Evaluation of soil test methods and development of a potassium fertilizer recommendation system for Montana
by Vincent Andrew Haby

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Crop and Soil Science
Montana State University
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Abstract:
A state-wide, intensive research effort was initiated in 1972 to resolve the anomaly of wheat response to fertilizer potassium on dry-land soils testing high in this element. Development and calibration of a new test, or recalibration of the presently used ammonium acetate potassium soil test method was a major part of this objective. Field crop yields, climatic data, and soil samples from these research sites were evaluated.

The effects of drying, grinding, and rehydration on the amount of N NH4OAc extractable soil K in 0 to 6 and 6 to 12-inch depth samples were evaluated. Differences in K extracted from moist vs. air dry samples were statistically significant only for the 6 to 12-inch depths.

Surface soils usually contained more extractable K than subsoils. When moist soils contained about 420 ppm K or less, release occurred on drying. Above this K level, soils fixed or maintained their extractable K level on drying. Extractable K reverted to its original moist soil level by rehydration to 40% water and freezing, then air drying to less than five percent water but not totally dry. Grinding soils finer than two mm had no significant effect on N NH4OAc extractable K.

Twelve methods were tested for the relationship of extractable soil K to crop yield or response to K on 17 experimental site soils. Only three methods, the DTPA, dilute cation solution, and resin-thimble methods were significantly calibrated with winter wheat response (95% level) on these soils. The R2 values were .57, .55, and .56, respectively. These R2 values were obtained from regression of fertilizer K and K in the 0 to 6 and 6 to 12-inch soil depths vs. winter wheat response to K. The regression using NH4OAc extractable K produced an R2 of only .32. Free energy computed from RTln[K]/[Ca]^½ gave the greatest R2 in the dilute cation method.

Selected K extraction methods tried on the above soil's were further tested on seven 1973 winter wheat experimental sites at which climatic data were also evaluated. Extractable soil K in the surface 6-inch depth by N NH40Ac and resin-thimble methods failed to generate significant stepwise multiple regression equations. The R2 values were .17 and .54, respectively. Free energy in the dilute cation equilibration methods computed from RTln[K]/[Ca]^½ in the 6 to 12-inch depth, was entered at regression step one. The R2 value was .28. The resin-thimble procedure for K had the lowest standard error among K extraction methods, but lacked precision between duplicate samples. This was due to non-uniformity of the thimbles. Soil K extracted by a strongly acid cation resin showed promise for predicting crop response to fertilizer K. Moist Soil NH4OAc extractable K was better related to crop response than was K extracted from dry soils. The reverse was true with resin.

Addition of climactic factors into the stepwise regression equations improved the potential tield predictability. Evaporation rate, soil temperature, growing season rainfall, and available soil water were entered after resin-thimble extractable K. These results indicate that, in addition to soil K, other plant growth factors should be included in regression equations to predict winter wheat response to K in

Montana.

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VINCENT ANDREW HABY

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree

of

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in

Crop and Soil Science

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ABSTRACT

A state-wide, intensive research effort was initiated in 1972 to resolve the anomaly of wheat response to fertilizer potassium on dryland soils testing high in this element. Development and calibration of a new test, or recalibration of the presently used ammonium acetate potassium soil test method was a major part of this objective. Field crop yields, climatic data, and soil samples from these research sites were evaluated.

The effects of drying, grinding, and rehydration on the amount of N NH_4OAc extractable soil K in 0 to 6 and 6 to 12-inch depth samples were evaluated. Differences in K extracted from moist vs. air dry samples were statistically significant only for the 6 to 12-inch depths.

Surface soils usually contained more extractable K than subsoils. When moist soils contained about 420 ppm K or less, release occurred on drying. Above this K level, soils fixed or maintained their extractable K level on drying. Extractable K reverted to its original moist soil level by rehydration to 40% water and freezing, then air drying to less than five percent water but not totally dry. Grinding soils finer than two mm had no significant effect on N NH_4OAc extractable K.

Twelve methods were tested for the relationship of extractable soil K to crop yield or response to K on 17 experimental site soils. Only three methods, the DTPA, dilute cation solution, and resin-thimble methods were significantly calibrated with winter wheat response (95% level) on these soils. The R^2 values were .57, .55, and .56, respectively. These R^2 values were obtained from regression of fertilizer K and K in the 0 to 6 and 6 to 12-inch soil depths vs. winter wheat response to K. The regression using NH_4OAc extractable K produced an R^2 of only .32. Free energy computed from $RT\ln[K]/[Ca]^{\frac{1}{2}}$ gave the greatest R^2 in the dilute cation method.

Selected K extraction methods tried on the above soils were further tested on seven 1973 winter wheat experimental sites at which climatic data were also evaluated. Extractable soil K in the surface 6-inch depth by N NH_4OAc and resin-thimble methods failed to generate significant stepwise multiple regression equations. The R^2 values were .17 and .54, respectively. Free energy in the dilute cation equilibration methods computed from $RT\ln[K]/[Ca]^{\frac{1}{2}}$ in the 6 to 12-inch depth, was entered at regression step one. The R^2 value was .28. The

resin-thimble procedure for K had the lowest standard error among K extraction methods, but lacked precision between duplicate samples. This was due to non-uniformity of the thimbles. Soil K extracted by a strongly acid cation resin showed promise for predicting crop response to fertilizer K. Moist soil NH_4OAc extractable K was better related to crop response than was K extracted from dry soils. The reverse was true with resin.

Addition of climatic factors into the stepwise regression equations improved the potential yield predictability. Evaporation rate, soil temperature, growing season rainfall, and available soil water were entered after resin-thimble extractable K. These results indicate that, in addition to soil K, other plant growth factors should be included in regression equations to predict winter wheat response to K in Montana.

INTRODUCTION

The 1 N NH_4OAc extraction procedure for soil potassium (K) has been found lacking in its ability to predict crop response to fertilizer K on Montana soils (Skogley, 1971). Crop yields may increase due to K application one year, but show a decreased yield the following year on an adjacent strip, despite the fact that the plow layer may contain 250 ppm or more extractable K per acre (greater than 500 lb K per acre six-inch depth). Doll and Lucas (1973) indicated most field crops do not respond to K fertilizer when the exchangeable soil K levels are greater than 250 lbs per acre. A barley crop would utilize only 90 lb of K per acre if it yielded 62.5 bu of grain, 3000 lb of straw and 3000 lb of roots per acre, all containing 1.0% K. Sixty pounds of this would be returned to the soil. This indicates that Montana soils should be well supplied with K for adequate crop yields. Why then, do crops grown in Montana soils often respond to K fertilizer?

An expanded state-wide research effort was initiated in 1972 to help resolve this apparent anomaly. The ultimate goal of this research was to develop a system for recommending K fertilizer for major Montana crops. Development and calibration of a new test, or recalibration of the presently used ammonium acetate K soil test method was a major part of this objective. Field crop yields, climatic data, and soil samples from research sites were to be evaluated in an effort to achieve this goal.

REVIEW OF LITERATURE

Agricultural soils commonly contain 1 to 2% total K. The amount present is usually greater than that of any of the other plant nutrient elements obtained from the soil minerals with the possible exception of calcium in semiarid to arid regions. Attoe and Truog (1945) described three major forms of soil K in relation to plant use. Exchangeable, organic, and water-soluble K constitute about 1% of the total and are considered the readily available (commonly called "exchangeable") form. The moderately available form includes fixed and biotite K (commonly called "fixed"). This form contains 1 to 2% of the total, is in equilibrium with the readily available soil K, and may revert to muscovite and/or feldspar K which are included in the difficultly available form. Difficultly available K (frequently called "native") contributes the remaining 97 to 98% of the total; this slowly becomes available through weathering processes.

Factors which influence exchangeable soil potassium.

Time of sampling. Childs and Jencks (1967) and Barrett, Engle, and Smith (1973) indicated that levels of exchangeable K increase during the fall, reach a maximum in the winter, and decrease during late spring and summer. Barrett, et al. (1973) found that a grass covered Cookport soil varied in exchangeable K from 225 to 425 ppm while the Gilpin soil, producing mixed pasture, varied from 45 to 150,

and 75 to 200 ppm K on the north and south slopes respectively, during one year. Rouse and Bertramson (1949) revealed that spring samples released more K on drying at 70 C than did fall samples from 20 of 23 soils.

Equilibrium levels of potassium. Bray and DeTurk (1938) found that release of K from fixed forms during moist storage follows soon after the removal of all, or part of the exchangeable K. Under the same conditions, but where no K has been added or removed, release of K from fixed forms is very small or negligible. Addition of K under moist conditions results in part of the exchangeable K being converted to the fixed form. They also showed that heating soils at 200 C resulted in release or fixation of K, depending on the initial level of this element. From these experiments they postulated that soil K is in equilibrium between exchangeable and fixed forms. This preserves K from leaching and luxury consumption by the plant, yet provides for its release as it is used by the crop. Pearson (1952) reported there was no apparent relationship between the capacity of soils to release K from fixed forms and the total K content. Of the soils he studied, those containing montmorillonite released fixed K more readily than kaolinite. McEwen and Matthews (1958) also established that oven-drying soils caused exchangeable K to be converted toward the equilibrium level. They reported that exchangeable K in the oven-dry soil was closely correlated with the K supplying power

of the soil.

In short-term cropping of undried soils, Tabatabai and Hanway (1968) found that plant uptake reduced exchangeable K by amounts comparable to those taken up by plants when the initial level of exchangeable K was high. In soils with low initial levels of exchangeable K, plant uptake caused little or no change in the amounts of exchangeable soil K. These results also support the equilibrium concept proposed by Bray and DeTurk (1938).

Oxygen. Larson (1954) reported that sugar beets grown in poorly aerated Montana soils showed K deficiency and contained 31% less petiole K than plants grown in better aerated soils. Harris and Van Bavel (1957) found that there was not a serious decrease in the K content of tobacco until the soil oxygen content decreased below 10%. An increase in K concentration in bluegrass with increased oxygen supply was reported by Letey, et al. (1964). This correlation of plant content of K versus soil oxygen may be due primarily to the physiological growth processes of the plants and nutrient absorption as they are related to the soil oxygen supply.

Moisture. Laboratory studies by Barrett, Engle, and Smith (1973) indicated that samples which had been stored for 21 days at different moisture contents showed essentially no change in available K until the moisture level dropped to 10%. At this point the K level dropped

abruptly, approaching that of air-dry samples. Brown (1953) discovered more K was exchanged from soil to hydrogen-saturated resin as moisture was increased, but this moisture effect varied with different soils. Jenne, et al. (1958) found that corn plants with low moisture supply contained only 71% as much K as plants receiving adequate moisture. Mederski and Wilson (1960) established a correlation coefficient of .97 between the percentage K in corn plants and soil moisture percentage. An inverse relationship between the amount of seasonal rainfall and the response of crops to added K was observed on wheat, potatoes, and canary grass by Van der Paauw (1958) in the Netherlands, and on corn and soybeans by Barber (1959) in Indiana. The smallest reponse to applied K occurred with the largest amount of rainfall, so it appears that the availability of soil K was increased by increasing moisture. Hanway and Scott (1957) found that K uptake by plants increased as soil moisture increased.

Mederski and Wilson (1960) have shown by split root experiments that the uptake of K from soil increases with increasing soil moisture content. Thomas and Hipp (1968) suggested that the above results are inconsistent with evidence that dry soils generally contain a greater concentration of exchangeable soil K. They suggest an explanation will be found in the relative increase of K compared to calcium (Ca) and magnesium (Mg) in the soil solution as moisture content increases, and in the similar effect on the K diffusion rate. However, Thomas

and Hipp were considering dry soils. If soils were dried sufficiently to release substantial amounts of K the plants were probably irreversibly desiccated.

