a higher rate of K release from nonexchangeable forms. The result of this interaction has been a higher correlation between exchangeable K and K uptake. The higher correlations with initial $\text{NH}_4\text{OAc-K}$ and $\Delta \text{NaBPh}_4\text{-K}$ over $\Delta \text{NH}_4\text{OAc-K}$ and initial $\text{NaBPh}_4\text{-K}$ can possibly be explained by the fact that the change in exchangeable K does not provide a good index of K release from nonexchangeable forms while the change in $\text{NaBPh}_4\text{-K}$ more accurately reflects the increased utilization of nonexchangeable K.

CONCLUSIONS

The results of these investigations revealed large differences in CEC, total K, and nonexchangeable K release between soil series. The differences between major soil series were consistent regardless of geographic location. The fact that the major soil series in the three states exhibit similar K chemistry is evidence that a regional approach to fertilizer recommendations in the tri-state area is merited. The results of this study also suggest that K recommendations should be made based on major soil association groups within the three states.

Even though NH_4OAc proved to be a more reliable index of plant available K, more work needs to be done with NaBPh_4 . The ability of this reagent to measure plant available K might be improved if a lower concentration of NaBPh_4 was used in the extracting solution or if samples were extracted for a shorter time. Long-term field experiments also need to be established on the major soil series at different sites

throughout Michigan, Indiana, and Ohio to more thoroughly evaluate the nature of K release from these soils and K uptake under different cropping systems.

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CHAPTER 2

THE RELATIVE IMPORTANCE OF CLAY CONTENT, CLAY MINERALOGY, AND CATION EXCHANGE CAPACITY TO THE POTASSIUM CHEMISTRY OF SOILS IN MICHIGAN, INDIANA, AND OHIO

ABSTRACT

Clay content and clay composition are important factors controlling potassium (K) availability in soils. The purpose of this study was to determine the relationship between clay content, clay mineralogy, and soil cation exchange capacity (CEC) and their relative importance with regard to the K chemistry of the whole soil. Clay contents were determined by the hydrometer and pipet methods. Four soils having a wide range in total K content were selected for clay mineralogical analysis by x-ray diffraction. Clay contents were highly correlated by the hydrometer and pipet methods, $r^2 = 0.993$. Plant uptake, ammonium acetate (NH_4OAc), and sodium tetraphenylboron (NaBPh_4) extractable K levels were better correlated with clay content than with soil CEC. Soil CEC was more highly correlated with clay content, $r^2 = 0.767$, than organic matter, $r^2 = 0.469$, but was more sensitive to changes in organic matter than to differences in clay content. Soils with high clay content tended to have larger amounts of total K than soils with low clay content. The coarse clay ($2-0.2\mu\text{m}$) and fine clay ($<0.2\mu\text{m}$) fractions were dominated by 2:1 clays. Illite contents ranged from 10 to 40% in the coarse clay and from 5 to 30% in the fine clay. These results suggest that K recommendations utilizing a

K sufficiency level based on soil clay content and dominate clay mineralogy may be more useful in predicting crop response to applied K than a sufficiency index based on soil CEC.

INTRODUCTION

The fundamental importance of soil mineralogy and its implications for soil management can hardly be over emphasized. Mineralogy profoundly affects many physical and chemical soil properties, including: cation and anion exchange reactions, soil structure, formation, and stability, water retention and movement, and suitability for construction and building purposes (Brady and Weil, p. 241, 1996). Knowledge of clay mineralogy is especially important in fertility management because the native fertility of soils is determined by the mineralogy of the soil parent material.

Clays are the sites of countless physical and chemical reactions in soils. The relative abundance and types of clay minerals and their rates of weathering influence the availability of essential mineral nutrients to plants (Bertsch and Thomas, 1985). The soil is a dynamic system in which minerals undergo continuous transformations through pedogenic, biological, and chemical weathering. These weathering reactions are of great importance for the release of nutrients to plants, particularly the reactions that result in K release from soil minerals

Studies by Mortland et al. (1957) and Lui et al. (1997) have demonstrated the ability of plants to convert biotite or intergrade vermiculite:illite into vermiculite. Other researchers have reported conversion of illite to smectite or interstratified illite:smectite under intensive cropping conditions (Moberg and Nielson, 1983; Nielson and Moberg,

1984; Tributh et al. 1987). Moberg and Nielson (1983) found that the total K content of Danish soils was reduced four to seven percent by intensive cropping. The illite content of the soils was decreased and the smectite content was increased. They found that the magnitude of change occurring in potted soil after five years was equal in magnitude to mineralogical changes occurring in the field after 60 years. Hydroxy-interlayered vermiculite may also form as a result of biological weathering of trioctahedral mica. Hinsinger et al. (1993) attributed this phenomenon to H^+ excretion by plant roots which causes dissolution of the crystal lattice of phlogopite and release and precipitation of octahedral aluminum in the interlayer space of the mineral. The transformation of mica to vermiculite may be reversed if large amounts of K are added to the soil. Ross et al. (1985) observed conversion of vermiculite to mica after six years of heavy applications of liquid dairy manure. This transformation was attributed to fixation of K and NH_4^+ by the soil clays.

Clay minerals are also susceptible to weathering with chemical reagents. Alteration of mineral structure often occurs with $NaBPh_4$ and HNO_3 which have been used for extraction of nonexchangeable K. Sodium tetraphenylboron weathers mica by removing K from the interlayers of the clay. This results in an expansion of the 10Å spacing of illite (Cox and Joern, 1997, Gil-Sotres and Rubio, 1992). Nitric acid is a more drastic treatment, dissolving vermiculite and clay sized chlorite (Conyers et al., 1969; Al-Kanani et al., 1984).

Knowledge of the mineralogy of soil clays is important to better understanding the processes of K fixation and release in soils. The objectives of this study were: 1) to determine the correlation between the hydrometer and pipet methods of particle size

analysis for determination of clay content; 2) to compare the clay content of common soil series in the tri-state area; 3) to determine the relationship between clay content and CEC to plant uptake and NH_4OAc and NaBPh_4 extractable K levels; 4) to determine the variability in clay mineralogy of soils of widely differing total K content; and 5) to determine the nature of the relationship between the clay content and mineralogy of these soils to the K chemistry of the whole soil. These data should help to further improve K recommendations in the tri-state area.

MATERIALS AND METHODS

Particle Size Analysis

Particle size analysis was determined by both the pipet and hydrometer methods. The particle size distribution for all soils is listed in appendix B. Eleven soils, listed in Table 2.1, were selected for detailed particle size characterization. These soils were sent to the Soil Characterization Laboratory at the Ohio State University for complete characterization of the sand, silt, and clay fractions by sieving and the pipet method.

Particle size analysis was also determined for all 54 soils by a modified Bouyous hydrometer method using an ASTM 152 H-type hydrometer. A procedure slightly modified from that of Gee and Bauder (1986) was used. A 40 gram sample of each soil, dried at 35° C, was placed into a 1 L beaker. Approximately 100 mL of deionized water was added to the samples. Ten mL of hydrogen peroxide (H_2O_2) were then added to initiate oxidation of organic matter. After approximately 10 minutes, when the most vigorous reaction had subsided, samples were placed on a hot plate at 70° C. More H_2O_2 was added in 10 mL increments until the strong frothing from oxidation of organic matter

had subsided to a moderate bubbling due to the thermal decomposition of H_2O_2 . After decomposition of H_2O_2 , beakers were removed from the hot plate and allowed to cool. After cooling, samples were quantitatively washed into 500 mL plastic bottles. One hundred mL of 5% sodium hexametaphosphate (SHMP) solution were added to the samples. The bottles were filled 2/3 full with deionized water and shaken overnight on a reciprocating shaker at 200 oscillations per minute. After shaking, samples were quantitatively washed into clean 1 L sedimentation cylinders and brought to volume with deionized water. A cylinder containing 100 mL SHMP solution and 900 mL deionized water was used as a blank to correct the hydrometer readings for the background concentration of SHMP in the soil suspension. Samples were allowed to equilibrate at room temperature. Before sedimentation, samples were thoroughly mixed with a metal plunger for one minute. Timing was initiated after removal of the plunger from the soil suspension. Readings for clay were taken after 24 hours of settling. After the clay readings were taken, samples were washed through a 270 ($<53\mu\text{m}$) mesh sieve to collect the sand. Sands were washed free of adhering silt and clay, then dried at 105°C , sieved, and subsequently weighed to determine the percent sand in the samples. A 10 gram sample of soil was also oven dried at 105°C to determine the oven dry weight of the soil. Percent sand was calculated by dividing the weight of the sand by the weight of oven dry soil. Percent clay was determined by subtracting the blank hydrometer reading from the clay suspension hydrometer reading of each soil and dividing the corrected reading by the mass of oven dry soil. The percent silt was calculated by difference as:

$$\% \text{Silt} = 100 - (\% \text{Sand} + \% \text{Clay}) \quad [1]$$

Mineralogical Analysis

Four soils (Table 2.5) were selected for semi-quantitative mineralogical analysis based on their range of total K contents. Thirty to 50 grams of each soil were weighed into each of four 250 mL centrifuge bottles. One hundred mL of 1 M NaOAc, pH = 5, were added to the samples to remove carbonates and soluble salts (Kunze and Dixon, 1986). Centrifuge bottles were placed in a water bath at 70° C to speed the reaction. Additional NaOAc was added, as necessary, until reaction was complete. Samples were cooled, centrifuged for 5 minutes at 2000 rpm and the supernatant discarded. Deionized water was added and samples again heated in a water bath. Hydrogen peroxide was added to the samples to oxidize organic matter. After oxidation was complete, samples were cooled and centrifuged at 2000 rpm for 5 minutes and the supernatant discarded. Deionized water was added and samples were shaken to disperse the soil suspension. Soil clays were separated into fine (<0.2 μ m) and coarse (0.2-2 μ m) fractions by swinging bucket centrifugation following methods described in Jackson (1975). After fractionation, portions of the clay separates were saturated with either MgCl₂ or KCl in preparation for x-ray diffraction (XRD) analysis. Clays were washed free of excess salts by sequential washing with deionized water and 95% ethyl alcohol. The supernatant was discarded. Absence of a cloudy precipitate upon addition of silver nitrate to the supernatant was used to determine removal of chlorides. After evaporation of ethanol, the clay paste was prepared for XRD analysis.

The clay paste was oriented on a glass slide with a semi-microspatula (Thiesen and Harward, 1962). When dry, the Mg-saturated clays were placed in a vented dessicator with a dish of ethylene glycol in the bottom. The dessicator was placed in an

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oven at 65° C for 4 hours to solvate the clays. After removal from the oven, the dessicator was evacuated with a vacuum pump and the vent closed until the clays were scanned. The K-saturated clays were scanned after being heated to 300° C for 5 hours in a muffle furnace. The K-saturated clays were then heated for an additional 5 hours in a muffle furnace at 550° C and scanned a second time. All x-ray analyses were performed with a Rigaku RTP 300 automated x-ray diffractometer system using CuK α radiation at 45 Kv and 100 mA, 1/2° divergence slit, 1/2° scatter slit, and a 0.03 mm receiving slit. Samples were scanned at a rate of 2° 2 θ min⁻¹ from 2 to 32° 2 θ at a step interval of 0.05° 2 θ .

Clay minerals were identified by their first-order (001) peaks in the clay samples. Expandable minerals were identified by the presence of a > 14Å peak in the Mg-EG solvated clay. Illite was identified by a 10Å peak in the Mg-EG sample. The 14Å peak in Mg-EG was a combination of chlorite and vermiculite. Presence of a 14Å peak in K-300 was attributed to chlorite. Vermiculite was calculated by the difference in peak area of the 14Å peak in Mg-EG and K-300. In K-300, the 7Å peak was attributed to the second-order (002) peak of chlorite and the first-order (001) peak of kaolinite. The disappearance of the 7Å peak in K-550 was attributed to kaolinite. Kaolinite was calculated by the difference in peak area of the 7Å peak in K-300 and the K-550 treatment. Quartz was identified by the presence of a 4.26Å peak in all treatments. Peak areas were calculated from the x-ray diffractograms. The x-ray diffractograms were photocopied onto plain white paper. The baseline was drawn and peaks were labeled and cut out with scissors. The peaks were weighed on an analytical balance. The individual weights were summed to calculate a total peak area. Individual peak weights (areas)

were divided by the total weight to obtain the relative percentage of each mineral. The mineral contents were estimated to the nearest five percent.

RESULTS AND DISCUSSION

Particle Size Analysis

Particle size analysis data, as determined by the hydrometer and pipet methods, for 11 soils in the tri-state region is presented in Table 2.1. The soils ranged from 9.1 to 61.1% clay (pipet method). This range in clay content would be representative of all but the most coarsely textured soils in the tri-state area. The agreement between the two methods is quite good. With the exception of the Paulding clay soil, the difference in clay content between the two methods is generally less than two percent. The correlation (Figure 2.1) between the two methods is very high, $r^2 = 0.993$, and the slope is almost unity. The regression equation gives confidence that the clay contents of all soils, as determined by the hydrometer method, are both precise and accurate. These data show that either method may be used for routine particle size determination with highly satisfactory results.