Mengel and Van Braunschweig (1972) found that for all K treatments, the highest yields and largest quantities of K taken up by corn shoots were obtained at pF 2. With increasing water tensions (pF 2.4 and 2.7) the yields and quantities of K taken up by the plants declined sharply. The yield level at the various pF treatments increased with an increase in exchangeable K in the soil. They found a linear, highly significant relationship between the K diffusion rates and the total K uptake by the plants. By a cation resin extraction procedure Haagsma and Miller (1963) found that decreasing soil moisture content decreased the rate of K release at higher temperature, but had no effect in the 5 to 25 C range. This moisture effect apparently resulted from an influence of K movement from the clay to the resin particle, rather than on release of K from the soil particles. Fried, Hawkes, and Mackie (1959) reported that rubidium (Rb) is a good indicator of K behavior in soils. Place and Barber (1964) showed that the rate of Rb-86 diffusion was increased by increasing soil moisture. This increased diffusion rate resulted in increased Rb uptake by plants.

Organic matter. The affinity of organic matter (O.M.) for K is low compared to that for Ca and Mg. McGeorge (1931) found that the

electrical conductivity of O.M. saturated with K was extremely high, indicating near complete ionization. Field experiments by Mehlich (1946) and Spencer (1954) with soils high in O.M. tended to confirm the view that K is loosely retained by the negative sites on O.M.

Texture. Olsen and Shaw (1943), Stewart and Volk (1946), MacLean (1961), and Tabatabai and Hanway (1968) have shown that the amount of K released from fixed forms tended to increase with increasing clay content of soils. Olsen and Shaw (1943) reported that K removal by chemical and plant methods increased as particle size decreased. The lower the readily available K in the soil the greater was the proportion of K taken up from the silt fraction by plants. Under some conditions field applied K may accumulate in significant quantities even in coarse-textured soils (Pearson, 1952). Doll and Lucas (1973) suggested that K is more readily available in coarse-textured soils than in fine-textured soils. Sands, however, were found to be only 3% and silts 9% as effective as clays in K supplying power.

Results of a soil fractionation study by Rouse and Bertramson (1949) revealed that the less than one micron clay fraction held the most K supplying power per unit of material. However, the silt and sand fractions in some soils supplied nearly half of the K supplying power due to the deficiency of clay in the samples. Phillips (1973) found significant positive correlations between soil clay content and extractable K. Decker (1973) analyzed 1081 soil samples and found

correlation coefficients of -.43, .08, and .45 for extractable K versus total sand, total silt, and total clay, respectively. Tabatabai and Hanway (1969) reported the mineral levels of readily available K are directly related to the less than 2-micron clay present. Exchangeable K increased 1.14 ppm for each 1% increase in the clay. MacLean (1960) revealed that values for percent uptake of K by plants were related to intensity of soil K as well as to exchangeable K in soils containing less than 16% clay. At greater than 16% clay, exchangeable K was the only measurement of soil K that was correlated with percent uptake. Sands released very little K, silts released from 15 to 50%, whereas clays contributed 40 to 80% of the total K released from soils studied by Merwin and Peech (1950).

Cation exchange capacity (CEC). Bear, Prince, and Malcolm (1944) evaluated the K supplying power of soils by intensive alfalfa cropping. One soil with a CEC of 16.5 meq/100 g released 108.7 meq of K/100 g. Stewart and Volk (1946) found that the CEC was not related to the amount of K extracted by the plants. Beckett and Craig (1967) emphasized that equilibrating a soil sample in a dilute solution of calcium chloride containing no K, must produce a solution in which the activity ratio is less than the true value for the soil by amounts varying between 10 or 50% according to the CEC of the soil.

Mineralogy. In micaceous clay minerals (muscovite, biotite, illite, hydrobiotite, and vermiculite) a large part of the negative

charge is balanced by K ions. This source of K is a part of the mineral structure (Thomas and Hipp, 1968). Salt solutions normally do not extract this reserve supply of potassium. Rich and Black (1964) proposed that small amounts of exchangeable K are frequently located in wedge shaped spaces in the interlayers of weathered micas. Potassium may be fixed in these wedge shaped zones. Islands of iron or aluminum "interlayers" or "props" would inhibit K fixation, but would allow the removal of K from wedge shaped positions by cations the size of K.

When most of the K is weathered out of trioctahedral micas the mineral becomes vermiculite (Barshad, 1948). With Ca and Mg replacing K in the layers there are fewer wedge shaped zones and the exchangeable K exists in fully expanded layers. When large quantities of ammonium (NH_4^+) are added to such a clay, it causes the edges to pinch down, trapping whatever cations are between the layers. Arnold (1958) evaluated the release of K by clay minerals to a hydrogen (H) resin. The dioctahedral minerals release little of their fixed K to the H resin, while the trioctahedral minerals suffered considerable loss of K. Biotite released all of its K in about 10 days. Phlogophite released a large amount of K to the resin in a few days, but the attack continues more slowly than with biotite. Muscovite and "hydrous mica" which are known to release K to crops slowly, are comparatively resistant to H resin attack.

Potassium release from muscovite, microcline, glauconite, and illite was increased by fineness of grind (Rouse and Bertramson, 1949). There was no relationship between the K supplying power and the height or area of the X-ray diffraction peak in the sand or silt fraction, nor for muscovite or illite in the coarse clay. The K supplying power was related to the area under the peak of the medium and fine illite clays. Doll, et al.(1965) reported that K in the fine clay could not be released until the activity of K in the surrounding solution was reduced below the activity of K in the fine clay fraction. The larger the clay size, the more K was released from it.

Soil pH. Soil pH is an indicator of the K fixation power of clay minerals. Williams and Jenny (1952) revealed that the release rate of fixed K is a direct function of pH. Hydrogen was the most effective K replacing cation. The release rate of K greatly increased above the exchangeable level at pH values less than 3. Martin, Overstreet and Hoagland (1946) found little K fixation in soils with a pH below 2.5. From 2.5 to 5.5 there was a rapid increase in K fixation. Above 5.5 the amount of fixation increased more slowly. Volk (1934) reported that K fixation against NH_4 extraction increased markedly when pH was elevated to 9 or 10 with sodium carbonate. At pH values below 3.5 the hydronium ion becomes an effective K replacer (Coleman and Harward, 1953). Rich and Obenshain (1955) emphasized the importance of interlayer hydroxyaluminum on fixation of K. The

increase in K fixation between pH 5.5 and 7.0 can be attributed to decreased numbers of hydroxyaluminum polymer cations which can effectively block collapse of the clay (Rich, 1960). Murdock and Rich (1965) observed a severe K deficiency in oats grown on a limed soil high in muscovite and containing very little hydronium ion and no ammonium. This is commonly termed lime induced K fixation and may be caused by poor replacement of K by Ca and Mg in dioctahedral micas (Thomas and Hipp, 1968).

Temperature. A reduction of exchangeable K following freezing of soils with high levels of exchangeable K was observed by Fine, Bailey, and Truog (1942). Soils of moderately low fertility and soil which had received moderate amounts of K fertilizers tended toward higher levels of exchangeable K after freezing. They suggested that illite may be the mineral responsible for fixation of K during freezing. Barrett, et al. (1973) reported that freezing a Cookport soil continuously at 18 F fixed nearly 85 ppm K but had no effect on Gilpin soil. However, alternate freezing and thawing released K from both soils. Haagsma and Miller (1963) studied the effect of temperature on the release of K to a strongly acid H resin. The release of fixed K was found to increase with increasing temperature from 50 to 80 C. The release was less from 5 to 50 C. Wallace (1957) reported the K content of barley increased when the soil temperature was increased from 12 to 22 C, but suffered a decrease when temperature was increased to

32 C. This decrease may have been caused by a dilution effect.

Potassium levels. Total K in soils is of no value as an index to the availability of K to plants (Pratt, 1965). Tabatabai and Hanway (1969) describe the minimal level of soil K as that level at which plants become K deficient. Plants may take up K from soils at this minimal level for an extended period without further reducing the exchangeable K content of the soil. Twenty-four times more K was removed by plants in a 758 day cropping period than was initially present in the soils as exchangeable K. Woodruff (1955b) reported adequately watered corn grown on Putnam soil was K deficient at 120 to 140 lbs of soil K per acre, whereas 200 to 300 lbs of K per acre was adequate. Doll and Lucas (1973) point out that most field crops do not respond to K fertilizer when readily available K is greater than 170 pp2m for sands and loamy sands, 200 pp2m for sandy loams and loams, and 250 pp2m for silt loams and clays. They stated that unpublished data from Illinois indicated that up to 350 pp2m is needed for a calcareous, imperfectly drained Drummer-Harpster silty clay loam. A reasonable hypothesis may be that soils in cooler climates must supply greater levels of readily available K to short growing season plants.

Soil depth sampled. Subsoil K can be used to improve the estimation of K availability to plants grown in the field (Hanway, et al. 1961, 1962). They reported subsoil samples were consistently lower

in exchangeable K than were corresponding surface samples.

Drying. The influence of drying on soil K has been researched by many people, and will be covered in detail later.

This review of factors which influence exchangeable K demonstrates the many variables which must be considered when researching soil K in relation to crop yields. Some of these variables are: (1) sampling time, (2) equilibrium levels of K, (3) oxygen content, (4) water, (5) organic matter, (6) texture, (7) cation exchange capacity, (8) mineralogy, (9) pH, (10) soil and air temperature, (11) sampling depth, and (12) sample handling, (e.g. effect of drying and grinding). In addition to these, MacLean (1960) found a greater concentration of K in solution following KCl than following K_2CO_3 treatments. These are the more commonly researched variables. Biological, genetic, and management factors also influence plant response to soil potassium.

Prior attempts to develop a reliable potassium soil test.

According to Hoagland and Martin (1933), when the amount of replaceable soil K is high the major portion of the K absorbed by the crop may be balanced by loss of replaceable K from the soil. As cropping continues, the proportion of K derived from non-replaceable forms grows larger until a point is reached at which no further loss of replaceable K can occur. At this point the solubility of the non-replaceable form determines the supplying power of the soil. In the

majority of cases, the K present in soil solution at any given moment was equivalent to a small percentage of the total amount of K absorbed by the crop.

As stated in earlier sections of this review, the response of plants to fertilizer K has been shown to be dependent on many soil and climatic factors. The following section of this review will show that a majority of the previous attempts to develop a K soil test have been correlated only with plant uptake of K in greenhouse pot culture experiments. The K composition of the crop consistently reflects the supplying power of a soil for K under suitably controlled conditions (Hoagland and Martin, 1933). However, until these methods have been calibrated with field crop yields, influenced by the many growth factors and potassium supply regulating mechanisms, they should be considered incompletely developed techniques for predicting crop response to applied K.

Early attempts to develop a potassium soil test. Wheeting (1930) published a review of the methods for the determination of available K in soils. According to Wheeting, Dyer, in 1894, first used a 1% citric acid solution to extract soil K. Working with Rothamsted soils, he attempted to correlate the amounts of essential elements extracted by citric acid with the actual yields of crops. Dyer (1901) decided that if less than 10 mg of K are dissolved from 100 g of soil, K fertilization was necessary. Gerlach (1896) and Schloesing (1897)

proposed the use of carbonated water as a soil extraction solvent. Maxwell (1899) employed 1% aspartic acid and recommended its use. Hall and Plymen (1902) compared weak acid solvents and agreed citric acid was best. Up to 1920, several investigators tried variations of, and comparisons with Dyer's method, but agreed 1% citric acid was best for predicting response of crops to K (Wheeting, 1930).

Neubauer (1923) devised a plant-pot culture test for determining plant available soil K. He grew a large number of rye seedlings in a small mass of soil for 18 days. The plants were ashed and analyzed for K. This method stimulated research by many scientists. Engels and Hirschberger (1924) proved the method was applicable to field conditions. Several soils yielding less than 18 mg of K_2O provided crop responses to fertilizer potassium. Thornton (1931) utilizing the Neubauer technique, concluded that 10 mg K_2O/100 g soil is the lowest amount that suffices for general farm crops in Indiana. Reitemeier, et al. (1957) determined a correlation coefficient of .90 for K uptake by clover versus K release from the same soils by the Neubauer method.

Wheeting (1930) compared the Neubauer test, distilled water, carbonic acid, citric acid, ammonium chloride, and steam as extraction techniques on Wisconsin soils. He concluded the Neubauer test detects quite accurately the K deficiencies of soils. Of the solvents used, ammonium chloride most closely simulated plant activity in removing

available K.

The Aspergillus niger method for measuring available K in soils was researched by Mehlich, Truog, and Fred (1933). They concluded that the test is simple and reliable and may be used in a practical way for the determination of potash needs of plants.

Mitscherlich (1930) utilized a pot culture technique to evaluate K in soils by growth of oats. He devised the equation:

$$b = \frac{\log A - \log(A-y)}{C}$$

where A = maximum yield with the largest addition of fertilizer, expressed as 100%; y = yields with no fertilizer added, expressed as a percentage of maximum yields; and C is a constant or growth factor equal to about 31.2 lb per acre.

Acid extraction of soil potassium. According to Wheeting (1930) Konig, Hasenbaumer, and Kroger (1923) reported that Liebscher extracted soils with a 10% solution of hydrochloric acid. If 500 mg of K_2O can be dissolved from 100 g of soil, no potash fertilization is necessary, but if only 150 mg are soluble, a definite potash requirement is indicated. Attoe and Truog (1945) studied the availability of fixed K versus readily available K by soil extraction with dilute HCl and growth of corn and oats in pots. They extracted soils for 1 hour at 25 C and removed 90% more K than was originally exchangeable. Soils which contained 164 lb of exchangeable K per acre yielded only

62% as much corn and oat dry matter after extraction of the soil with a salt solution. Crops grown on soils extracted with N HCl yielded only 20 and 18% compared to the unextracted soils. Garman (1957) leached soils with 0.01 N HCl and trapped the leachate K on a cation exchange resin. Potassium removal by five crops compared to that removed by 1, 3, and 10 liters of 0.01 N HCl gave highly significant correlation coefficients of .94, .96, and .96, respectively. The correlation coefficients for ammonium acetate (NH_4OAc) extraction vs. K uptake was .95, for N nitric acid (HNO_3) extraction, .92, and for sodium acetate (NaOAc) extraction, .94. A plot of volume of HCl leachate vs. cumulative K removed produced a curve with three distinct slopes. According to Garman (1957) the initial fraction of K removed represented the water soluble and easily replaceable K. Exchangeable K by N NH_4OAc represented the upper limit of this abrupt slope, after which the fixed K was removed more slowly. The upper, slightly increasing, portion of the curve indicated interlayer K removed by the 4 through 10 liter volumes of 0.01 N HCl. MacLean (1968) confirmed Garman's finding of release of fixed K by continued leaching with 0.01 N HCl. Conyers and McLean (1969) revealed that 0.5 N HCl was one of the best extractants of soil K when correlated with plant uptake of this element. Potassium extracted by leaching soils with 0.01 N HCl versus K uptake by plants gave a correlation coefficient of 0.60 (MacLean and Byrdon, 1971).

Various concentrations of HNO_3 have been employed to estimate plant available K in soils. The K supplying power of Indiana soils was investigated by Rouse and Bertramson (1949) using a soil:solution ratio of 1:10 and a boiling time of 10 min for N HNO_3 extraction. Potassium extracted vs. uptake of K by greenhouse cropping gave a correlation coefficient of .96 for 20 soils. Garman (1957), Reitemeier, et al. (1957), and Hunter and Pratt (1957), found correlation coefficients of .92, .94, and .84, respectively, for K release by N HNO_3 vs. K uptake by cropping. Pope and Cheney (1957) stated that total K extracted ($r = .96$), and release of K from nonexchangeable forms by boiling HNO_3 ($r = .94$), appeared to be better indexes of K uptake by clover than exchangeable K prior to cropping. The correlation between K release from nonexchangeable forms during cropping and the amount of exchangeable K before cropping was very low ($r = .17$). Conyers and McLean (1967) reported that N HNO_3 extraction of soil K was one of the better extractants for predicting K uptake by crops. Although N HNO_3 extractable K was highly correlated with K removed by exhaustive perennial ryegrass cropping in the greenhouse, the plants removed five times more soil K than did the HNO_3 (Oliveira, Ludwick, and Beatty, 1971). Even though exchangeable K and K removed by strong acids were highly correlated with plant uptake ($r = .74$ and .88 respectively), all extractants greatly underestimated actual plant available K under intensive cropping. Total soil K did not

significantly correlate with plant uptake (r = .21 on 21 soils). Ramamoorthy and Paliwal (1965) failed to obtain a significant calibration between K extracted by 0.5 N HNO_3 and percentage crop response.

Extraction with 0.1 N NH_4OAc + 0.05 N sulfuric acid (H_2SO_4) at a 1:10 soil:solution ratio was used by Matthews and Smith (1957) to evaluate the readily available K in soils in comparison to K removed after 17 hours leaching with water. Water percolation for 17 hours removed equal or greater amounts of K. Hunter and Pratt (1957) stated that with the volume of research that has been done with respect to plant availability of K, it has become increasingly obvious that a measure of only one form of soil K, by itself, cannot serve as a sufficient criterion for assessing the plant available K of all soils. They extracted soils with varying concentrations of H_2SO_4 and leached the extracted soils with 15 ml portions of 0.1 N H_2SO_4 to 100 ml volume. The K extracted by a 1.4 N H_2SO_4 solution versus K uptake by alfalfa was highly correlated (r = .99, nine samples). Ekpete (1972) using potted millet (Pennisetum spp) and sorghum (S. vulgare) reported that K extracted with 6 N H_2SO_4 gave the best indication of dry matter yields when K was not applied (r = .91), and of the percentage response when K was applied (r = -.93).

Wilcox (1937) developed a hydrofluoric-perchloric acid digest method for total soil K which could be analyzed by trisodium cobaltinitrate in the presence of nitric acid, as a gravimetric or

titrimetric procedure. Extraction of K from soils with a solution of sulfuric-perchloric-hydrofluoric acid (H_2SO_4-$HClO_4$-HF) failed to produce a significant correlation with plant uptake of K (Conyers and McLean, 1969). Oliveira, et al. (1971) also found that total soil K did not significantly correlate with plant uptake of K ($r = .21$).

Ramamoorthy and Paliwal (1965) failed to develop a calibration between 1% citric acid extractable K and percentage crop response. Conyers and McLean (1969) reported that K removed by NH_4OAc, HNO_3, HCl, and sodium tetraphenyl boron ($NaBPh_4$) from soils prior to cropping, correlated better with amounts of K uptake than did amounts of K removed by 0.5 N magnesium acetate [$Mg(OAc)_2$], saturated paste extraction, HNO_3-NH_4OAc, and $NaBPh_4$-NH_4OAc. Ramamoorthy and Paliwal (1965) reported a poor calibration between percentage crop response and K extracted by Morgan's solution (1941, sodium acetate and acetic acid, pH 4.0).

Salt solutions for extraction of soil potassium. Volk and Truog (1934) in an attempt to develop a rapid chemical method for determining the potash needs of soils, studied the relation between readily available and exchangeable potash and methods of extracting the latter. They found N NH_4OAc, pH 6.8, was more satisfactory as an extractant than other salt solutions and dilute acids. The use of 15 parts of this extractant to 1 part of soil in 5 min of intermittent hand shaking resulted in an average extraction of 96% of the exchangeable

potash. Analysis of K_2O involved precipitation and titration as the cobaltinitrite salt. One analyst could do 25 to 30 determinations per day. Ten mg per 100 g of plow layer soil was set as the minimum amount of K_2O to suffice for good growth of corn, small grains, and clover in the north. They stated that the minimum level would be modified by subsoil K_2O, crop being grown, length and temperature of growing season, and the number of cloudy days. To this day a modified version of this procedure is the one predominantly used in the United States for exchangeable soil K. Hipp and Thomas (1968) obtained a correlation coefficient of .89 between percent K in leaves of grain sorghum plants and saturated paste solution K + log (1 + exchangeable K) in the field study. Rouse and Bertramson (1949) stated it is generally agreed that the best evaluation of the K supplying power of soils is the amount of nonexchangeable K that can be extracted by plants from a soil by continuous cropping. They found a very poor correlation ($r = .18$) between the K supplying power by the plant method and the exchangeable K in the soil by the N NH_4OAc method. MacLean and Simon (1958) attempted to evaluate the K supplying power of three Ohio soils by extraction with N NH_4OAc for seven-day intervals to seven-weeks following the initial NH_4OAc extraction. They found that the Hoytville and Clermont soils released more K over the seven-week extraction period than that which was removed by the initial extraction.

In laboratory comparisons of NH_4OAc versus other extractants, Rich and Black (1964) found that 150 ml of $Mg(OAc)_2$ removed only 74% of the K removed by NH_4OAc. More K was removed by $MgCl_2$ than by $Mg(OAc)_2$ in the first 25 ml. Magnesium chloride eventually removed more K than did NH_4OAc. This suggests that H produced by exchange or hydrolysis may exchange for K. Rich (1964) demonstrated that the extent of K exchange is determined by the diameter of the exchanging solvated cation and by the pH of the system. Potassium exchange by monovalent or divalent cations increased from 0.0 to 0.36 meq per 100 g with decreasing effective cation size. Exchange of K by H_3O ions, produced by the reaction of the nonbuffered $MgCl_2$ with the acid soil, probably accounted for most of the K exchange. Ramoorthy and Paliwal (1965) determined that heated 0.5 N HNO_3 removed more K than NH_4OAc. Matthews and Sherrell (1960) found that 0.1 N NH_4OAc released the same amount of K as did the 1.0 NH_4OAc on Ontario soils.

Schulte and Corey (1965) reported that extraction of soils with $NaBPh_4$ provided a better estimate of plant available K by continuous cropping ($r = .99$) than did N NH_4OAc. Beckett and Nafady (1967) reported that sufficient K for 100-years cropping was removed from the interlayers of illite by extraction with $NaBPh_4$.

An attempt was made by Bray (1932) to devise a better K soil test. He extracted 2.5 g of air dry soil with three parts of 5.33 N HNO_3 plus seven parts of 5.08 N NaOAc with stirring for 30 sec.