The average clay content of the six soil series common to the tri-state area is presented in Table 2.2. There are no statistically significant differences in clay content between any of the soil groups. However, the greatest differences occur between the Miami soils, 16.3% average clay content, and the Pewamo soils, 27.4% average clay content. The difference in clay content between these soils probably accounts for the differences in K chemistry that were discussed in Chapter 1. It is worthwhile to mention that the A horizon of the poorly drained Brookston and Pewamo soils have the highest

Table 2.1. Particle size distribution of selected soils as determined by the hydrometer and pipet methods of particle size analysis.

Soil	County	State	Hydrometer			Pipet		
			Sand†	Silt	Clay	Sand	Silt	Clay
			———— % ————			———— % ————		
Blount	Monroe	MI	36.5	41.2	22.3	38.6	38.2	23.2
Conover	Genesee	MI	41.9	45.0	13.1	41.6	43.9	14.5
Marlette	Allegan	MI	37.8	43.4	18.8	36.5	43.0	20.5
Miami	Ottawa	MI	54.8	36.1	9.1	55.5	35.3	9.2
Miamian	Preble	OH	26.1	40.3	33.6	25.7	40.6	33.7
Morley	Randolph	IN	19.5	51.6	28.9	19.8	50.2	30.0
Morley	Whitley	IN	27.9	50.8	21.3	26.2	52.6	21.2
Morley	Genesee	MI	53.0	35.4	11.6	55.3	33.4	11.3
Morley	Washtenaw	MI	40.6	46.8	12.6	40.8	44.4	14.8
Paulding	Paulding	OH	4.9	37.9	57.2	5.2	33.7	61.1
Pewamo	Allegan	MI	3.0	58.5	38.5	2.5	59.9	37.6

†The percent sand was determined by sieving in both the hydrometer and pipet methods.

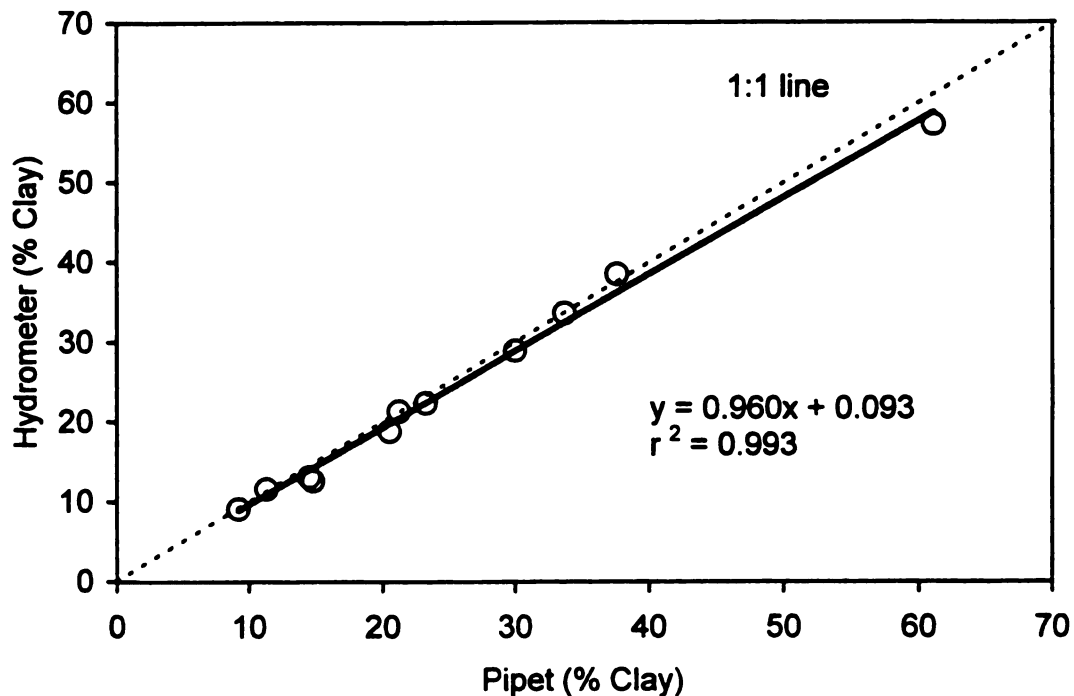


Figure 2.1. Relationship between the hydrometer and pipet methods of particle size analysis for determination of clay content in 11 soils from the tri-state area.

Table 2.2. Mean clay content of the six soil series common to Michigan, Indiana, and Ohio.

Soil Group	Number of soils	Clay Content	
		Mean	SE†
		%	
Miami‡	7	16.3	3.1
Conover§	8	20.1	3.0
Morley¶	7	20.4	3.2
Blount	7	20.8	1.4
Brookston#	7	22.7	2.4
Pewamo	6	27.4ns	3.4

ns = Means in the same column are not significantly different at the 0.05 probability level.

†SE = Standard error of the mean.

‡Miami includes Miamian soils.

§Conover includes Crosby and Celina soils.

¶Morley includes Glynwood soils.

#Brookston includes Kokomo soils.

Table 2.3. Clay content of the six soil series common to Michigan, Indiana, and Ohio. Individual series are compared across states, not between series.

Soil Group	Number of soils	Clay Content					
		Michigan		Indiana		Ohio	
		Mean	SE†	Mean	SE	Mean	SE
		%					
Miami‡	7	11.0	0.9	15.7	2.5	24.7ns	9.0
Conover§	8	22.5	8.0	14.7	1.5	21.3ns	2.5
Brookston¶	7	19.9	0.9	19.1	2.8	30.5ns	4.5
Morley #	7	18.2	5.2	25.6	4.4	18.7ns	8.7
Blount	7	20.6	2.0	21.6	0.2	20.3ns	5.1
Pewamo	6	26.6	11.0	32.2	3.7	23.4ns	2.1

ns = Means in the same row are not significantly different at the 0.05 probability level.

†SE = Standard error of the mean.

‡Miami includes Miamian soils.

§Conover includes Crosby and Celina soils.

¶Brookston includes Kokomo soils.

#Morley includes Glynwood soils.

clay content. This is as expected because these soils are saturated for longer periods and are less leached. Thus, less eluviation of clay from the upper portion of the soil profile has occurred.

In Table 2.3, the clay contents of the six common soil series are compared across states. The clay contents of the individual soil series are not significantly different between Michigan, Indiana, or Ohio. The largest difference in clay content is seen in the Miami and Brookston soils. In both cases, the soils from Ohio have higher clay content.

Correlations between Clay Content, CEC, and Extractable Potassium Levels

An important objective of this study was to determine whether clay content or soil CEC is better correlated with plant uptake and extractable K levels of the whole soil. This information would help determine if K recommendations should be based in some way on clay content or CEC of the soils. The correlation between clay content and plant uptake, $r^2 = 0.216$ ($P < 0.001$), is shown in Figure 2.2. Although the correlation between clay content and plant uptake is low, it is better than the correlation between CEC and plant uptake, $r^2 = 0.129$ ($P < 0.01$), Figure 2.3. Initial exchangeable K levels were not well correlated, $r^2 = 0.163$, with clay content (Figure 2.4) although the relationship was highly significant ($P < 0.01$). The correlation between initial NaBPh₄-K levels and clay content, $r^2 = 0.764$, (Figure 2.5) was much better and was very highly significant ($P < 0.001$). This indicates that the K extractable by NaBPh₄ more closely reflects the quantity of K released from the soil clay than NH₄OAc.

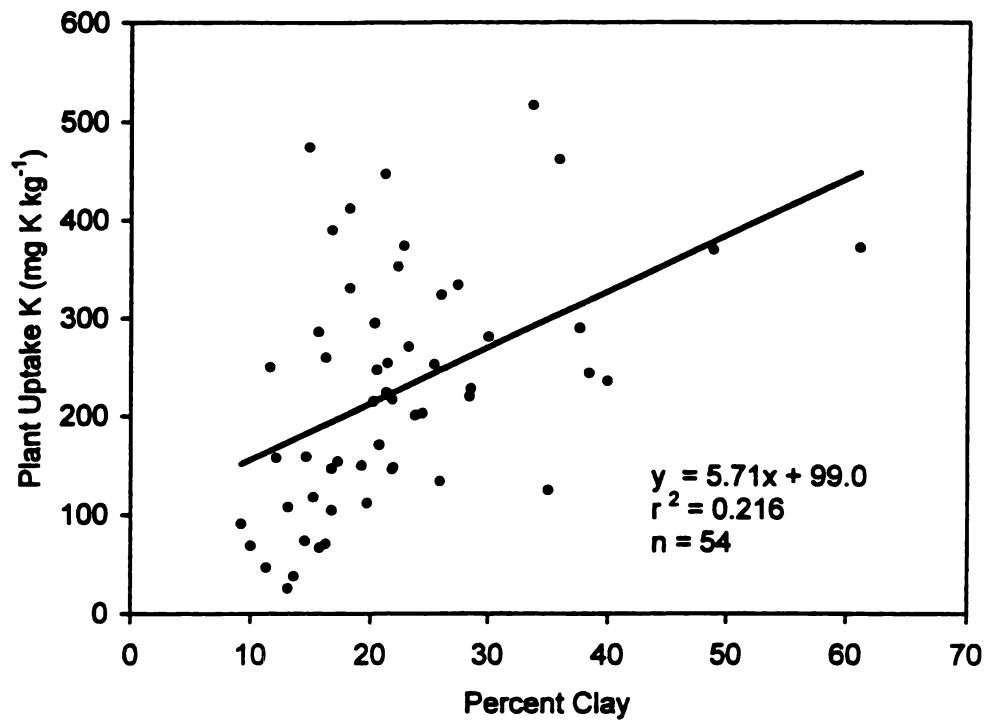


Figure 2.2. Relationship between the percent clay and plant uptake K for all soils.

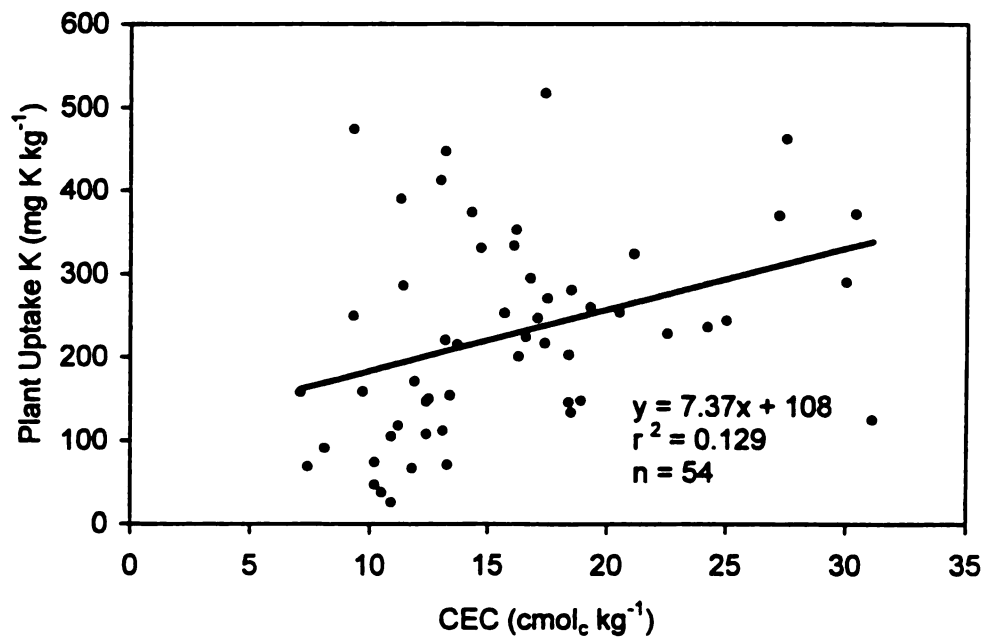


Figure 2.3. Relationship between CEC and plant uptake K for all soils.

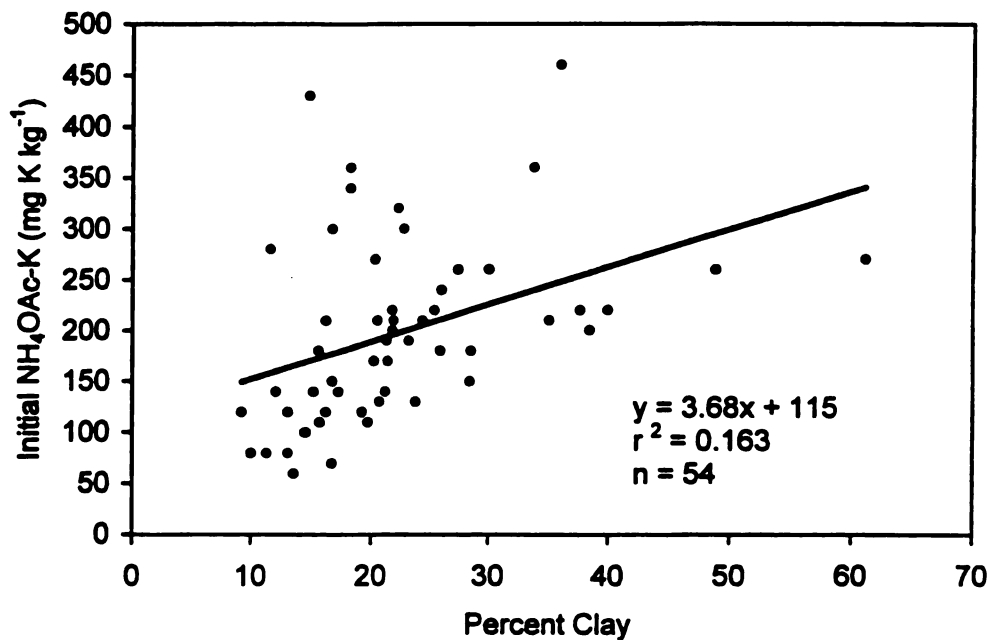


Figure 2.4. Relationship between the percent clay and initial $\text{NH}_4\text{OAc-K}$ for all soils.

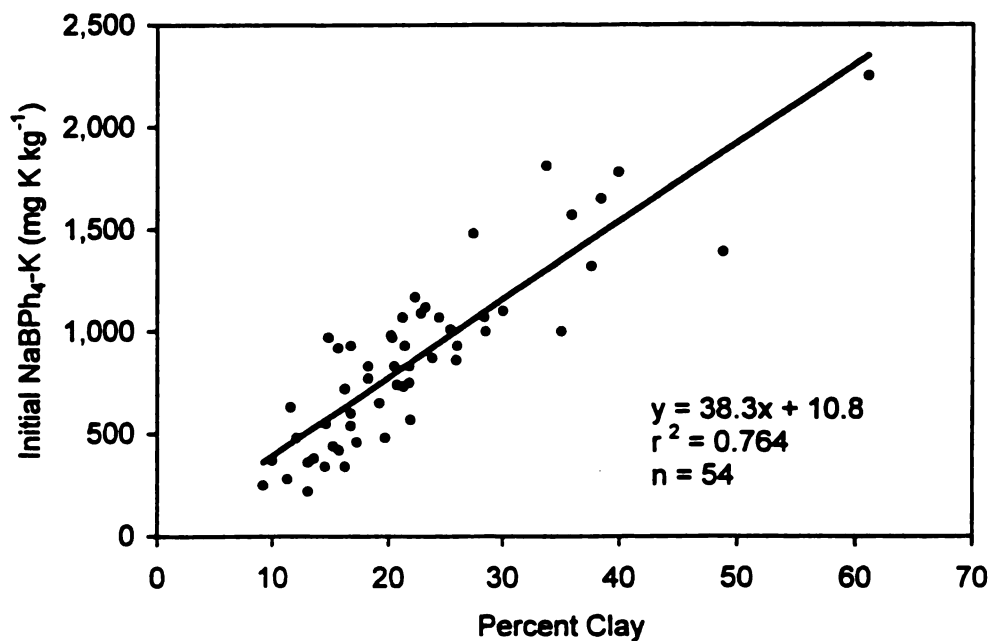


Figure 2.5. Relationship between the percent clay and initial five-minute $\text{NaBPh}_4\text{-K}$ for all soils.

Exchangeable K levels after cropping were more highly correlated with clay content, $r^2 = 0.887$, (Figure 2.6) than NaBPh_4 -K levels after cropping, $r^2 = 0.848$, (Figure 2.7). The dramatic improvement in the coefficient of determination for the NH_4OAc -K levels after cropping suggests that the majority of these soils had been cropped to levels at or near the minimum exchangeable K level. After the most easily accessible K had been removed, probably the K added as fertilizer K, the replenishment of exchangeable K became directly dependent upon K release from nonexchangeable forms. Sharpley and Buol (1987) found minimum exchangeable K levels to be closely related to soil clay content. The correlation was improved when the soils were grouped by dominant mineralogy -- kaolinitic, mixed, or smectitic.

Figure 2.8 shows that soils with high clay content tended to have higher total K contents than soils with low clay content. The regression equation implies that much of the total K in these soils is in the silt and sand fractions. This portion of total K represents a large reservoir of nonexchangeable K that would become slowly available for plant uptake. The clay fraction, however, contains the more labile K which is very important for supplying the K requirements of rapidly growing crops during a single growing season.

The correlation between clay content and CEC, $r^2 = 0.767$ is shown in Figure 2.9. There is a higher correlation between clay content and CEC than between organic matter and CEC, $r^2 = 0.469$, (Figure 2.10). When both the organic matter and clay content are combined in a multiple regression equation, the correlation improves slightly, $R^2 = 0.859$. The multiple regression equation takes the following form:

$$\text{CEC} = -1.24 + 0.43\text{clay} + 2.14\text{OM} \quad [2]$$

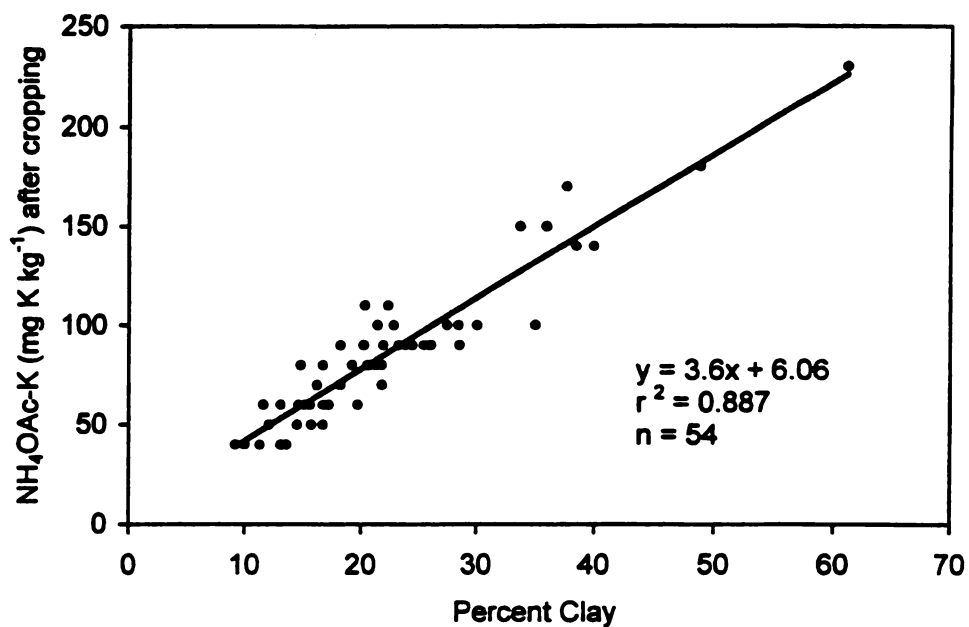


Figure 2.6. Relationship between the percent clay and $\text{NH}_4\text{OAc-K}$ after cropping for all soils.

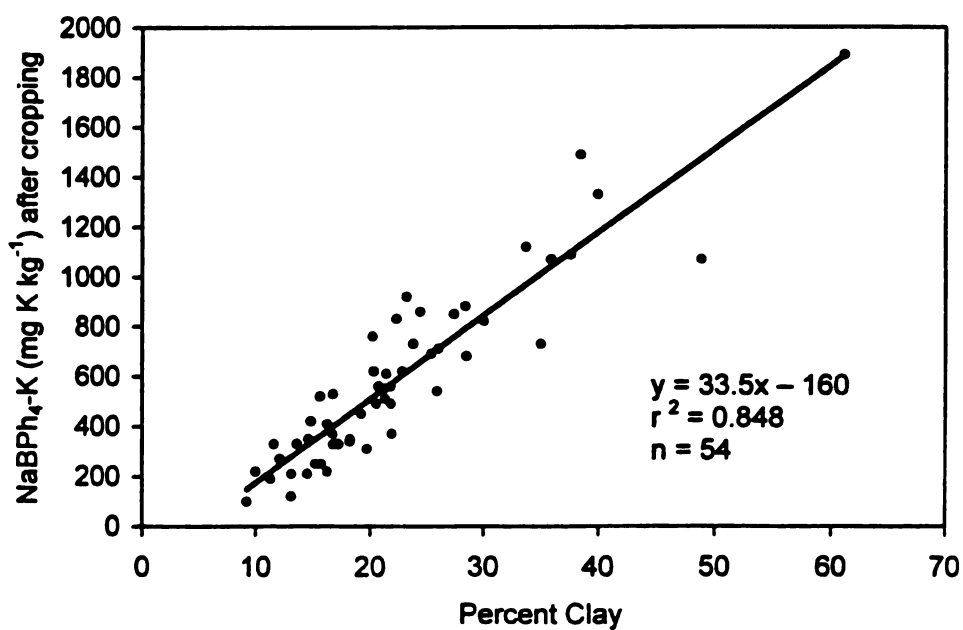


Figure 2.7. Relationship between the percent clay and five-minute $\text{NaBPh}_4\text{-K}$ after cropping for all soils.

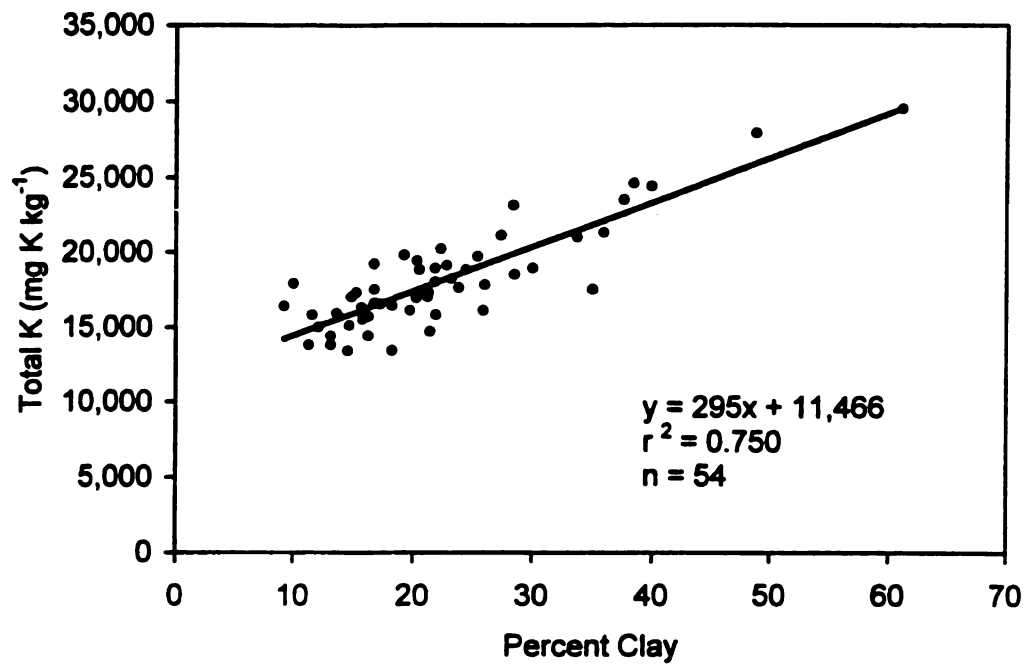


Figure 2.8. Relationship between the percent clay and total K for all soils.

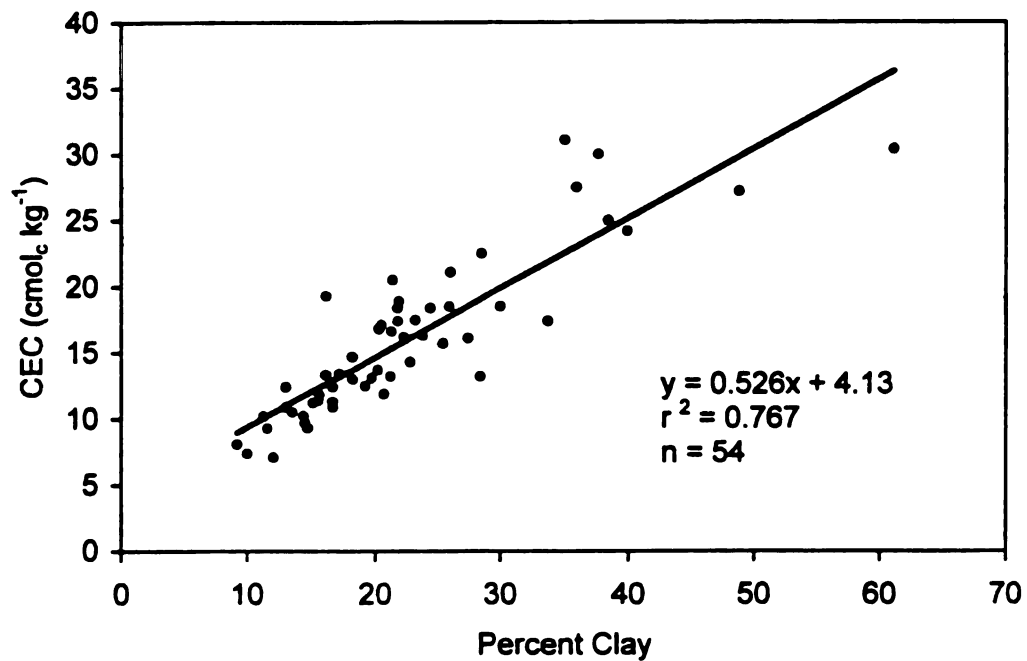


Figure 2.9. Relationship between the percent clay and CEC for all soils.