The K in an aliquot of the filtrate was precipitated as cobaltinitrite and the turbidity developed was compared to that on a chart. He later switched to extraction with 25% sodium perchlorate ($NaClO_4$) (Bray, 1936). Peech, et al. (1947) reintroduced the use of NaOAc for extraction of soil K. Peech and English (1944) developed a NaOAc-HOAc extraction method for soil K. Matthews (1952) showed that the concentration of K extracted by NH_4^+ alone was less than the total amount extracted by Ca^{++} followed by NH_4^+ even though the total volume of solution leached through the soil was the same in both instances. MacLean (1968) utilized a 0.5 N NaCl solution for sodium (Na) extraction of fixed soil K. A correlation coefficient of .76 was obtained by MacLean and Brydon (1971) for K extracted by leaching soils with 0.1 N $BaCl_2$ versus K uptake by plants. A 0.001 M solution of $SrCl_2$ for extraction of K from soils has been devised by Goedert and Corey (1973). Parameters derived from this system include intensity and capacity factors of K in the equilibrium solution. Conyers and McLean (1969) evaluated the saturated paste extraction technique for K. They concluded this method was inferior to procedures which extract a greater conc of K. A highly significant calibration between water soluble K in the soil versus greenhouse yields was obtained by Hood, Brady, and Lathwell (1956). For the Ladino clover crop having a short growing season and hence a short period of nutrient absorption, this procedure accounted for 49% of the variation in yields, compared to

16.4% accounted for by exchangeable K. MacLean (1960) determined the K intensity of 27 surface soils by extracting cations with a 1:2 soil:water suspension followed by computation of the ratio pK - $\frac{1}{2}$p(Ca+Mg). The values for percentage K uptake by oats were significantly correlated with those for intensity of soil K. Matthews and Smith (1957) found the total K taken up by 8 crops of alfalfa tops and roots was highly correlated with the total K released during 100 hours of water percolation through the soils (r = .91). Bear, Prince, and Malcolm (1944) showed it possible to extract 108.7 meq K/100 g from a soil having a CEC of 16.5 meq/100 g. They stated these data verified the previously known fact that the most reliable index of the capacity of the soil to supply K to the crop is not the total soil content of K but the amount that exists in the exchangeable form. The soils studied varied enormously in their capacity to renew the amount of exchangeable K from reserves.

However, these researchers did not discuss the importance of exchangeable plus fixed K together. Olsen and Shaw (1943) found that yields increased as a straight line function of the increase in percentage saturation of the exchange complex with bases. Reitemeier, et al. (1957) developed a correlation coefficient of .96 for K uptake by Ladino clover versus release of K from soils by 30 day electrodialysis.

Cation resin for extraction of soil potassium. Arnold (1958)

reported that a sodium saturated IR-120 "Amberlite" resin takes up approximately the amount of K that is NH_4^+ exchangeable. Potassium extracted by H-resin can continue to increase over a month or more of intermittant shaking. Haagsma and Miller (1963) utilized Dowex 50-W-X8, +2% on a 16-mesh and the remainder passing a 40-mesh screen, in a 1:1 soil + resin:water ratio to extract soil K. They found nonexchangeable K was not released to Na- or Ca-saturated resin, but that K release increased linearly with the proportion of H-saturated resin added in combination with Na- or Ca-saturated resin. It could not be determined whether the mechanism of release involved an exchange of H or Al for K in the mineral lattices or an acid decomposition of the K-bearing minerals. Pratt (1951) was one of the first soil chemists to utilize cation exchange resin to determine nonexchangeable soil K. He calculated K released from nonexchangeable forms by subtracting the original exchangeable K for the soil from the exchangeable K found on the resin following incubation with the soil.

Normal HNO_3 extracted a greater amount of K than did a corn crop or a H-amberlite resin (Schmitz and Pratt, 1953). Potassium released to the HNO_3 gave the highest correlation with K release during cropping (.93). The difference between K released to HNO_3 and to the resin as indexes to K release to plants however, was not statistically significant. Both these K extraction methods were significantly better, statistically, than the exchangeable K before cropping as indexes

of K release by cropping (.93 and .86 vs. .63, respectively, on 18 samples).

Massee (1973) reported that K diffusion to a neutral mixture of Amberlite IR-120H and IRA-4100H resins appeared to be a valuable technique for predicting short-term K uptake by plants. MacLean (1961) extracted soils by shaking a mixture of 2 g of Amberlite IR-120 H resin with 1 g of soil for one week. Potassium in the mixture was replaced with N NH_4OAc without separation of the soil and resin. The difference between K extracted by resin-NH_4OAc and K extracted with N NH_4OAc was termed nonexchangeable K. Nonexchangeable K was significantly correlated with uptake of K by plants. The amounts of nonexchangeable K taken up by H resin in suspension was usually lower after, than before cropping. Barber and Matthews (1962) utilized a multiple quadratic regression to analyze the predictive ability of NH_4OAc exchangeable K and moderately available plus exchangeable K by resin-NH_4OAc extraction versus yield increase. They reported that this method, on the average, for corn, wheat, oats, and potatoes, accounted for 56% of the variability in response. However, their methods are not suitable for routine soil testing due to the length of the extraction time.

Cation effectiveness for K release from soils. Table 1 demonstrates there is little agreement among researchers as to which cation is the most effective replacer of soil K. Obviously, the effectiveness

of a cation to replace soil K depends on the clay properties. Barshad

Table 1. Relative cation effectiveness for replacing soil K

Relative cation effectiveness	Investigators
Ba>Mg>Na>Ca	Barshad (1954), Calif.
Na>H>NH_4>Mg>Ca>Ba	Merwin and Peech (1950), N.Y.
Ca>H>NH_4>Al	Pratt, Simon, and Volk (1956), Ohio
Ca≈Mg	Thomas and Hipp (1968), Texas
H>Na>Li>Ca>Mg>NH_4	Williams and Jenny (1952) Calif.

(1954) reported the replaceability of interlayer K with cations other than NH_4^+ is easier, the smaller the interlayer charge and the smaller the particle size of the mineral. The soils investigated by Merwin and Peech (1950) failed to release K to 0.5 N barium and calcium acetate solutions and effectively removed the trace of K present as an impurity in these salt solutions. They reported that sodium acetate and acetic acid continued to extract K, but that ammonium acetate gave a very clear-cut separation of the exchangeable K. Pratt, Simon, and Volk (1956) found that increasing Ca saturation gave increases in K release. According to Williams and Jenny (1952) the rate of release of nonexchangeable K is a direct function of pH, with H being the most effective K replacing cation. This is in agreement with the findings of Haagsma and Miller (1963), reported earlier in this review.

Potassium percentage of soil cation exchange capacity.

Ramamoorthy and Paliwal (1965) found that the degree of K saturation of the CEC was significantly calibrated (5% level) with percentage crop response. This is contrary to the results of Stewart and Volk (1946) that the percentage K saturation of the CEC did not show a definite relationship to the amount of K extracted by plants. Hossner and Doll (1970) reported that data which use percentage K saturation of the CEC have not been adequate for developing fertilizer recommendations on soils varying widely in texture and organic matter. When used with relatively uniform soils, percentage saturation data have been more useful.

Ionic equilibria and the potassium supplying power of soils. Schofield (1947a) introduced the ratio law governing the equilibrium of cations in the soil solution. According to Woodruff (1955a) cations in solution exist at chemical potentials which are related to the activities of the cations by the familiar expression, $\mu = RT\ln a$, where μ = chemical potential, R = universal gas constant, 1.987 cal/mole degree, T = the absolute temperature, and "a" is the concentration in moles per liter of the cation in solution. The transfer of one mole of a cation from one chemical potential to another involves a change in molar free energy. If the standard state of a cation is one molar, the change in free energy associated with the transfer of one mole of a cation from the standard state to a solution in which its activity is "a" moles per liter, is $dF = RT\ln a$. In a

heterogeneous system such as soil, electrolytes may be used as a device with which to evaluate the energetics of cation exchange between the clay and the standard state. Woodruff (1955a) gave this example:

$$\Delta F = 1364 \log \frac{(K)}{(Ca)^{\frac{1}{2}}} \; ; \quad (\;) \text{ denote activity}$$

Activity may be caluclated by multiplying the ion concentration in the dilute solution by the activity coefficient, $a = [c]f$, where $[\;]$ denote molar concentration. Compute the activity coefficient "f" as follows:

$$\log f = -.509 \, Z^2 \, \mu^{\frac{1}{2}}$$

where Z is the ionic charge and μ is the ionic strength computed as follows:

$$\mu = \tfrac{1}{2} \Sigma \, m \, Z^2$$

where m is the molar concentration of the ions in the reaction. This treatment of the computation of activities is presented by Morris (1968) who states that the activity coefficient equation above is applicable only to aqueous solutions whose ionic strength is less than about 0.01 M. Woodruff (1955b) reported energies of exchange of Ca with K ranging from -3500 to -4000 calories were associated with K deficiencies in plants, -2500 to -3000 cal represent a suitable balance between Ca and K, and -2000 cal or less were associated with excessive amounts of K in relation to Ca in soils. Adams (1971) discussed the effect of ion pairing on ionic concentrations and activities in soil

solutions. In general the effect of ion pairing of cations with monovalent anions can be neglected. Multivalent cations pair extensively with sulfate and HPO_4^{2-} and with HCO_3^- at high pH or at above normal CO_2 pressure. This pairing must be taken into account when computing ionic activities.

In 1958, Taylor stated that the ratio law relationship between the K and Ca concentration, $(K)/(Ca)^{\frac{1}{2}}$ = constant, is found to be strictly obeyed only in soils of low K status. Because Ca and Mg show very similar exchange properties it is assumed that they may be aggregated to give a complex activity ratio such as $(K)/(Ca+Mg)^{\frac{1}{2}}$ (Nichol and Turner, 1957 and Turner and Nichol, 1958). In an effort to justify the use of pooled activities, Beckett (1964b) studied Ca and Mg exchange in soil. He concluded that except for specific sites, Ca and Mg are held with approximately equal attraction by exchange surfaces. As a consequence, $pK - \frac{1}{2}p(Ca+Mg)$ is independent of (Mg)/(Ca) over a wide range of [Mg]/[Ca]. If considerable amounts of Ca and Mg are held at specific sites, then the conc of these ions in the equation Ca/Mg x Mg/Ca = K are inflated by quantities beyond the scope of the equation. Beckett (1964a) showed that the activity ratio (AR) may be expected to provide a satisfactory measure of the ruling chemical potential of labile K in a soil, provided it is not used to compare soils of widely different Ca (and Mg) status, or a few soils of which the AR is not independent of the concentration of the soil

solution. Tinker (1964a) explains that although we are interested in the activity of a single ion we must deal with an activity ratio so that the other ion of the pair becomes a reference ion which should be the dominant ion in the soil, and if a range of soils are to be compared, the same ion should be dominant in all of them. Tinker (1964b) stated that the AR_{Ca} value appears to be most closely comparable with the exchange energies of Woodruff (1955b). Tinker showed that K deficiency occurs somewhere between AR_{Ca} 0.01 to 0.015. This corresponds to -2,700 to -2,500 cal/mole, which is higher than Woodruff's estimate of -3,500 cal/mole. Beckett (1964a) lists five complications: (1) The AR provides a measure of the potential of K labile at the time of measurement so that after prolonged cropping the potential of the pool of labile K may be lower than that of the soil's reserve of fixed K to which it will revert as this K is released; (2) The AR will not necessarily provide a good measure for comparing soils of widely different Ca status; (3) If the uptake of K is regulated mainly by the presence of an antagonistic ion such as Mg, an AR such as $(K)/(Mg)^{\frac{1}{2}}$ may provide a better measure of the availability of K; (4) The AR is not expected to measure the availability of K in the case of a few soils in which the exchange surfaces exhibit a low density of negative charge; (5) The procedure for measuring the AR must not alter the potentials of the ions concerned. To avoid altering the ion potentials in an acid soil, Schofield and Taylor (1955) proposed the inclusion of

the cube root of the activity of aluminum (Al) along with the square root of Ca and Mg in the denominator. By computing AR in this manner, Tinker (1964b) was able to show a good relationship of oil palm response to fertilizer K in field experiments. However, Wild, Rowell, and Ogunfowora (1969) found that yields of dry matter and uptake depended on the concentration of K rather than on the activity ratio $(K)/(Ca)^{\frac{1}{2}}$ in solution when tested in sand culture experiments with ryegrass and flax.

According to Tinker (1964a), most recent work indicates that ion uptake is from the solution and not directly from the solid phase. Olsen and Peech (1960) presented evidence in favor of plant uptake of ions from solution. Beckett (1964b) and Beckett, et al. (1966) defined the Quantity/Intensity relationship as that between the quantity (Q = fixed and native K) of labile K present and its availability or intensity (I = exchangeable K) as measured by the AR. By equilibrating a given soil with increasing concentrations of KCl in M/100 $CaCl_2$ solution and graphing the results, these researchers described the change in K and AR as the Q/I relation for immediately labile K in the soil. The slope of this curve is termed potential buffering capacity, or the ability of a soil to maintain its K potential against depletion. Beckett and Nafady (1967a) found that the form of the Q/I relation is almost unchanged either by additions of K up to 3750 kg K_2O/ha, by fixation of up to 1900 kg K_2O/ha, or by depletion of the soil of both

labile and some fixed K, equivalent ot 5 to 20-years cropping. Beckett and Nafady (1967b) showed that when large amounts of interlayer K are removed from illite (enough for 100 years cropping) by $NaBPh_4$, there is considerable change in the form of the Q/I relation. These changes are similar to the difference between the Q/I relations of the K depleted and K fertilized plots of the 120 year Broadbalk trial. Zandstra and MacKenzie (1968) defined K potential as the product of the total amount of exchangeable K (-dK) and the potential buffering capacity (PBC). Potassium potential was calibrated more closely to crop responses than the activity ratio measurement and the PBC. It compared favorably with available K. These authors showed the activity ratio and PBC determination were not satisfactory indicators of the K fertility of soils and showed poor calibration with crop response. Generally, the K pool as an index to the amount of available K appears to be a slight improvement over values for exchangeable K, especially in soils with a limited capacity for releasing nonlabile K during the crop growing period (Koch, Orchard, and Summer, 1970). Baker (1971) attempted to apply Woodruff's (1955a) energy of exchange theory as a practical soil test. Baker utilized a soil:solution ratio of 1:10 and a shaking time of one hour, followed by equilibration over-night. The solutions initially contained 0.00024 molar potassium chloride (KCl), 0.00096 molar $MgCl_2$, and 0.0048 molar $CaCl_2$ along with 0.0005 moles of $Ca(OAc)_2$. A change in K value of 0.0001

molar represents 40 ppm soil K. Negative changes in K values represent amounts of K in the soil greater than those required for minimum levels of availability. He concluded that the K requirement of soils could be determined directly from changes in concentration of K in solution, and that the mineralogy, cation exchange capacity and other soil properties need not be measured even though they influence the available K in soils. However, these conclusions were not verified by yield response in field experiments.

Rezk and Amer (1969) approaching K availability from yet another angle, reported that the ratio-product $\bar{K}/k$ accounted for as much as 95.3% of the variation in K uptake by barley plants during 24 days of growth (bars over elements indicate N NH_4OAc extractable in meq/100 g soil and $k = \bar{K}/ Ca+Mg \cdot [Ca+Mg]^{\frac{1}{2}}/[K]$).

Having survived the preceeding lengthy review (which is by no means complete) of attempts by researchers to find the perfect K soil test, one tends to agree with Collis-George and Davey (1960). The majority of the attempts to develop a K soil test were based on correlation with plant uptake of K in the greenhouse and were never given the ultimate trial of predicting field crop response to applied K as influenced by variable soil and climatic factors.

Effect of drying on change in soil K and correlations.

Many scientists have found more exchangeable soil K in dried

soils than was initially exchangeable in the field-moist soil [Attoe (1947), Reitemeier, Brown, and Holmes (1951), Luebs, Stanford, and Scott (1956), Scott, Hanway, and Stickney (1957), Hanway and Scott (1957), Jones, et al. (1961), Hanway, et al. (1961) and (1962), and Bates and Scott (1965) and (1969)]. Other researchers have reported that exchangeable soil K increases or decreases on drying the soil, depending on the initial level in the soil [Bray and DeTurk (1938), McEwen and Matthews (1958), Matthews and Sherrell (1960), Cook and Hutcheson (1960), and Dowdy and Hutcheson (1963)]. A soil which is initially low in K will release K on drying while one which is initially high in K will fix K on drying.

Bray and DeTurk (1938) suggested soils have an equilibrium level of exchangeable K, and postulated a double buffer system involving two types of base-exchange reactions as the protection nature has provided for the preservation of K against leaching and luxury consumption by the plant, yet providing for its release as it is used by the plant. Regardless of soil type, release of K to exchangeable form was likely to occur upon drying the soil if the percent K saturation of the CEC was less than 1.11, and fixation was likely to occur if the percent saturation was greater than 1.11 (Matthews and Sherrell, 1960). They also found the amount of exchangeable K necessary before fixation occurred on drying was highly correlated with the CEC ($r = .97$).

Dowdy and Hutcheson (1963) reported that drying resulted in K fixation when the exchangeable K was 0.45 meq/100 g or greater, whereas K was released when the level was below this. Beckett (1964b) found that oven drying led to a 10 to 15% fall in AR of all samples while air drying led to only a 5% decrease. This indicates K was released on drying. Jones, et al. (1961) detected that K release from air drying Ohio soils varied from 25 to 100 lb/acre, but this response was found to not have a significant effect on interpretation of soil tests for K recommendations. Further drying at 110 C for 24 hours slightly increased or decreased the amount of exchangeable K depending on soil type. Rouse and Bertramson (1949) disclosed that drying at 70 C resulted in a greater release of K from spring samples than from fall samples for 20 to 23 soils. The increase was from 7 to 100%. The K supplying power (N HNO_3, boiling) of these soils was only slightly affected by drying.

Hanway, et al. (1961) discovered up to 10-fold increases in exchangeable K on drying subsoils. Based on this finding they stated it is imperative that analyses for exchangeable K be made on undried subsurface samples. Luebs, et al. (1956) studying field conditions, found fluctuations in soil moisture levels in the surface one-inch layer were accompanied by marked changes in content of exchangeable K over an 11-week period. Below this layer, exchangeable K remained nearly constant since moisture content did not drop so low as in the

surface. Little increase in K occurred until the soil moisture level had dropped to 5% or below. This agrees with the results of Burns and Barber (1961) who reported that soils held at moisture equivalents of 60 to 100% failed to release K over a temperature range of 1 to 80 C.

Bates and Scott (1965) showed that soil dessication is the cause of the release on drying. They found that drying samples for 40 days at 110 C caused the release of 223 ppm K from Marshall subsoil samples. Similar heat treatments without drying increased the exchangeable K level by only 33 ppm. Scott and Smith (1968) observed that fixation and release of K in biotite could occur simultaneously. Upon drying of biotite some of the silicate layers are forced apart exposing interlayer potassium to exchange and thereby causing K to be released. Drying also caused collapse of the clay lattice and fixation of K. Only a small number of layers were separated upon drying, but the number was sufficient for a net release of K. Van der Paauw (1962) has suggested that exchangeable K levels fluctuate depending upon rainfall distribution, and that wet periods are accompanied by a decrease in exchangeable K. According to Scott, et al. (1957) and Woodruff and McIntosh (1960) the K release process is slowly reversible when the water content of the soil is restored.

The question of whether better correlations with crop response can be obtained by analysis of a field moist sample or an air dried

sample remains unsettled. Luebs, et al. (1956), Hanway, et al. (1961 and 1962), and Schulte and Corey (1965) favor the analysis of field moist soil samples for predicting K uptake by plants. However, Jones, et al. (1961) and Rouse and Bertramsen (1949) favor the analysis of air dried soil samples for predicting crop response to applied K. Rouse and Bertramsen based their conclusion on the finding that field moist sample analysis gave a poorer correlation with the K supplying power (N HNO_3 extractable K) of these soils than did the dry soil analysis. Correlations between soil test levels and corn yield response to K fertilization were the same or better using air dried samples as compared to field moist samples.

Luebs, et al. (1956) disclosed that the effects of K absorption by plants, associated with drying of the soils, was equivalent to applying 60 to 120 pounds of K per acre. Changes in plant uptake of K corresponded with the field-moist to air-dry K fluctuation in the soils under greenhouse conditions. The K supplied to plants under greenhouse conditions was better correlated with exchangeable K content of undried than of air dried soils. Correlation coefficients were .99 and .96, respectively. Under field conditions, fluctuations in soil moisture levels in the surface 1-inch layer were accompanied by marked changes in content of exchangeable K over an 11 week period. Below this layer, exchangeable K remained nearly constant due to more constant moisture levels. They found exchangeable K did not show much

increase until soil moisture levels had dropped to 5% or below. They concluded that exchangeable K in field moist soils was more reliable in predicting plant available K in Iowa soils.

Field moist soil K is a better predictor of the concentration of K in alfalfa and corn plants (Hanway, et al., 1961 and 1962), and of corn grain yields (Hanway, et al., 1962). Schulte and Corey (1965) reported that sodium tetraphenyl boron extractable K determined in nondried soil samples was better correlated with available K (r = 0.97) than was exchangeable K determined in dried soil samples (r = 0.79). Matthews and Sherrell (1960) reported that only the exchangeable K from oven dried soils showed significant calibration with response of wheat.

Soil potassium fixation and release.

The release of K associated with drying was entirely eliminated by addition of high boiling point, organic compounds to the soil samples prior to drying (Bates and Scott, 1964 and 1965). Addition of 20 moles of dextrose to 10 g of moist soil is a practical way to prevent K release on drying. Bates and Scott (1969) reported that dextrose does not eliminate the problem of fixation on drying soils high in exchangeable K.

The different forms of K in soils were described at the beginning of this review. Fixed K is considered to be nonexchangeable with added

cations in solution, but may become plant available. Barber and Matthews (1962) utilized a hydrogen saturated cation-exchange resin in a timed extraction to delineate the three major forms of soil K. Potassium released to N NH_4OAc at day zero was considered exchangeable. After two days equilibration with the hydrogen resin, the soil-resin mixture was extracted with N NH_4OAc. The amount of K in this extract less that in the time zero extract was considered to be fixed potassium. After the two day resin extraction period the K extracted increased as a linear function of time. This K was considered native or mineral potassium. Scott and Bates (1967) reported K reversion occurred when dry samples of Marshall subsoil were rewet, but for complete reversion it was necessary to mix the rewet soils with organic compounds and re-dry the mixture.

Barrett, Engle, and Smith (1973) found indications from laboratory data that decreases in exchangeable K in a surface soil during winter months may be caused by fixation due to freezing, and increases due to freezing and thawing. Fine, Bailey, and Truog (1942) reported that freezing moist soils increased the exchangeable K level associated with these soils.

There is a wide range in the tenacity with which applied K is retained by different soils against solution (Pearson, 1952). Of the soils included in his study, those containing montmorillonite released fixed K more readily than did kaolinitic soils. This should be

expected based on the difference in these clay minerals. In the 2:1 Si:Al montmorillonite clays (micaceous minerals) interlayer K binds the clay layers together, whereas the kaolinitic clay layers are held together more strongly by hydrogen bonding. Potassium trapped between these kaolinite layers would be less readily released. Bray and DeTurk (1938) found that increasing the replaceable K by addition of a K salt under moist storage conditions results in part of the replaceable K being changed over to a nonreplaceable form. Attoe and Truog (1945) fertilized moist soils with 100 to 3,200 lb of K as KCl per acre. Continued moist storage and analysis of these soils in the moist condition revealed no K fixation after 18 months. When samples were dried at room temperature after storage, fixation took place in every case.

Scott, Hanway, and Stickney (1957), using similar conditions as Bray and DeTurk (1938), showed a continuous net fixation on drying moist soils. When lesser amounts of KCl were added, both fixation and release were observed in the same sample during the drying sequence. Wood and DeTurk (1940) reported that the larger the amount of K applied the greater is the acid insoluble form which is fixed. Schmitz and Pratt (1953) found that exchangeable K predicted only 47% of the variation in yield percentage whereas N HNO_3 extractable K (exchangeable, fixed, and probably some mineral K) predicted 88% of the variations in yield percentage. Pearson (1952) reported that exchangeable K was

the chief factor determining the total amounts of K absorbed by five greenhouse grown crops. He also found no relationship between release of fixed K and the original K content, total K content, or K distribution among the particle size separates.