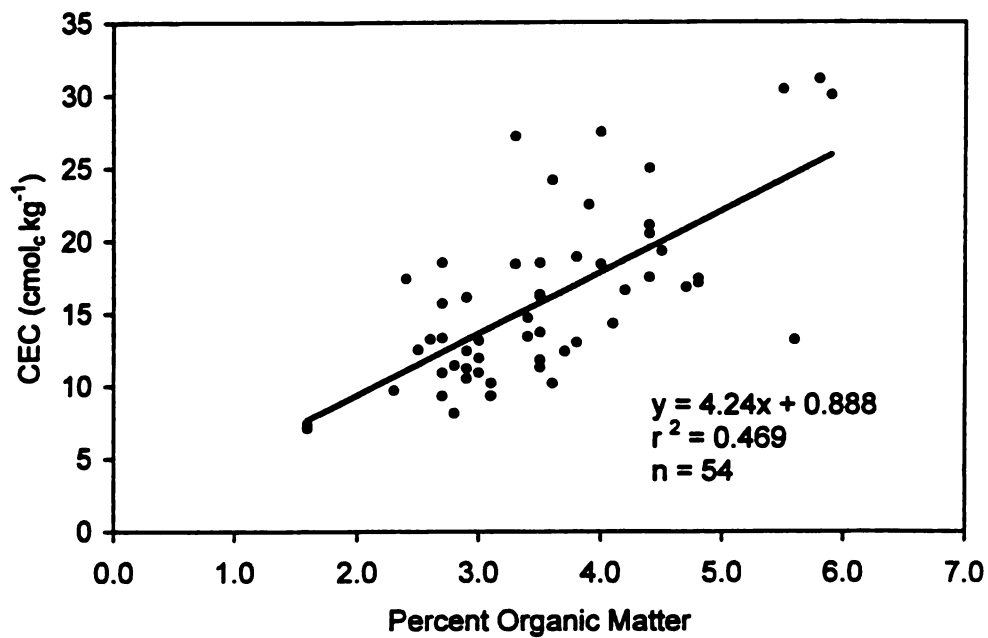


Figure 2.10. Relationship between the percent organic matter and CEC for all soils.

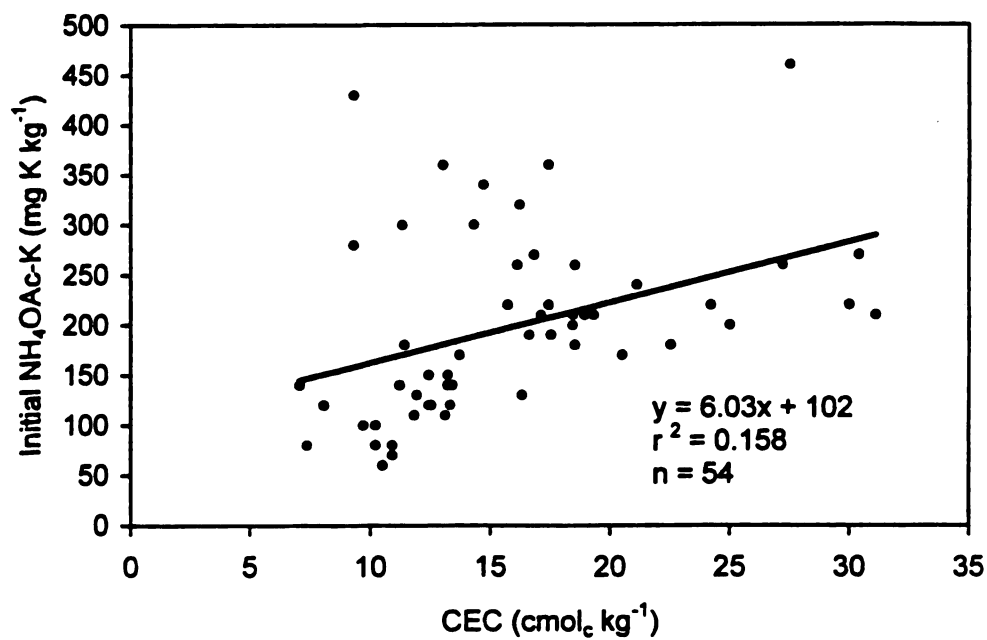


Figure 2.11. Relationship between CEC and initial NH₄OAc-K for all soils.

These simple and multiple regression equations show that although CEC is more highly correlated with clay content, the CEC is more sensitive to changes in organic matter than to changes in clay content. For soils low in clay content, organic matter is likely to contribute more to total CEC than clay content. However, as the clay content of the soil increases, the importance of the organic contribution to total CEC becomes less.

The correlation between CEC and $\text{NH}_4\text{OAc-K}$ or $\text{NaBPh}_4\text{-K}$ before and after cropping is shown in Figures 2.11 to 2.14. The correlation trends found between clay content and NH_4OAc or NaBPh_4 extractable K also hold true for CEC. The correlation between CEC and initial $\text{NH}_4\text{OAc-K}$, although highly significant ($P < 0.01$) is low, $r^2 = 0.158$. The correlation improves, however, for exchangeable K after cropping and for $\text{NaBPh}_4\text{-K}$ both before and after cropping. It is important to notice that the correlations between CEC and extractable K levels are consistently lower than the correlations between clay content and extractable K levels. These results suggest that K recommendations based on clay content might provide a more satisfactory fertility index than a K sufficiency level based on CEC. The coefficients of determination for clay content and CEC are summarized in Table 2.4.

Conflicting reports on the importance of CEC in determining K availability in soils can be found in the literature. McLean (1976, 1978) considered CEC to be an important factor to consider when establishing K recommendations. Researchers in South America have found exchangeable K levels and CEC to be well correlated in soils from Argentina. Illite concentration and initial exchangeable K levels accounted for 90% of the variability in K uptake by ryegrass during cropping experiments (Zubillaga and Conti, 1996). They found that the clay contributed 73 to 80% of the exchangeable K and

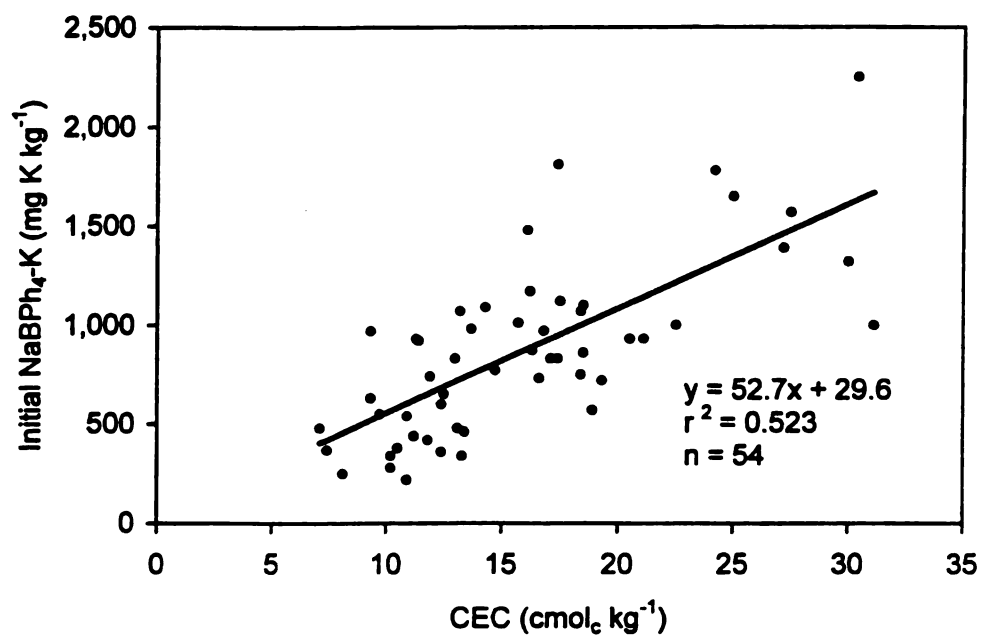


Figure 2.12. Relationship between CEC and initial five-minute NaBPh₄-K for all soils.

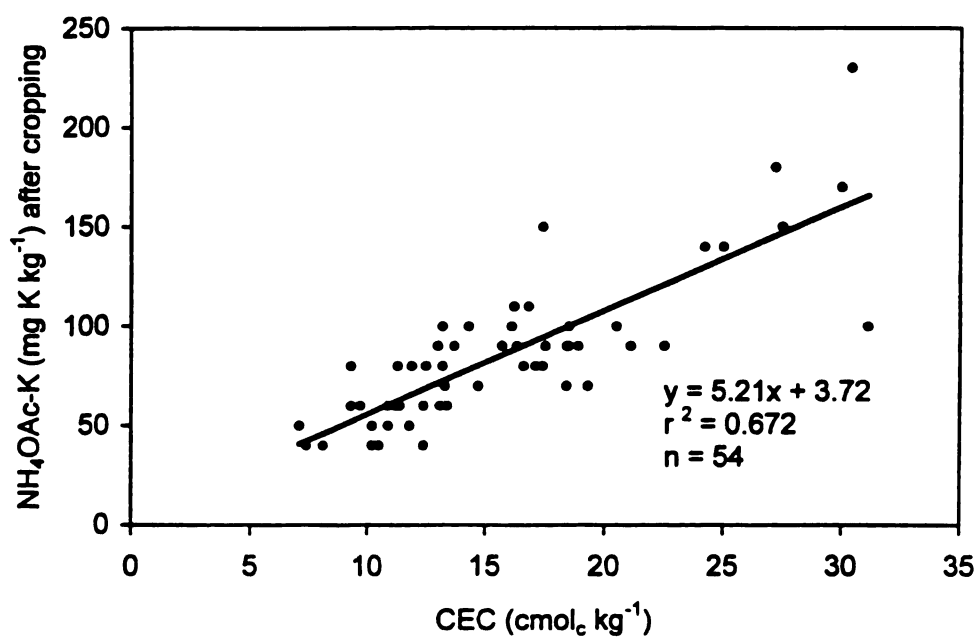


Figure 2.13. Relationship between CEC and NH₄OAc-K after cropping for all soils.

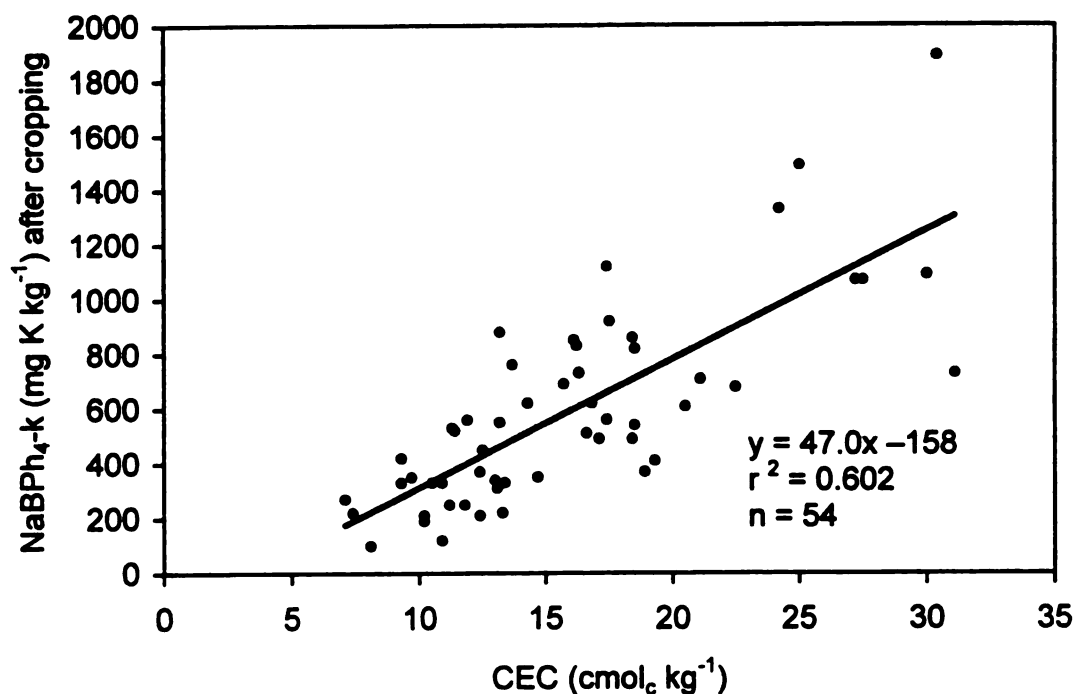


Figure 2.14. Relationship between CEC and five-minute NaBPh₄-K after cropping for all soils.

Table 2.4. Summary of coefficients of determination from regression analysis of percent clay and CEC versus plant uptake and extractable K levels before and after cropping.

	Plant Uptake K	Initial NH ₄ OAc-K	Initial NaBPh ₄ -K	NH ₄ OAc-K after cropping	NaBPh ₄ -K after cropping
	r^2				
Percent Clay	0.216***	0.163**	0.764***	0.887***	0.848***
CEC	0.129**	0.158**	0.523***	0.672***	0.602***

,* Significant at the 0.01 and 0.001 probability levels, respectively.

concluded that clay content and CEC were important considerations for K (Zubillaga and Conti, 1994). Nemeth et al. (1970) reported a positive correlation between the percent K saturation of the inorganic CEC and K concentration in the soil solution. The soil solution K concentration increased with increasing exchangeable K. McLean and Watson (1985) stated that a K sufficiency level based on soil CEC works best when changes in CEC are a result of differences in clay content and not organic matter content.

Walker and Barber (1962) considered the total amount of exchangeable K per volume of soil to be important in controlling K uptake. The percent K saturation affected K availability only where small quantities of K were absorbed by roots. Barber (1981) and Shaw et al. (1983) presented data showing that differences in K uptake of soils were not predicted by differences in CEC. Shaw et al. (1983) stated that the K concentration in solution and average rate of diffusion more nearly reflected differences in K availability. Barber (1995, p. 253-255) concluded that CEC may affect K uptake in soils having vastly different CEC but at intermediate values of CEC the importance was likely to be minimal. The relative importance of CEC as a factor controlling K availability is probably related to differences in clay mineralogy.

Relationship of Clay Mineralogy to Potassium Chemistry of Soils

To determine the variability in clay mineralogy of the soils in this study, four soils representing a wide range in total K content were selected for further investigation. The estimated illite content in the clay fraction, total soil K content, and total, coarse, and fine clay content are presented in Table 2.5. The objective was to see what differences in the

Table 2.5. Estimated illite clay content, total soil potassium content, and total, coarse, and fine clay content of four soils from the tri-state area selected for mineralogical analysis on the basis of total K content.†

Soil	County	State	Estimated Illite Clay g kg ⁻¹	Total K mg K kg ⁻¹	Total Clay (< 2µm) %	Coarse Clay (2-0.2µm) %	Fine Clay (<0.2µm) %
Conover	Genesee	MI	13	13,400	14.5	10.9	3.6
Blount	Monroe	MI	63	18,200	23.2	16.9	6.3
Pewamo	Allegan	MI	73	23,500	37.6	27.1	10.5
Paulding	Paulding	OH	240	29,500	61.1	37.8	23.3

†The percent total, coarse, and fine clay was determined by the Ohio State University Soil Characterization Laboratory.

Table 2.6. Estimated mineral content in the coarse clay (2-0.2µm) and fine clay (<0.2µm) fractions of soils selected for mineralogical analysis from the tri-state area.

Minerals	Conover		Blount		Pewamo		Paulding	
	CC†	FC‡	CC	FC	CC	FC	CC	FC
	%							
Illite	10	5	30	20	25	5	45	30
Vermiculite	35	40	25	15	15	nd	15	nd
Chlorite	<5	nd§	<5	nd	<5	<5	<5	nd
Kaolinite	30	<5	10	<5	20	<5	5	<5
Quartz	<5	nd	<5	nd	<5	nd	<5	nd
Expandable¶	<5	25	15	30	30	80	15	45
Interstratified#	10	25	20	35	<5	10	15	20

†CC = Coarse Clay.

‡FC = Fine Clay.

§ nd = not detected.

¶Expandable = Minerals that have variable expansion beyond 14 Å upon solvation with ethylene glycol.

#Interstratified = Interstratified 10 to 14 Å clay minerals.

K chemistry of the whole soil could be attributed to differences in the clay mineralogy of these soils. Estimated mineral contents of the coarse and fine clay are given in Table 2.6.

Table 2.6 shows that these soils are dominated by 2:1 clays. The fine clay contains more expandable and interstratified minerals than the coarse clay. Illite contents are consistently higher in the coarse clay than in the fine clay of the four soils. The Conover soil has the lowest illite content, and the Paulding soil has the highest illite content. The x-ray diffractograms from these soils are presented in Figures 2.15 to 2.18.

As previously stated, an objective of this study was to determine the mineralogy of the clay fraction and determine what inferences could be made regarding the K chemistry of the whole soil. This can be achieved by assuming that one kg of pure illite contains 72g K₂O (Burrass, et al. 1996). Burrass et al. (1996) used the reference illite, ITM-1 (Clay Mineral Society, Columbia, MO) to estimate illite content in the fine clay fraction of soils of western Ohio because it gave diffraction properties similar to the 10Å peak in the soils they studied. If we assume that the K₂O content of this reference illite is an accurate estimate of the K₂O content of the illite in these soils, then the following comparison can be made. An example for the Conover soil is shown although the logic would follow for the other soils.

For the Conover soil, assume:

Coarse Clay

1000 g soil x 10.9% CC = 109g CC
109g CC x 10% illite = 10.9g illite

Fine Clay

1000 g soil x 3.6% FC = 36g FC
36g FC x 5% illite = 1.8g illite

10.9g + 1.8g = 12.7g illite

Then: $\frac{1000\text{g illite}}{72\text{g K}_2\text{O}} = \frac{12.7\text{g illite}}{X\text{ g K}_2\text{O}}$ X = 0.9g K₂O in illite of Conover soil

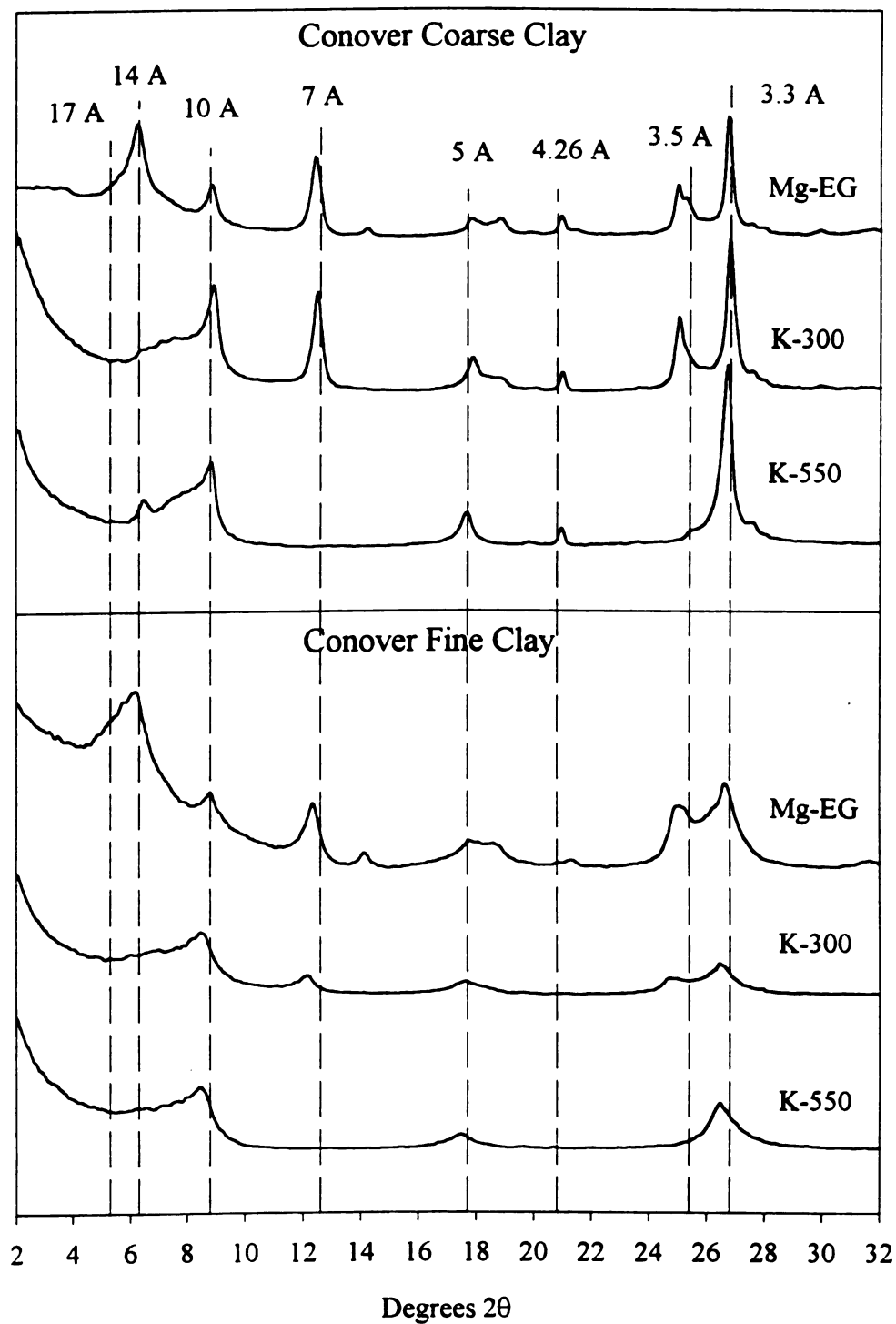


Figure 2.15. X-ray diffraction patterns of coarse clay and fine clay from the Conover soil.

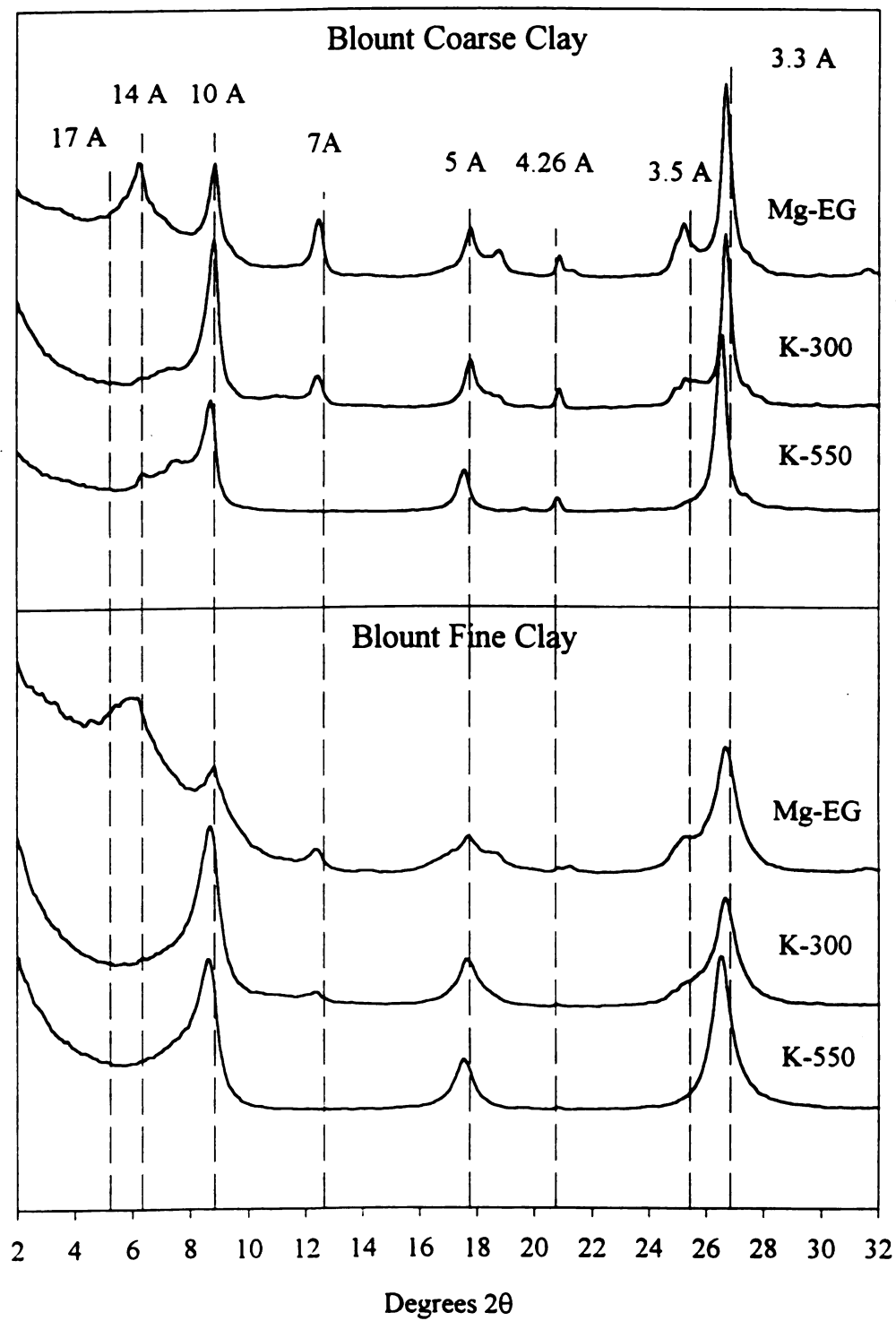


Figure 2.16. X-ray diffraction patterns of coarse clay and fine clay from the Blount soil.