In an experiment by MacLean(1968), fixed fertilizer K in the surface and subsurface samples of three soils accounted for about 48% of the K uptake by oats and alfalfa. MacLean and Simon (1958), using a repeated extraction experiment on these soils, found that seven extractions over a 45 day period removed more K which was originally fixed than that which was originally exchangeable in the Hoytville and Clermont soils.

Soil temperature measurement and plant growth.

Richards, Hagen, and McCalla (1952) stated that field studies are a disappointing method for elucidating the influence of soil temperature on plant growth. They went on to describe the daily maximum and minimum values at a given depth as the best values used to characterize the temperature for a given day. The daily mean value of the soil temperature is usually the average of the maximum and minimum values. Also, they reported that weekly temperatures compare favorably with hourly or 15 min averages.

Plant growth stage influence on potassium uptake.

Nutrient uptake occurs at a faster rate than the plant growth

rate so that uptake is essentially complete well before the grain is mature. Hanway, et al. (1962) reported that corn plants at silking time contained 90% of the total K taken up during the season, and K uptake appeared to be complete by 10 to 15-days after silking. Application of K at stages 3 and 10.3 to 10.5 increased the concentration of K in oat plants (Nielsen, et al., 1960). Chapman and Keay (1971) found that after head emergence (stage 10.5) there was no significant effect of inadequate available soil K on wheat yield. A marked decrease in K concentration of wheat and oats with the approach of maturity was noted by Miller (1939) and Klebesadel (1969), respectively.

Methods for expressing yield for correlation purposes.

There are several methods available for expressing yield increase due to fertilizer treatment. Bray (1944) utilized the Mitscherlich equation (Mitscherlich, 1930) to express yield of the control treatment as a percentage of the maximum yield, $\text{Log}(100 - y) = \text{Log } 100 - cb$, where 100 is the maximum yield percentage, y is yield of the control divided by maximum treatment yield, expressed as a percentage, c is a constant, and b is the measured soil K. This method plots as a positive curvilinear response type curve. Barber and Matthews (1962) utilized only the left-hand portion of the Mitscherlich equation as an expression of yield in their regression models.

Tinker (1964b) expressed yield of the check treatment as a percentage of the maximum yield:

$$\text{Percentage Yield} = \frac{\text{Maximum Yield - Control Yield}}{\text{Maximum Yield}} \times 100$$

By plotting control yield percent as the dependent and soil K as the independent variables, a positive curvilinear response curve is attained. Jackson and Moore (1968) presented a negative curvilinear response curve when they plotted soil test values versus treatment yield increase as a percentage of the check. Treatment yield increase is computed as follows:

$$\text{Percentage Yield} = \frac{\text{Treatment yield - Check yield}}{\text{Check yield}} \times 100$$

According to Fitts and Hanway (1971), use of percentage yields provides another means of comparing yields from different sites where the yields vary due to factors other than soil fertility and fertilizer treatments, but the levels of these and other factors are not measured in the field experiment. They presented the computation as:

$$\text{Percentage Yield} = \frac{\text{Yield without fertilizer nutrient}}{\text{Yield with fertilizer nutrient}} \times 100$$

Percentage yields may give erroneous impressions, especially when working with low yields. Also, percentage yields do not consider the interactions among factors that influence yields. Barber (1970) found that the average percent response to applied K for crops grown in rotation over an 18-year period to be: corn, 29%; soybeans 24%;

wheat, 6%; and alfalfa, red clover, and bromegrass hay, 26%.

Multiple regression factors and yield predictive equations.

Before 1950, the effect of only one experimental variable was studied in most field experiments. Dumenil and Nelson (1948) emphasized that more detailed investigations, such as factorial fertility experiments were necessary to provide information on interactions. Cline (1944) emphasized that soil is not homogeneous, even within the small area of a carefully selected site. In order to interpolate and extrapolate research results from one soil to another and from various soil-climate relationships, Voss and Pesek (1967) and Hanway (1971) indicated the need for quantitative measurement of variables on an individual plot basis. This is the direction Collis-George and Davey (1960) urged should be taken. They suggested that since the influence of soil physical and micrometeorological factors is known to be of great significance in determining the biological response of plants, the time is now appropriate to restrict the number of unrecorded, conventional field experiments, and replace some of them with completely instrumented experiments. Until complete descriptions of experiments are available, the quantitative importance of environment and its interaction with fertilizer and cultural practices cannot be determined.

Although Collis-George and Davey may have been somewhat extreme

in calling for completely instrumented experiments, their ideas are timely even today. Some variables in crop production can be quantitatively determined by observation. In the past several years much more emphasis has been given to estimating and utilizing plant growth variables in the field as an aid in determining a fertilizer predictive equation. Laird and Cady (1969) utilized applied nitrogen (N), total soil N, previous crop, moisture, drought, depth of rooting, soil slope, soil texture, hail, blight, and weeds in their attempt to determine a nitrogen requirement predictive equation for corn. Jackson (1970) reported predictions of winter wheat yields based on measurement of applied N, available soil Nitrate-N, available soil water, soil temperature, evapotranspiration, growing season rainfall, and depth to lime. According to Voss, Hanway, and Fuller (1970), variables for which standard methods and measurements can be utilized, are needed to predict response of corn to N, P, and K fertilizer. These should include soil sampling and analyses for the physical and chemical properties, plant sampling and analyses, evaluation of weed and insect damage, measurement of meteorological factors, and evaluation of past cropping and other management factors. Including subsoil K contents in multiple regression equations improved the degree of correlation (Hanway, et al., 1962).

More recently, research investigators have been experimenting with methods for statistically evaluating these controlled and

uncontrolled variables in relation to their influence on crop yields. Barber and Matthews (1962) found simple linear regression analysis of yield on exchangeable K or exchangeable plus moderately-available K accounted for only 16 and 27% respectively, of the variability in yield response of corn, wheat, oats, and potatoes to K fertilizer in the field. Multiple linear regression of yield on exchangeable and moderately available K accounted for an average of 37% of the variation in crop response; but a multiple quadratic regression of Log (100 - percent yield) on exchangeable and moderately-available potassium accounted for an average of 56% of the variability in Log(100 - percent yield). Multiple quadratic regression of absolute yield or percentage yield on exchangeable and moderately-available K accounted for 46 and 50% respectively, of the variability in crop response to K fertilizer.

Laird and Cady (1969) experimented with three regression procedures - stepwise, backward elimination, and an approach based on agronomic considerations, along with a full model multiple quadratic regression to develop a prediction equation for N on corn. Of these four regression methods, the stepwise and the agronomic were the best. The approach based on agronomic considerations predicted better than the stepwise. Coefficients of determination for all models were in the range of .79 to .82. These researchers provide an excellent discussion on multiple regression which should be required study for

anyone contemplating this type of analysis. Voss, et al. (1970) discussed the necessity for this type of field experimentation, especially on soils which rate "medium" or "high" in exchangeable K and responded only slightly or negatively to applied K fertilizer. They suggested methods of experimentation, interpretation and practical applications of yield prediction equations along with examples.

Soil test correlation and calibration research has been conducted for at least three-quarters of a century. Only recently has the computer enabled us to extend this type of research to include more than one or two plant growth factors and thus make calibration research more meaningful.

EXPERIMENTAL PROCEDURES

Field trials, 1973.

Barley, spring wheat, and corn K fertilizer trials were conducted in north central Montana by personnel from the Northern Montana Agricultural Research Center.[1/] The experimental design was a partially randomized, three-block, stripped, split-plot. Barley and spring wheat yields from the K soil test study were taken from plots receiving 0, 40, 80, and 120 lb of K, and blanket applications of 40 and 44 lb of N and P per acre, respectively. Soil samples from 0 to 6 and 6 to 12-inches were taken randomly throughout the experimental site and composited to provide one representative sample for each depth. These samples were maintained in a moist condition. All of the yield data used in this soil test research were taken from plots which had been fertilized with K in the form of KCl, except the control plots.

In north eastern Montana, three-block, split-plot experiments were conducted by Montana Cooperative Extension Service personnel from Bozeman, to study time of fertilizer application on spring wheat.[2/] Yield data from the early fertilizer applications were

1/ Houlton, H. 1973. Unpublished data. Northern Montana Agricultural Research Center. Havre.

2/ Christensen, N. 1973. Unpublished data. Montana Cooperative Extension Service. Bozeman.

utilized for this soil test study. The K fertilizer treatments consisted of 0, 10, and 35 lb of K and uniform applications of 60 lb of N and 20 lb of P per acre. Ten pounds of K were banded with the seed. With the 35 lb K rate, 25 lb were broadcast prior to planting. Representative soil samples from the 0 to 6 and 6 to 12-inch depth were collected and held in a moist condition.

The effects of added K on sugarbeets grown in the Yellowstone Valley of south central and eastern Montana, were studied by personnel from the Southern[3/] and Eastern[4/] Montana Agricultural Research Centers, respectively. All experiments were designed in a randomized, complete-block. The eastern experiments included three replications while six were used in the southern station experiments. Representative soil samples were taken at depths of 0 to 6 and 6 to 12-inches from each site and analyzed moist. Additional deep soil samples were taken at 12 to 24, 24 to 36, and 36 to 48-inches, but their K content was not allowed to enter the regressions. Analysis revealed that the K content with depth was similar to that of the 6 to 12-inch depth. This should have been expected due to the alluvial origin of these soils.

3/ Baldridge, D. 1973. Unpublished data. Southern Montana Agricultural Research Center. Huntley.

4/ Hartman, G. 1973. Unpublished data. Eastern Montana Agricultural Research Center. Sidney.

These samples were taken by blocks in southern Montana, so that samples from blocks 1 and 2, 3 and 4, and 5 and 6 from each site could be composited. Each of the three composited samples was handled as a separate experimental site. One additional experiment of similar design at Huntley, Montana was sampled and harvested as six individual experiments. Fertilizer treatments in eastern Montana were uniform additions of 110 lb of N, 75 lb of P, and rates of K equal to 0, 125, or 250 lb per acre. Fertilizer treatments on the south central Montana sites consisted of blanket application of 100 lb of N and 50 lb of P with K at rates of 0 or 80 lb per acre. On the one large site at Huntley, 100 lb each of N and P and 0 or 100 lb of K per acre were applied.

Winter and spring wheat and barley experiments were conducted throughout Montana, east of the continental divide, by Montana Agricultural Experiment Station personnel located in Bozeman.[5/] The experimental design was partially randomized, complete block with three replications and two possible directions for analyzing block effects. Potassium fertilizer rates were 0, 20, 40, 80, or 120 lb along with 40 lb of N and 50 lb of P per acre. Representative soil samples were taken at 0 to 6 and 6 to 12-inch depths and kept moist

5/ Skogley, E. 1973. Unpublished data. Montana Agricultural Experiment Station. Bozeman.

for K analysis. Rainfall, pan evaporation, and soil temperature readings at 50 cm were taken at weekly intervals. In addition, plant available soil water determinations were made on one foot increment samples to the depth of the root zone.

Field trials, 1967 through 1971.

Attempts to improve the K soil test were begun on an initial set of soil samples and yield data collected from selected Montana Agricultural Experiment Station[6/] and Cooperative Extension Service[7/] research trials conducted over a period of eight years. The soil samples from these selected sites were taken from the 0 to 6 and 6 to 12-inch depths and had been stored dry for varying periods up to six years. These winter wheat sites had been fertilized with either 40 lb of N, 40 lb of P and 0, 25, or 100 lb of K per acre, or with 40 lb of N, 20 lb of P, and 0 or 25 lb of K per acre. The experimental design for these sites was a randomized complete block with three replications of each treatment.

6/ Sims, J. and E. Skogley. 1971. Unpublished data. Montana Agricultural Experiment Station. Bozeman.

7/ Smith, C. 1967 through 1971. Unpublished data. Montana Cooperative Extension Service. Bozeman.

Soil characterization.

The individual research personnel requested that nitrate-nitrogen tests be done on all depth samples, including depths they took below 18 or 24-inches. A portion of each moist sample submitted for K analysis was air dried at room temperature and analyzed for fertility by the routine soil test methods used by the Montana State University soil testing lab. Where N and P may have been limiting, a corrective blanket application of these nutrient elements was applied along with the K fertilizer. Electrical conductivity and pH determinations were made in a 2:1 water:soil suspension which had settled for $\frac{1}{2}$ hour following stirring. The pH electrodes were placed into the sediment.[8/] Nitrate-N was determined by the phenol 2, 4-disulfonic acid method modified from Jackson (1958) by extraction of soil nitrate with a saturated calcium sulfate solution containing silver sulfate to remove chlorides. Phosphorus was determined by the method of Smith, Ellis, and Grava (1957). This is a modified Bray No. 1 extraction using 50 ml of solution of one g of soil. Calcium, Mg, K, and Na were determined by N NH_4OAc extraction using 2.5 g of soil to 50 ml of solution and shaking for 30 min, followed by analysis with a Model 290-B Perkin-Elmer atomic absorption spectrophotometer.

8/ Klages, M.G., unpublished data, Montana State University, Bozeman.

The soil samples used directly in the K soil test research were analized for CEC by the method of Bower, Reitemeier, and Fireman (1952). Organic matter determinations were done by the Walkley-Black method as modified by Sims and Haby (1971). Percent sand, silt, and clay analysis was done by the Bouyoucos hydrometer method using modifications suggested by Kilmer and Alexander (1949), specifically, addition of 10 ml of N sodium hexametaphosphate to the soil-water mixture followed by stirring, then allowing dispersion to occur for 15 hours prior to homogenization and analysis.

Precipitation.

Where recorded, rainfall was measured with a Tru-Chek[9/] Accuracy rain gauge at daily or approximately weekly intervals. Evaporation from the rain gauge was prevented by placing a layer of mineral oil (approximately 1 cm thick) on top of 0.15 inches of water.

Pan evaporation.

At many locations measurements of evaporated water were taken at approximately weekly intervals by the method of Sims and Jackson (1971).

9/ Edwards Mfg. Co., Albert Lea, Minnesota.

Soil temperature.

Soil temperature was measured each time precipitation and evaporation were determined. Temperature was measured with a Wesson dial thermometer with an eight inch stem which was inserted into the side of a freshly opened pit at the 50 cm depth.

Soil moisture.

The soil water content of samples from each location where measured was determined gravimetrically and based on the oven-dry weight (60C for 48 hours). Samples were taken in the spring, prior to broadcasting N fertilizer, and again in the summer at harvest time. Plant available water in these soils at the initiation of each experiment, was determined by subtracting the percent water in the fall samples from that in the spring samples, then multiplying this difference by the depth in inches (Cole and Matthews, 1954). Theoretically, under dry land conditions, the plant roots had reduced the moisture levels to what they were at harvest time. This should be a better estimate of the wilting point than the 15 bar laboratory determination, provided no rain was received on these sites for at least three weeks prior to crop maturity.

Caution must be exercised when interpreting effects of precipitation, pan evaporation, soil temperature, and soil moisture on crop production. The earliest recorded measurement of these factors was

May 15. Thus the climatic variables for the first 2 to 4 weeks of the growing season were not included.

Experimental soil extraction procedures for potassium.

The experimental sites, from which the 1967 through 1971 soil samples were taken, were carefully selected from all the Extension Service and Experiment Station research sites for those years. The selection criteria were based on these factors: (1) A coefficient of variation of approximately 10 or less for a given experiment, (2) Uniform data for a treatment across replications, i.e., the yield from each replication of a treatment must be within 10% of the mean yield; this may even be too liberal, (3) A consistant yield pattern due to increasing K rates in all replications. The K rate selected was that one which put crop yield just below the leveling off point of a response curve, and (4) no severe limitations to crop growth based on the judgement of the researcher involved.

This initial series of soil samples was analyzed by several extraction methods which would be convenient for routine soil test methods. All potassium analyses were done on a Model 290-B Perkin-Elmer atomic absorption spectrophotometer at a wave length of 766.5 nm and a 2 nm slit setting. The analyzed solution contained 0.5% strontium in the chloride form for interference suppression. Calcium, Mg, and Na were analyzed in extracts at 422.7, 285.2, and 589.0 nm,

respectively.

Saturated paste extraction. Approximately 100 g of each soil sample were saturated with water and extracted according to the procedure outlined in the USDA Agricultural Handbook 60 (1954). Free energies of exchange were calculated as described by Woodruff (1955a). Since the molar concentrations of Ca, Mg, K, and Na were less than 0.01, concentration of each element was used in lieu of calculating ionic activity (Morris, 1968). The following ratios were computed and multiplied by 1364 to obtain free energies of exchange: (1) $[K]/[Ca]^{\frac{1}{2}}$, (2) $[K]/[Ca+Mg]^{\frac{1}{2}}$, and (3) $[K]/[Mg]^{\frac{1}{2}}$. Percentage yield increase [(treatment yield-check yield/check yield) x 100] was regressed over K applied and free energy of exchange. Single analysis was done on each sample.

Yeast cell extraction technique. Based on results of experiments by Leggett, Olsen, and Spangler (1962), yeast cells were tried as a soil K extraction method. A technique was devised whereby 2 g of soil were placed into an extraction thimble[10/] which was then stoppered with a No. 000 rubber stopper.

10/ S-31655, Whatman, paper, single thickness, Sargent-Welsch Scientific Company, 4040 Dahlia Street, P.O. Box 7196, Denver, Colorado 80207

This system was placed into a 160 ml polyethylene beaker and a 10 ml aliquot of yeast cell suspension and 40 ml of nutrient solution were added. This system was placed on a centrifugal shaker[11/] at 150 cycles per min for 15 hours. The soil-thimble was removed and the cells centrifuged. After decanting the supernatent solution the cells were dissolved by addition of Soluene-100[12/] (Jackson, Michael, and Schumacher, 1972) in preparation for K analysis. A complete description of the cell culture method is in Appendix table 1.

A separate experiment was constructed to determine the uptake of K by yeast cells. Forty ml of solutions containing 0, 20, 40, 60, 80, and 100 mg of K as KCl per liter were placed into separate test tubes followed by addition of 10 ml of purified yeast cells. These suspensions were equilibrated 15 hours on the shaker at 150 cycles per min, centrifuged, and the supernatent analyzed for K.

Equilibrium extraction with a dilute potassium solution. In recent years attempts have been made by researchers to use a dilute solution of a particular element to estimate the quantity and intensity of that element in soils (Baker, 1971). This idea appeared to have merit. Fifty ml of a solution containing 0.0179 g of KCl per liter were added to 2.5 g of soil in a 160 ml beaker, and equilibrated

11/ Erbach Corporation, Ann Arbor, Michigan.

12/ Packard Chemical Company, Downers Grove, Ill. 60515.

by shaking at 250 cycles per min for $\frac{1}{2}$ hour. These samples remained cloudy following filtration through Whatman No. 1 paper. Each filtrate was centrifuged and 4 ml of supernatant liquid were added to 4 ml of 1% Sr (as Cl) solution prior to analysis. The original KCl solution was analyzed for its content of Ca, Mg, K, and Na. The conc of each of these ions in solution following equilibration was utilized to compute free energy of exchange by the same equations as used in the saturated paste extraction, along with these: (1) $[K]/[Ca+Mg]^{\frac{1}{2}}+[Na]$, (2) $[K]/[[Ca+Mg]/2]^{\frac{1}{2}}$, and $[K]/[[Ca+Mg]/2]^{\frac{1}{2}}+[Na]$. Percentage yield increase was regressed over K applied and ppm K in solution or free energy. Correlations were made to determine the relations among the computed free energy values. Duplicate analyses were done on each soil sample.

Equilibrium extraction with a dilute solution of Ca, Mg, and K. Baker (1971) proposed the equilibration of soils with dilute Ca, Mg and K solutions as a good method to use for predicting the K fertilizer requirements of soils for optimum crop production. The seventeen 0 to 6 and 6 to 12-inch depth, dry soil samples from the 1967 to 1971 sites were extracted with a dilute cation solution according to Baker's (1971) suggested procedure. Five g of soil were weighed into extraction beakers and 50 ml of a solution containing 2.4×10^{-4} moles of KCl, 9.6×10^{-4} moles of $MgCl_2.6H_2O$, 48×10^{-4} moles of $CaCl_2.2H_2O$ and 5×10^{-4} moles of CaOAc were added. Samples were equilibrated for

15 hours on the shaker at 150 cycles per minute. Then, following a 1 min shaking at 250 cycles per min, the suspension was filtered through Whatman No. 1 paper. All filtrates were clear. An aliquot of filtrate was mixed 1:1 with 1% Sr solution and analyzed for Ca, Mg, K, and Na. The concentration of each ion in solution was used to compute free energy of exchange by Woodruff's (1955a) method using the ratios $[K]/[Ca]^{\frac{1}{2}}$, $[K]/[Ca+Mg]^{\frac{1}{2}}$, and $[K]/[Mg]^{\frac{1}{2}}$. Percentage yield increase was regressed over K applied and ppm K in solution or free energy computed from the above ratios. Duplicate analyses were done on each soil sample.

Soil extraction with sodium bicarbonate. Sodium bicarbonate ($NaHCO_3$, 0.5 M) is commonly used as a phosphorus extracting solution in many western soil testing laboratories. Several western U.S. soil testing laboratories analyze K in this same extract. This was thought to be a convenient, time saving technique and thus was tried as a K extraction solution. However, this procedure was ruled impractical due to equipment limitations and solution problems encountered. The Perkin-Elmer 290B atomic absorption spectrophotometer developed a very unstable signal when the sodium bicarbonate extract was burned in the flame. Strontium chloride, normally added to suppress chemical interference in the N NH_4OAc solution, forms an insoluble precipitate of $SrCO_3$ when added to $NaHCO_3$. An attempt will be made to overcome these problems later.

Soil extraction with ammonium acetate. The most commonly used procedure for extraction of "plant available" soil K in the United States is the 1 N NH_4OAc (pH 7) extraction solution. This procedure is currently used in the Montana State University soil testing laboratory and has been modified from that devised by Volk and Truog in 1934. In this research NH_4OAc will be used as a standard of reference against which other extraction procedures will be evaluated.

This procedure involves extraction of 2.5 g of soil with 50 ml of neutral, N NH_4OAc for $\frac{1}{2}$ hour at 250 cycles per minute. The suspensions are filtered, diluted 1:1 with 1% Sr solution and analyzed for K. Percentage yield increase was regressed over applied K and ppm K in the soil, calculated from ppm K in solution times 40. Duplicate analyses were made on each soil sample.

Soil extraction with hydrogen saturated ethylene diamine tetra-acetic acid, (HEDTA). A simple extraction procedure utilizing HEDTA as used by Olsen (In press, 1975) was tried for extracting K. Theoretically, the pH of this chelate in a water system should approximate the pH in the immediate vicinity of the plant roots in soil, thus extracting equivalent amounts of plant nutrients from the soil. The water-HEDTA pH was 3.32. Two and one-half g of soil were weighed into a 160 ml polyethylene beaker followed by 0.15 g of HEDTA crystals and 50 ml of distilled water. This extraction was conducted at 150 cycles per minute for 15 hours. The suspensions were filtered through

Whatman No. 1 paper. The extract was diluted 1:1 with 1% Sr and analyzed for K. If the filtrate remained cloudy it was refiltered through the same paper to produce a clear solution. Percentage yield increase was regressed over pounds of fertilizer K applied and ppm K extracted from the soils by this procedure. A single analysis was done on each soil sample.