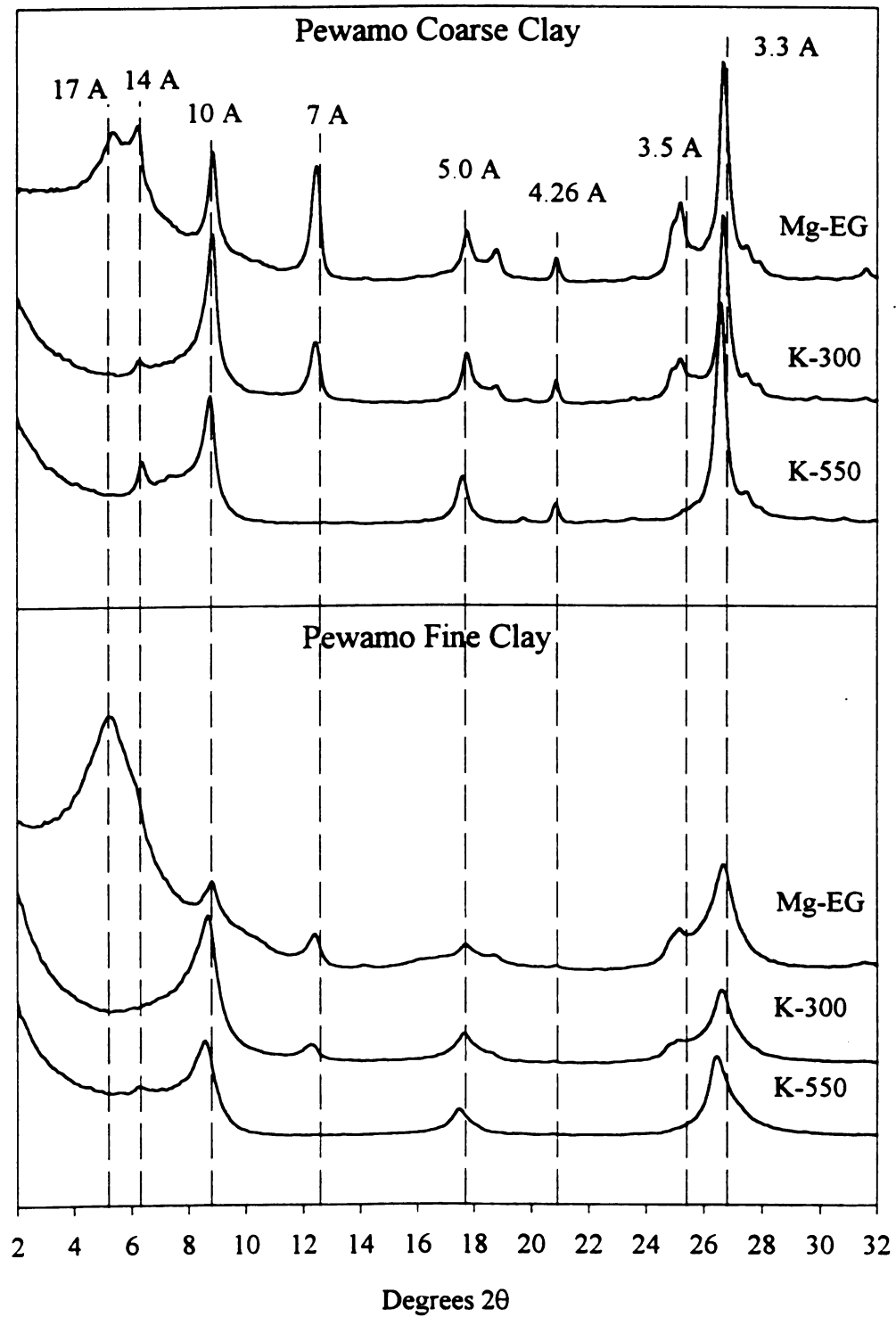


Figure 2.17. X-ray diffraction patterns of coarse clay and fine clay from the Pewamo soil.

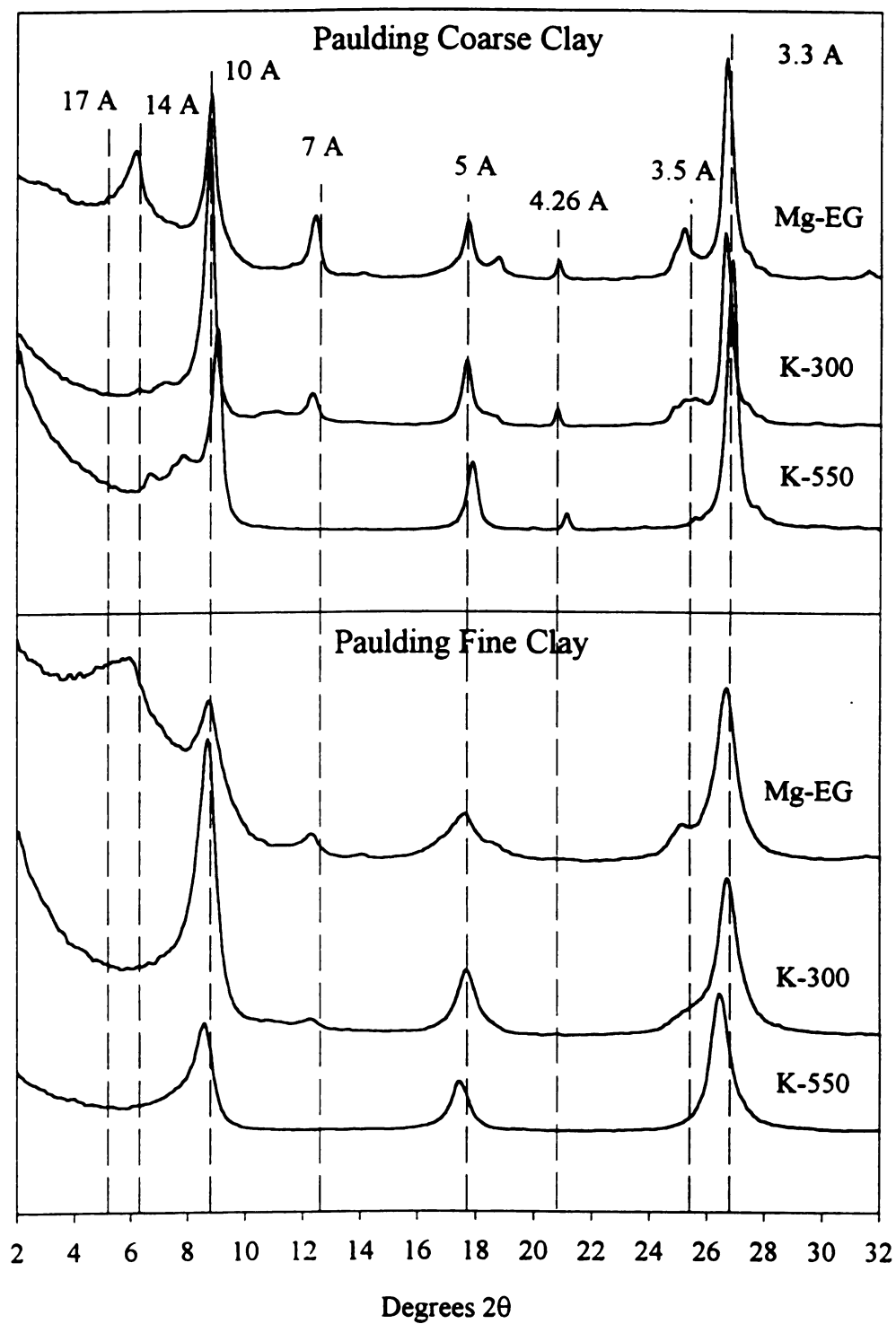


Figure 2.18. X-ray diffraction patterns of coarse clay and fine clay from the Paulding soil.

Using the same logic, the following values would be obtained for the soils: Conover = 0.9g K₂O; Blount = 4.6g K₂O; Pewamo = 5.3g K₂O; Paulding = 17.3g K₂O. The correlation between K₂O content in the illitic clay fraction and total K is, $r^2 = 0.850$ ($P < 0.1$), for these four soils. This would indicate that some prediction of total K content can be made based on the illitic K content of the clay fraction. In reality though, the calculated K₂O values are probably low because the K in the interstratified and expandable minerals was not accounted for. However, this estimate does give an approximate idea of the range in K content and mineral composition of the clay fraction that could be expected in soils with widely differing total K contents in the tri-state region.

A comparison of the illite:vermiculite ratios in the coarse clay is also interesting because it reveals increasing ratios of 0.3 to 3 from the Conover to the Paulding soil. This ratio suggests that soils high in total K will have higher illite:vermiculite ratios in the coarse clay than soils low in total K. Cox et al. (unpublished data) found that the coarse clay contains larger amounts of NaBPh₄ extractable K than any other size fraction.

Mineralogy of Other Soils in the Tri-State Region

Burras et al. (1996) found that smectite was the dominate mineral in loess derived soils of a Birbeck-Reesville-Ragsdale toposequence in western Ohio. Loess covers much of the glaciated region of Ohio (Wilding and Drees, 1968; Hock et al. 1973). Smectite comprised a larger portion of the A horizon of the very poorly drained Ragsdale soil than of the A horizon of the Birbeck or Reesville soils. The poorly drained Pewamo soil in this study also contained large quantities of expandable minerals. Smeck et al. (1981)

reported that mica comprised 20%, 44%, and 76% of the total clay fraction of the A horizon in a Brookston, Pewamo, and Hoytville soil respectively from western Ohio. They concluded that clay mineral weathering decreases in a south to north direction across Ohio. Illite content increased with depth in the soil profile. Wilding et al. (1971) found that in Celina and Morley soils, illite comprised 25% of the total clay fraction in the A horizon and increased in relative percentage with depth. It was the dominant mineral in the soil profile. Smeck et al. (1968) reported similar findings in Celina and Morley soils of western Ohio. Smith and Wilding (1972) compared Napanee soils from southeastern Michigan and northwestern Ohio and found them to contain similar quantities of mica, 30 to 40% in the A horizon. Cremeens and Mokma (1987) reported that in a Marlette, Capac, and Parkhill toposequence of south central Michigan, illite comprised 60 to 80% of the fine clay mineralogy in these soils. These values are much higher than the illite content found in the soils of this study. A second study with the Marlette, Capac, Parkhill toposequence in Clinton and Iona counties revealed that in the total clay fraction illite comprised 25 to 30% of the clay mineralogy (Haile-Mariam and Mokma, 1996). These findings are more in agreement with the results of this study. Cummings (1959) estimated illite contents in the total clay fractions of Michigan soils to range from less than 10 to 70% in the A horizon. Reports from Indiana also show a wide range in illite content. White et al. (1957) reported illite contents in coarse clay ranging from 17 to 50%. Fehrenbacher et al. (1965) reported illite values of 38 to 60% in the coarse clay and from 34 to 52% in the fine clay. Post (1967) found similar values, the coarse clay contained 25 to 60% illite and the fine clay was 22 to 45% illite.

Relative Importance of Clay Content, Clay Mineralogy, and CEC in Establishment of Potassium Recommendations

Given the wide range in illitic clay content of soils throughout the tri-state, it is not surprising to see large differences in the K chemistry of these soils. The mineralogical composition of the clay governs, in large measure, the quantity and rate of release of K to growing plants. In a fundamental investigation, Sharpley (1990) studied the K chemistry of 102 soils representing 10 soil orders from the United States and Puerto Rico. The soils were divided into three groups (kaolinitic, mixed, or smectitic) based on their dominate clay mineralogy. Potassium was added to the soils at rates of 0 to 250 mg K kg⁻¹ and incubated for 25 weeks. Sharpley found that indexes of water soluble, exchangeable and fixed K were closely related to the clay content for each soil group. The K buffering capacity was significantly greater for the smectitic soils than the mixed or kaolinitic soils and was closely related to the clay, CEC, and K saturation for each group of soils. Sharpley (1990) found that K added to the soil was distributed in water soluble, exchangeable, and nonexchangeable forms in proportion to the clay content and dominate mineralogy of the soil. These findings suggest that for accurate K recommendations to be made, the clay content and dominate mineralogy of the soil must be known. The results from this study and other studies in the tri-state region reveal that the soils in the tri-state area can be placed in the broad category of smectitic mineralogy. This is probably the reason why CEC is not a major factor controlling K availability in soils of the tri-state region. If one considers the dominate mineralogy of soil groups, then the relative importance of CEC is likely to be: kaolinitic > mixed > smectitic. The original concept of incorporating CEC into a sufficiency index for K recommendations

originated with Dr. Fred Adams in Alabama. Fisher used the concept and applied it to Missouri soils (Dr. Jay Johnson, personal communication). It is reasonable to assume that a sufficiency relationship based on CEC might be appropriate for the more highly weathered soils of the southern USA. These Ultisols would have very little illite remaining in them. Therefore, the main supply of K would be from the exchangeable K. It would logically follow that K recommendations based on a percentage saturation of the exchange complex might be a good approach under these conditions. In the tri-state, however, despite the large degree of variability in illite content, soils still contain significant reserves of nonexchangeable K in the clay and coarser fractions which can continue to supply K to plants under intensive cropping conditions. Exchangeable K levels on research plots at the Hoytville research station in northwest Ohio have maintained an exchangeable K level of 150 ppm without fertilization for the past 35 years (Dr. Jay Johnson, personal communication). In Ohio, a response to K is not seen on silt loam soils in most years if soils have an exchangeable K level above 90 ppm. In light of this fact, it is doubtful whether the high soil test levels achieved by use of Fisher's equation:

$$K_{\text{ sufficiency level (ppm)}} = 110 + 2.5 \times \text{CEC} \quad [3]$$

are merited for soils in the tri-state. Because the soil CEC is very sensitive to changes in organic matter relative to changes in clay content, it may be more appropriate to base K recommendations on the clay content of soils in the tri-state area. The data from this study and data from Sharpley (1990) would support this approach. As long as soil test levels are maintained at a reasonable level, most soils will be able to supply K in amounts adequate for maximum crop yields.

CONCLUSIONS

The results of this study suggest that clay content and mineralogy are more important factors to consider than CEC when establishing K recommendations. Soils in the tri-state region are dominated by complex mixtures of 2:1 clays and have large reserves of nonexchangeable K in the clay fraction which can supply K to crops. The silt and sand fractions also contain large quantities of nonexchangeable K that may become slowly plant available over time. This suggests that the practice of increasing soil test values to high levels and fertilizing the *soil per se* rather than the crop is not generally necessary and may represent an unjustifiable economic cost to the producer.

The base soil test level that is adopted for sufficiency will affect K fertilization practices. The choice of 110 ppm proposed by Fisher (1974) seems rather arbitrary and should be investigated in more detail to determine if it truly is an accurate approximation of the minimum K soil test value required for sufficiency. McLean (1985) acknowledged that the equation did overestimate the K sufficiency level on soils of low CEC but felt that this should not be a problem because leaching losses of K were more likely on soils of low CEC. Potassium recommendations calculated from a sliding scale that is related to clay content may be a closer approximation of the true sufficiency level for many soils in the tri-state area. Field experiments need to be conducted to determine which approach has the greater merit.

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APPENDICES

APPENDIX A

Table A.1. Location of soils and their taxonomic classification.

Soil Series	County	State	Map Sheet	Location	Soil Family
Blount	Allegan	MI	5	NW ¼, sec. 3, T. 4 N., R. 14 W.	Fine, illitic, mesic Aeric Ochraqualf
Blount	Clinton	MI	26	SW ¼, sec. 19, T. 7 N., R. 3 W.	Fine, illitic, mesic Aeric Ochraqualf
Blount	Monroe	MI	36	SE ¼, sec. 16, T. 6 S., R. 6 E.	Fine, illitic, mesic Aeric Ochraqualf
Blount	Whitley	IN	29	NE ¼, sec. 31, T. 31 N., R. 10 E.	Fine, illitic, mesic Aeric Ochraqualf
Blount	Randolph	IN	22	SE ¼, sec. 5, T. 20 N., R. 13 E.	Fine, illitic, mesic Aeric Ochraqualf
Blount	Hancock	OH	23	SW ¼, sec. 14, T. 1 S., R. 9 E.	Fine, illitic, mesic Aeric Ochraqualf
Blount	Seneca	OH	62	NE ¼, sec. 6, T. 1 N., R. 17 E.	Fine, illitic, mesic Aeric Ochraqualf
Brookston	Allegan	MI	22	NW ¼, sec. 30, T. 4 N., R. 15 W.	Fine-loamy, mixed, mesic Typic Argiaquoll
Brookston	Genesee	MI	23	NE ¼, sec. 18, T. 7 N., R. 5 E.	Fine-loamy, mixed, mesic Typic Argiaquoll
Brookston	Washtenaw	MI	23	NW ¼, sec. 29, T. 2 S., R. 4 E.	Fine-loamy, mixed, mesic Typic Argiaquoll
Brookston	Hendricks	IN	24	SE ¼, sec. 31, T. 16 N., R. 1 W.	Fine-loamy, mixed, mesic Typic Argiaquoll
Brookston	Pulaski	IN	72	SW ¼, sec. 36, T. 29 N., R. 1 W.	Fine-loamy, mixed, mesic Typic Argiaquoll
Capac	Allegan	MI	22	NW ¼, sec. 29, T. 4 N., R. 15 W.	Fine-loamy, mixed, mesic Aeric Ochraqualf
Capac	Clinton	MI	26	SW ¼, sec. 19, T. 7 N., R. 3 W.	Fine-loamy, mixed, mesic Aeric Ochraqualf
Capac	Sanilac	MI	120S	SE ¼, sec. 30, T. 9 N., R. 14 E.	Fine-loamy, mixed, mesic Aeric Ochraqualf
Celina	Preble	OH	34	NW ¼, sec. 27, T. 8 N., R. 2 E.	Fine, mixed, mesic Aquic Hapludalf
Conover	Ottawa	MI	62	NW ¼, sec. 14, T. 5 N., R. 14 W.	Fine-loamy, mixed, mesic Udollic Ochraqualf
Conover	Genesee	MI	23	SE ¼, sec. 6, T. 7 N., R. 5 E.	Fine-loamy, mixed, mesic Udollic Ochraqualf
Conover	Washtenaw	MI	23	SE ¼, sec. 29, T. 2 S., R. 4 E.	Fine-loamy, mixed, mesic Udollic Ochraqualf
Crosby	Hendricks	IN	34	NW ¼, sec. 19, T. 15 N., R. 1 W.	Fine, mixed, mesic Aeric Ochraqualf
Crosby	Pulaski	IN	72	SW ¼, sec. 36, T. 29 N., R. 1 W.	Fine, mixed, mesic Aeric Ochraqualf
Crosby	Clinton	OH	7	Lat. 39° 32' 45" N Long. 83° 38' 42" W	Fine, mixed, mesic Aeric Ochraqualf
Crosby	Preble	OH	34	NW ¼, sec. 27, T. 8 N., R. 2 E.	Fine, mixed, mesic Aeric Ochraqualf

Table A.1. (cont'd)

Soil Series	County	State	Map Sheet	Location	Soil Family
Glynwood	Allegan	MI	15	SW ¼, sec. 14, T. 4 N., R. 14 W.	Fine, illitic, mesic Aquic Hapludalf
Glynwood	Hancock	OH	24	SW ¼, sec. 1, T. 1 S., R. 9 E.	Fine, illitic, mesic Aquic Hapludalf
Glynwood	Seneca	OH	62	NE ¼, sec. 4, T. 1 N., R. 17 E.	Fine, illitic, mesic Aquic Hapludalf
Hoytville	Monroe	MI	10	SW ¼, sec. 15, T. 5 S., R. 6 E.	Fine, illitic, mesic Mollic Ochraqualf
Hoytville	Paulding	OH	5	NE ¼, sec. 24, T. 2 N., R. 1 E.	Fine, illitic, mesic Mollic Ochraqualf
Kokomo	Clinton	OH	3	Lat. 39° 30' 20" N Long. 83° 36' 45" W	Fine, mixed, mesic Typic Argiaquoll
Kokomo	Preble	OH	34	NW ¼, sec. 27, T. 8 N., R. 2 E.	Fine, mixed, mesic Typic Argiaquoll
Marlette	Allegan	MI	29	NW ¼, sec. 28, T. 4 N., R. 11 W.	Fine-loamy, mixed, mesic Glossoboric Hapludalf
Marlette	Clinton	MI	3	SE ¼, sec. 3, T. 8 N., R. 3 W.	Fine-loamy, mixed, mesic Glossoboric Hapludalf
Marlette	Sanilac	MI	107S	NW ¼, sec. 17, T. 9 N., R. 14 E.	Fine-loamy, mixed, mesic Glossoboric Hapludalf
Miami	Ottawa	MI	64	SE ¼, sec. 10, T. 5 N., R. 13 W.	Fine-loamy, mixed mesic Typic Hapludalf
Miami	Genesee	MI	10	NW ¼, sec. 35, T. 9 N., R. 7 E.	Fine-loamy, mixed mesic Typic Hapludalf
Miami	Washtenaw	MI	23	SW ¼, sec. 32, T. 2 S., R. 4 E.	Fine-loamy, mixed mesic Typic Hapludalf
Miami	Hendricks	IN	24	SE ¼, sec. 31, T. 16 N., R. 1 W.	Fine-loamy, mixed mesic Typic Hapludalf
Miami	Pulaski	IN	55	SW ¼, sec. 5, T. 29 N., R. 1 W.	Fine-loamy, mixed mesic Typic Hapludalf
Miamian	Clinton	OH	19	Lat. 39° 28' 25" N Long. 83° 41' 50" W	Fine, mixed, mesic Typic Hapludalf
Miamian	Preble	OH	27	SW ¼, sec. 17, T. 8 N., R. 2 E.	Fine, mixed, mesic Typic Hapludalf
Misteguay	Saginaw	MI	52	NE ¼, sec. 9, T. 11 N., R. 3 E.	Fine, mixed, (calcareous), mesic Aeric Endoaquent
Morley	Genesee	MI	10	NW ¼, sec. 25, T. 9 N., R. 7 E.	Fine, illitic, mesic Typic Hapludalf
Morley	Washtenaw	MI	11	NE ¼, sec. 27, T. 1 S., R. 5 E.	Fine, illitic, mesic Typic Hapludalf
Morley	Randolph	IN	29	NW ¼, sec. 15, T. 20 N., R. 13 E.	Fine, illitic, mesic Typic Hapludalf
Morley	Whitley	IN	29	SE ¼, sec. 28, T. 31 N., R. 10 E.	Fine, illitic, mesic Typic Hapludalf

Table A.1. (cont'd)

Soil Series	County	State	Map Sheet	Location	Soil Family
Parkhill	Clinton	MI	26	SW ¼, sec. 19, T. 7 N., R. 3 W.	Fine-loamy, mixed, nonacid, mesic Mollic Haplaquept
Parkhill	Sanilac	MI	120S	SE ¼, sec. 30, T. 9 N., R. 14 E.	Fine-loamy, mixed, nonacid, mesic Mollic Haplaquept
Paulding	Paulding	OH	3	SE ¼, sec. 19, T. 3 N., R. 3 E.	Very-fine, illitic, nonacid, mesic Typic Haplaquept
Pewamo	Allegan	MI	9	SE ¼, sec. 1, T. 4 N., R. 12 W.	Fine, mixed, mesic Typic Argiaquoll
Pewamo	Monroe	MI	10	SE ¼, sec. 15, T. 5 S., R. 6 E.	Fine, mixed, mesic Typic Argiaquoll
Pewamo	Randolph	IN	23	SE ¼, sec. 3, T. 29 N., R. 13 E.	Fine, mixed, mesic Typic Argiaquoll
Pewamo	Whitley	IN	29	NE ¼, sec. 31, T. 31 N., R. 10 E.	Fine, mixed, mesic Typic Argiaquoll
Pewamo	Hancock	OH	23	SW ¼, sec. 14, T. 1 S., R. 9 E.	Fine, mixed, mesic Typic Argiaquoll
Pewamo	Seneca	OH	50	SE ¼, sec. 27, T. 2 N., R. 15 E.	Fine, mixed, mesic Typic Argiaquoll

Appendix B

Table B.1. Selected physical and chemical properties of all soils.

Soil	County	State	Glacial Lobe	pH	OM %	CEC cmol _c kg ⁻¹	Sand %	Silt %	Clay %	Texture†
Marlette	Allegan	MI	Michigan	5.8	4.8	17.1	36.5	43.0	20.5	L
Marlette	Clinton	MI	Saginaw	5.8	3.7	12.4	35.7	47.6	16.7	L
Marlette	Sanilac	MI	Huron-Erie	7.6	3.0	10.9	42.0	41.3	16.7	L
Capac	Allegan	MI	Michigan	6.9	2.5	12.5	38.6	42.2	19.2	L
Capac	Clinton	MI	Saginaw	7.0	4.1	14.3	25.8	51.4	22.8	SiL
Capac	Sanilac	MI	Huron-Erie	6.0	2.9	10.5	43.9	42.5	13.6	L
Parkhill	Clinton	MI	Saginaw	7.0	4.7	16.8	26.9	52.8	20.3	SiL
Parkhill	Sanilac	MI	Huron-Erie	7.3	3.0	13.1	34.4	45.9	19.7	L
Miami	Ottawa	MI	Michigan	7.1	2.8	8.1	55.5	35.3	9.2	SL
Miami	Genesee	MI	Saginaw	7.8	1.6	7.1	56.4	31.5	12.1	SL
Miami	Washtenaw	MI	Huron-Erie	6.0	3.1	9.3	43.9	44.5	11.6	L
Miami	Pulaski	IN		6.1	3.4	14.7	47.1	34.7	18.2	L
Miami	Hendricks	IN		7.0	2.7	10.9	31.1	55.8	13.1	SiL
Miamian	Preble	OH		7.7	2.4	17.4	25.7	40.6	33.7	CL
Miamian	Clinton	OH		5.6	3.5	11.8	18.8	65.5	15.7	SiL
Conover	Ottawa	MI	Michigan	6.2	4.4	25.0	13.7	47.9	38.4	SiCL
Conover	Genesee	MI	Saginaw	6.4	3.1	10.2	41.6	43.9	14.5	L
Conover	Washtenaw	MI	Huron-Erie	6.6	2.3	9.7	51.0	34.4	14.6	L
Crosby	Pulaski	IN		6.2	2.9	12.4	52.5	34.4	13.1	SL
Crosby	Hendricks	IN		6.9	2.7	13.3	31.8	52.0	16.2	SiL
Celina	Preble	OH		7.0	3.0	11.9	34.1	45.2	20.7	L
Crosby	Preble	OH		7.0	3.4	13.4	18.8	64.0	17.2	SiL
Crosby	Clinton	OH		7.7	2.7	18.5	16.5	57.6	25.9	SiL
Brookston	Allegan	MI	Michigan	6.8	3.8	13.0	42.1	39.7	18.2	L
Brookston	Genesee	MI	Saginaw	5.6	3.5	13.7	40.2	39.6	20.2	L
Brookston	Washtenaw	MI	Huron-Erie	7.1	4.4	20.5	48.6	30.0	21.4	L
Brookston	Pulaski	IN		6.5	4.5	19.3	49.6	34.2	16.2	L
Brookston	Hendricks	IN		7.8	3.8	18.9	19.1	59.0	21.9	SiL
Kokomo	Preble	OH		7.1	4.4	21.1	13.8	60.2	26.0	SiL
Kokomo	Clinton	OH		5.9	5.8	31.1	9.7	55.3	35.0	SiCL

† Texture (L = Loam, SiL = Silt Loam, CL = Clay Loam, SiCL = Silty Clay Loam, SL = Sandy Loam
C = Clay, SiC = Silty Clay)

Table B.1. (cont'd)

Soil	County	State	Glacial Lobe	Total K	NaBPh ₄ -K 7 Days†	Total K Extracted By NaBPh ₄ In 7 Days	Nek 7 Days§	NaBPh ₄ -K Before Plant Uptake¶	NaBPh ₄ -K After Plant Uptake‡
				— mg K kg ⁻¹ —	— % —				
Marlette	Allegan	MI	Michigan	18,800	5,110	27	4,900	830	490
Marlette	Clinton	MI	Saginaw	17,500	4,690	27	4,540	600	370
Marlette	Sanilac	MI	Huron-Erie	16,600	5,190	31	5,120	540	330
Capac	Allegan	MI	Michigan	19,800	6,130	31	6,010	650	450
Capac	Clinton	MI	Saginaw	19,100	5,500	29	5,200	1,090	620
Capac	Sanilac	MI	Huron-Erie	15,900	4,490	28	4,430	380	330
Parkhill	Clinton	MI	Saginaw	19,400	5,680	29	5,410	970	620
Parkhill	Sanilac	MI	Huron-Erie	16,100	5,850	36	5,740	480	310
Miami	Ottawa	MI	Michigan	16,400	1,570	10	1,450	250	100
Miami	Genesee	MI	Saginaw	15,000	4,160	28	4,020	480	270
Miami	Washtenaw	MI	Huron-Erie	15,800	3,470	22	3,190	630	330
Miami	Pulaski	IN		13,400	2,580	19	2,240	770	350
Miami	Hendricks	IN		14,400	1,900	13	1,820	220	120
Miamian	Preble	OH		21,000	8,030	38	7,670	1,810	1,120
Miamian	Clinton	OH		15,500	3,720	24	3,610	420	250
Conover	Ottawa	MI	Michigan	24,600	11,200	46	11,000	1,650	1,490
Conover	Genesee	MI	Saginaw	13,400	3,190	24	3,090	340	210
Conover	Washtenaw	MI	Huron-Erie	15,100	4,240	28	4,140	550	350
Crosby	Pulaski	IN		13,800	1,590	12	1,470	360	210
Crosby	Hendricks	IN		15,700	2,370	15	2,250	340	220
Celina	Preble	OH		17,300	5,200	30	5,070	740	560
Crosby	Preble	OH		16,500	3,270	20	3,130	460	330
Crosby	Clinton	OH		16,100	5,210	32	5,030	860	540
Brookston	Allegan	MI	Michigan	16,400	4,040	25	3,680	830	340
Brookston	Genesee	MI	Saginaw	16,900	5,770	34	5,600	980	760
Brookston	Washtenaw	MI	Huron-Erie	14,700	4,290	29	4,120	930	610
Brookston	Pulaski	IN		14,400	2,560	18	2,350	720	410
Brookston	Hendricks	IN		15,800	3,180	20	2,970	570	370
Kokomo	Preble	OH		17,800	5,400	30	5,160	930	710
Kokomo	Clinton	OH		17,500	6,250	36	6,040	1,000	730

†NaBPh₄-K 7 Days = K extractable by NaBPh₄ in 7 days§Nek 7 Days = Nonexchangeable K released in 7 days (Nonexchangeable K = NaBPh₄ extractable)¶NaBPh₄-K Before Plant Uptake = K level of the soil determined by a five-minute extraction with

#Nek Before Plant Uptake = Nonexchangeable soil K level before Neubauer growth study (five-m

††NH₄OAc-K Before Plant Uptake = Exchangeable K level of the soil determined by a five-minut

‡‡Plant Uptake = Amount of K taken from the soil by barley plants during Neubauer growth study

§§Plant Uptake From Exk = The percent of K taken up by plants from the exchangeable soil K da

¶¶Plant Uptake From Nek = The percent of K taken up by plants from the nonexchangeable soil K

	Nek Before Plant Uptake#	Nek After Plant Uptake	Delta Nek	NH ₄ OAc-K Before Plant Uptake††	NH ₄ OAc-K After Plant Uptake	Delta NH ₄ OAc-K	Plant Uptake‡‡	Plant Uptake From Exk§§	Plant Uptake From NeK¶¶
	mg K kg ⁻¹							%	
340	620	410	210	210	80	130	247	53	47
230	450	310	140	150	60	90	147	61	39
210	470	280	190	70	50	20	105	19	81
200	530	370	160	120	80	40	150	27	73
170	790	520	270	300	100	200	374	53	47
150	320	290	30	60	40	20	38	53	47
150	700	510	190	270	110	160	295	54	46
170	370	250	120	110	60	50	112	45	55
150	130	60	70	120	40	80	91	88	12
110	340	220	120	140	50	90	158	57	43
100	350	270	80	280	60	220	250	88	12
120	430	280	150	340	70	270	331	82	18
100	140	60	80	80	60	20	26	77	23
190	1,450	970	480	360	150	210	517	41	59
170	310	200	110	110	50	60	67	90	10
160	1,450	1,350	100	200	140	60	244	25	75
130	240	160	80	100	50	50	74	68	32
100	450	290	160	100	60	40	159	25	75
150	240	170	70	120	40	80	108	74	26
120	220	150	70	120	70	50	71	70	30
180	610	480	130	130	80	50	171	29	71
130	320	270	50	140	60	80	154	52	48
120	680	450	230	180	90	90	134	67	33
190	470	250	220	360	90	270	412	66	34
120	810	670	140	170	90	80	215	37	63
120	760	510	250	170	100	70	254	28	72
110	510	340	170	210	70	140	260	54	46
100	360	280	80	210	90	120	148	81	19
120	690	620	70	240	90	150	324	46	54
170	790	630	160	210	100	110	125	88	12

minus NH₄OAc extractable K).

Ph₄ before Neubauer growth study.

NaBPh₄ extractable K minus five-minute NH₄OAc extractable K).

reaction with NH₄OAc before Neubauer growth study.

Neubauer growth study.

15 min Neubauer growth study.

Table B.1. (cont'd)

Soil	County	State	Glacial Lobe	pH	OM %	CEC cmol _c kg ⁻¹	Sand %	Silt %	Clay %	Texture†
Glynwood	Allegan	MI	Michigan	6.8	2.6	13.2	36.3	35.3	28.4	CL
Morley	Genesee	MI	Saginaw	7.1	3.6	10.2	55.3	33.4	11.3	SL
Morley	Washtenaw	MI	Huron-Erie	5.8	2.7	9.3	40.8	44.4	14.8	L
Morley	Whitley	IN		6.5	5.6	13.2	26.2	52.6	21.2	SiL
Morley	Randolph	IN		7.9	3.5	18.5	19.8	50.2	30.0	SiCL
Glynwood	Hancock	OH		7.1	1.6	7.4	58.1	31.9	10.0	SL
Glynwood	Seneca	OH		7.1	2.9	16.1	19.8	52.8	27.4	SiCL
Blount	Allegan	MI	Michigan	5.9	3.5	11.3	48.3	35.0	16.7	L
Blount	Clinton	MI	Saginaw	5.9	4.8	17.4	23.4	54.8	21.8	SiL
Blount	Monroe	MI	Huron-Erie	6.5	4.4	17.5	38.6	38.2	23.2	L
Blount	Whitley	IN		6.2	3.3	18.4	27.2	51.0	21.8	SiL
Blount	Randolph	IN		7.1	4.2	16.6	10.6	68.1	21.3	SiL
Blount	Hancock	OH		6.6	2.9	11.2	34.4	50.4	15.2	SiL
Blount	Seneca	OH		5.8	2.7	15.7	19.7	54.9	25.4	SiL
Pewamo	Allegan	MI	Michigan	6.8	5.9	30.0	2.5	59.9	37.6	SiCL
Pewamo	Monroe	MI	Huron-Erie	5.7	2.8	11.4	47.1	37.3	15.6	L
Pewamo	Whitley	IN		6.9	3.9	22.5	30.6	40.9	28.5	CL
Pewamo	Randolph	IN		7.7	4.0	27.5	13.9	50.2	35.9	SiCL
Pewamo	Hancock	OH		5.6	4.0	18.4	23.1	52.5	24.4	SiL
Pewamo	Seneca	OH		5.8	3.5	16.2	19.7	58.0	22.3	SiL
Hoytville	Monroe	MI	Huron-Erie	6.5	3.5	16.3	46.8	29.4	23.8	L
Hoytville	Paulding	OH		6.2	3.6	24.2	13.6	46.5	39.9	SiCL
Paulding	Paulding	OH		6.5	5.5	30.4	5.2	33.7	61.1	C
Misteguay	Saginaw	MI	Saginaw	7.9	3.3	27.2	5.3	45.9	48.8	SiC

†Texture (L= Loam, SiL= Silt Loam, CL = Clay Loam, SiCL = Silty Clay Loam, SL = Sandy Loam
C = Clay, SiC = Silty Clay)

Table B.1. (cont'd)

Soil	County	State	Glacial Lobe	Total K	NaBPh ₄ -K 7 Days†	Total K Extracted By NaBPh ₄ In 7 Days	Nek 7 Days§	NaBPh ₄ -K Before Plant Uptake¶	NaBPh ₄ -K After Plant Uptake¶	Nek Before Plant Uptake¶
				— mg K kg ⁻¹ —	— % —					
Glynwood	Allegan	MI	Michigan	23,100	8,250	36	8,100	1,070	880	9
Morley	Genesee	MI	Saginaw	13,800	2,870	21	2,790	280	190	2
Morley	Washtenaw	MI	Huron-Erie	17,000	4,590	27	4,160	970	420	5
Morley	Whitley	IN		17,000	5,250	31	5,110	1,070	550	9
Morley	Randolph	IN		18,900	7,930	42	7,670	1,100	820	8
Glynwood	Hancock	OH		17,900	3,260	18	3,180	370	220	2
Glynwood	Seneca	OH		21,100	8,790	42	8,530	1,480	850	12
Blount	Allegan	MI	Michigan	19,200	5,730	30	5,430	930	530	6
Blount	Clinton	MI	Saginaw	18,900	5,380	28	5,160	830	560	6
Blount	Monroe	MI	Huron-Erie	18,200	5,710	31	5,520	1,120	920	9
Blount	Whitley	IN		18,000	5,410	30	5,210	750	490	5
Blount	Randolph	IN		17,300	4,150	24	3,960	730	510	5
Blount	Hancock	OH		17,300	3,740	22	3,600	440	250	2
Blount	Seneca	OH		19,700	7,140	36	6,920	1,010	690	2
Pewamo	Allegan	MI	Michigan	23,500	7,640	33	7,420	1,320	1,090	13
Pewamo	Monroe	MI	Huron-Erie	16,300	3,620	22	3,440	920	520	13
Pewamo	Whitley	IN		18,500	5,940	32	5,760	1,000	680	8
Pewamo	Randolph	IN		21,300	7,680	36	7,220	1,570	1,070	13
Pewamo	Hancock	OH		18,800	6,950	37	6,740	1,070	860	13
Pewamo	Seneca	OH		20,200	6,420	32	6,100	1,170	830	13
Hoytville	Monroe	MI	Huron-Erie	17,600	5,200	30	5,070	870	730	13
Hoytville	Paulding	OH		24,400	10,700	44	10,480	1,780	1,330	13
Paulding	Paulding	OH		29,500	16,200	55	15,930	2,250	1,890	13
Misteguay	Saginaw	MI	Saginaw	27,900	9,000	32	8,740	1,390	1,070	13

†NaBPh₄-K 7 Days = K extractable by NaBPh₄ in 7 days

§Nek 7 Days = Nonexchangeable K released in 7 days (Nonexchangeable K = NaBPh₄ extractable K)

¶NaBPh₄-K Before Plant Uptake = K level of the soil determined by a five-minute extraction with NaBPh₄ before growth

#Nek Before Plant Uptake = Nonexchangeable soil K level before Neubauer growth study (five-minute extraction with NaBPh₄ before growth)

††NH₄OAc-K Before Plant Uptake = Exchangeable K level of the soil determined by a five-minute extraction with NH₄OAc before growth

‡‡Plant Uptake = Amount of K taken from the soil by barley plants during Neubauer growth study

§§Plant Uptake From Exk = The percent of K taken up by plants from the exchangeable soil K determined by Neubauer growth study

¶¶Plant Uptake From Nek = The percent of K taken up by plants from the nonexchangeable soil K determined by Neubauer growth study

minus NH_4OAc extractable K).
 3Ph_4 before Neubauer growth study.
 e NaBPh_4 extractable K minus five-minute NH_4OAc extractable K).
 traction with NH_4OAc before Neubauer growth study.
 Neubauer growth study.
 ing Neubauer growth study.

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