Soil extraction with diethylene triamine pentaacetic acid, triethanolamine (DTPA). Diethylene triamine pentaacetic acid, triethanolamine (Lindsay and Norvell, 1969) is presently used for extraction of iron, zinc, copper, and manganese in the soil testing laboratory at Montana State University. This experiment was done to determine the feasibility of using DTPA for K extraction. The DTPA solution was prepared by the following procedure. Eight hundred ml of distilled-deionized water were placed into a liter volumetric flask. Into this water was added 5.78 ml of DTPA (Versenex 80)[13/], 1325 ml of triethanolamine, and 1.47 g of calcium chloride, followed by swirling to mix each compound after it was added. This was followed by addition of approximately 6.75 ml of conc HCl to reduce the pH to 7.3. The solution was brought to volume with distilled-deionized water.

13/ Trade name of Fisher Scientific Company, Chicago, Illinois.

Twenty ml of DTPA solution were added to ten g of soil in a 160 ml polyethylene beaker. The suspension was shaken for 2 hours at 250 cycles per minute, filtered through Whatman No. 40 paper, diluted 1:1 with 1% Sr and analyzed for K. Percentage yield increase was regressed over pounds of applied K and ppm K in the surface 6-inch and 6 to 12-inch depth of soil. A single analysis was done on each sample.

Initial research on selected soil samples from the 1973 state-wide K research sites was designed to determine if there would be any difference in the N NH_4OAc extractable Ca, Mg, K, or Na in soils which were air dried compared to field moist, dried at 60 C and ground to pass a 20-mesh screen compared to 60 C oven dried but unground soils, or to 20-mesh samples dried at 60 C and rehydrated to 40% moisture immediately prior to extraction.

Rehydration study. Ten soils, each with 0 to 6 and 6 to 12-inch depth samples were selected for this rehydration study to determine if samples which had been air dried or dried at 60 C could be reverted to their original field moist K status. Five g samples of air dried soils were weighed into a series of 7 plastic, snap cap vials and 2 ml of distilled H_2O were added to each. The vials were capped and stored in a cool dark cabinet. Each week, one vial of each soil was removed and analyzed for moist soil K content by extracting approximately 2.5 g of soil with 50 ml of N NH_4OAc. Percentage moisture content was determined gravimetrically based on drying at 105 C for 15 hours.

Statistical analyses included regressions of rehydration time versus moist soil K and percentage moisture. Paired t-tests were also made.

A second study was designed to determine the effect of rehydration followed by freezing, thawing, and air drying on N NH_4OAc extractable K. Five g of the 0 to 6-inch depth of the air dried soils used in the previous rehydration study were weighed into 10 vials. Each vial received 2 ml of distilled H_2O. All vials were frozen at -29 C for 15 hours. Two vials of each soil were uncapped and allowed to dry at room temperature immediately following removal from the freezer. Two additional vials of each soil were uncapped at 12, 24, 36, and 48 hours following removal from the freezer. Moisture content and N NH_4OAc extractable K were determined on these samples after the appropriate drying intervals. Averages of the duplicate analyses were taken and correlations of percentage moisture in the soil at the time of analysis versus extractable K were calculated. Paired t-tests were computed comparing the treated soil K content with the original field moist soil K content.

The soil samples collected from research sites in 1973 were analyzed moist, and again after they were air dried, by two techniques employing cation exchange resin, by the N NH_4OAc procedure, and Baker's technique (1971) as used on the 1967 through 1971 samples.

Resin-thimble soil extraction technique for K. Dowex 50x8-50[14], 20 to 50-mesh, 8% cross-linked and having a CEC of 1.7 meq per ml on a wet volume basis was used for this procedure. Ten pounds of the resin were air evacuated under water in a vacuum dessicator, then placed in a leaching column and leached with 0.05 N HCl. All traces of chloride were removed by leaching with distilled, deionized water. The Whatman extraction thimbles were constructed of single thickness cellulose with dimensions of 10 x 50 mm.

Approximately 2 g of soil were weighed into the thimble which was then sealed with a No. 000 rubber stopper and put into a 160 ml polyethylene beaker. Approximately 5.3 g of wet cation resin (64.81% w/w H_2O) were measured into each beaker, followed by 50 ml of distilled, deionized water. The beaker was capped and the soils were equilibrated with the resin for 15 hours at 150 cycles per minute on the shaker. Following extraction, the thimble with soil was discarded leaving the resin in the clear water, which was decanted and aspirated out of the beaker by use of a pipet tip covered with cheese cloth. The resin was extracted by shaking at 250 cpm for 30 min with 50 ml of N NH_4OAc spiked with 0.5% Sr. After the resin had settled to the bottom of the beaker (immediately) the clear supernatant was analyzed directly for Ca, Mg, and K. Acetate and NH_4^+ are volatile in the air-acetylene

14/ Sigma Chemical Co., St. Louis, Missouri. Lot # 81C-0390.

flame, leaving no salt residue in the burner slit.

In the initial trial of this resin technique the equilibrating water medium was analyzed and found to contain no more than 0.7 ppm K and no Ca or Mg. Duplicate analyses were done on each of the 1973 and 1967 through 1971 site soil samples.

An evaluation of the resin-thimble soil extraction technique for precision was done on three soils having different textural classifications, three screen fractions of each soil, six extraction time periods and three replications of each treatment. The percentage sand, silt, clay, and CEC of each soil is shown in table 2. Each soil was screened to produce three particle sizes, 1 to 2, 0.5 to 1, and < 0.5 mm. The extraction time periods were 2, 4, 8, 16, 32, and 64-hours.

Table 2. Soil textures used for evaluation of resin procedures.

Textural Classification	Sand %	Silt %	Clay %	C. E. C. meq/100 g
Clay	12.86	36.57	50.57	30.64
Clay loam	28.86	42.57	28.57	19.36
Sandy loam	71.44	12.00	16.56	11.88

Resin equilibration-ammonium acetate extraction of soil K. Barber and Matthews (1962) devised a procedure whereby the soil and a strongly acidic, cation exchange resin are combined in a water solution and equilibrated for 48 hours. This mixture was then extracted

with 10 ml of NH_4OAc (1 g NH_4OAc per ml) and leached with 200 ml of neutral normal NH_4OAc. A duplicate sample of the soil was extracted and leached with the same concentrations of NH_4OAc. The difference between the K extracted by resin-NH_4OAc and that extracted by NH_4OAc alone was considered moderately available soil K. A modification of this procedure which would be suitable for routine soil analysis was developed and tried on the 1973 field trial soil samples.

A determination of the amount of resin to use was made by means of the following experiment. Ten, 2 g samples of each soil described in Table 2 were weighed into extraction beakers held in racks (10 per rack). The beakers in each rack were grouped by two so that one g of resin was added to the first two beakers, two g into the second two beakers, etc., to five g in the last two beakers of each rack. Twenty ml of distilled, deionized water were added to each beaker. The samples were equilibrated by shaking at 250 cycles per minute for 16 hours. Thirty ml of 1.67 N NH_4OAc were added to each sample followed by extraction at 250 cycles per min for 30 min. The suspension was filtered into 250 ml volumetric flasks. The soil-resin sediment was extracted 4 times with 50 ml of N NH_4OAc, each suspension being filtered through the sediment on the filter paper, into the 250 ml volumetric flask. Each solution was diluted to a volume of 250 ml. Aliquots of each solution were diluted 1:1 with one percent Sr in N NH_4OAc and analyzed for K.

The second step toward adapting Barber and Matthew's (1962) procedure to routine soil analysis involved the determination of extraction time. This experiment was designed to take advantage of the same soils (Table 2), soil fractions, and extraction times as utilized in the precision experiment for the resin-thimble procedure. Triplicate, two g samples of each fraction of each soil were weighed into racked, extraction beakers. These three racks of soil samples were equilibrated with resin for 2 hours. Similar distributions of these soil fractions were made into additional extraction beakers for extraction times of 4, 8, 16, 32, and 64 hours. Two g of dry Dowex 50x8-50 resin were added to each beaker followed by 10 ml of distilled, deionized water. These samples were equilibrated with the resin by shaking at 250 cycles per minute for the required time intervals, after which 40 ml of 1.25 N NH_4OAc were added and extraction continued for $\frac{1}{2}$ hour. These suspensions were filtered through Whatman No. 1 paper. An aliquot of this extract was diluted 1:1 with 1% Sr and analyzed for K. Each beaker was capped during the resin equilibration time. A 2 g sample of each fraction of each soil was extracted by N NH_4OAc alone and the amount of K extracted was considered the K removed at time zero.

The 1973 field trial soil samples were analyzed as follows. Two g of soil were equilibrated with 2 g of resin in 10 ml of H_2O for 16 hours, then extracted with 40 ml of 1.25 N NH_4OAc for $\frac{1}{2}$ hour. These

suspensions were filtered, an aliquot was diluted 1:1 with 1% Sr, and analyzed for K.

These same samples were analyzed by the N NH_4OAc extraction procedure described earlier. Extractable K by this method was considered as time zero for the resin equilibration-ammonium acetate extraction procedure.

Percentage potassium saturation of the cation exchange capacity. The percentage K saturation was computed based on moist soil, N NH_4OAc extractable K and soil CEC (pH 8.2), by the equation: 100 x (meq K/100 g)/(CEC in meq/100 g).

Data analyses. Stepwise multiple regression analyses (Dixon, 1970) of (1) potential yield and (2) check yield, bu/acre, and (3) fertilizer rate in lb/acre vs. indigenous soil K extracted by the various soil test methods, and other soil and climatic factors, were performed on the 1973 field trial data. Multiple linear regressions of percentage yield response vs. soil test K were run on the 1967 through 1971 soil test K values by Lund's (1972) regression program. The computations preparing the data for the computer were done with the aid of a Monroe 1766 programmable calculator. The statistical computations were made on the XDS Sigma 7 computer in the Montana State University Computing Center. The regression analyses and partial regression coefficients were tested by the methods of Snedecor and Cochran (1967). The partial regression coefficients were tested by the t-test, while

a standard F-test was used for the regression equations.

RESULTS AND INTERPRETATIONS

Soil particle size and moisture relations.

Initial data were needed to determine the effect of soil sample treatment on cation release characteristics of Montana soils. Eighteen selected samples were analyzed by N NH_4OAc extraction for Ca, Mg, K, and Na after the following treatments: (1) field-moist; (2) air-dried at 25 C and ground to pass a 20-mesh screen; (3) oven-dried at 60 C and ground to pass a 20-mesh screen; (4) oven-dried at 60 C and unground; and (5) oven-dried at 60 C, ground to pass a 20-mesh screen, and rehydrated to 40% water for 15 hours. Correlation analyses were performed on the 0 to 6 and 6 to 12-inch depth, field-moist soil K versus air-dried soil K and on field moist soil K versus oven-dried soil K. Graphs of these data are shown in Fig. 1 and 2, respectively. The results illustrate that there was a tremendous release of K from the soil upon drying when the field-moist soil exchangeable K content was near 100 ppm.

In some soils there was greater than a 100% increase in exchangeable K on drying. Greater concentrations of K were released as the drying temperature was increased from 25 to 60 C. The results of research by Attoe (1947) and others agree with this finding. Further scrutiny of Figures 1 and 2 reveals that as the moist soil exchangeable K concentration increased, the percentage increase in exchangeable K content of the dried soils was lowered. At 420 ppm K in the air-dried

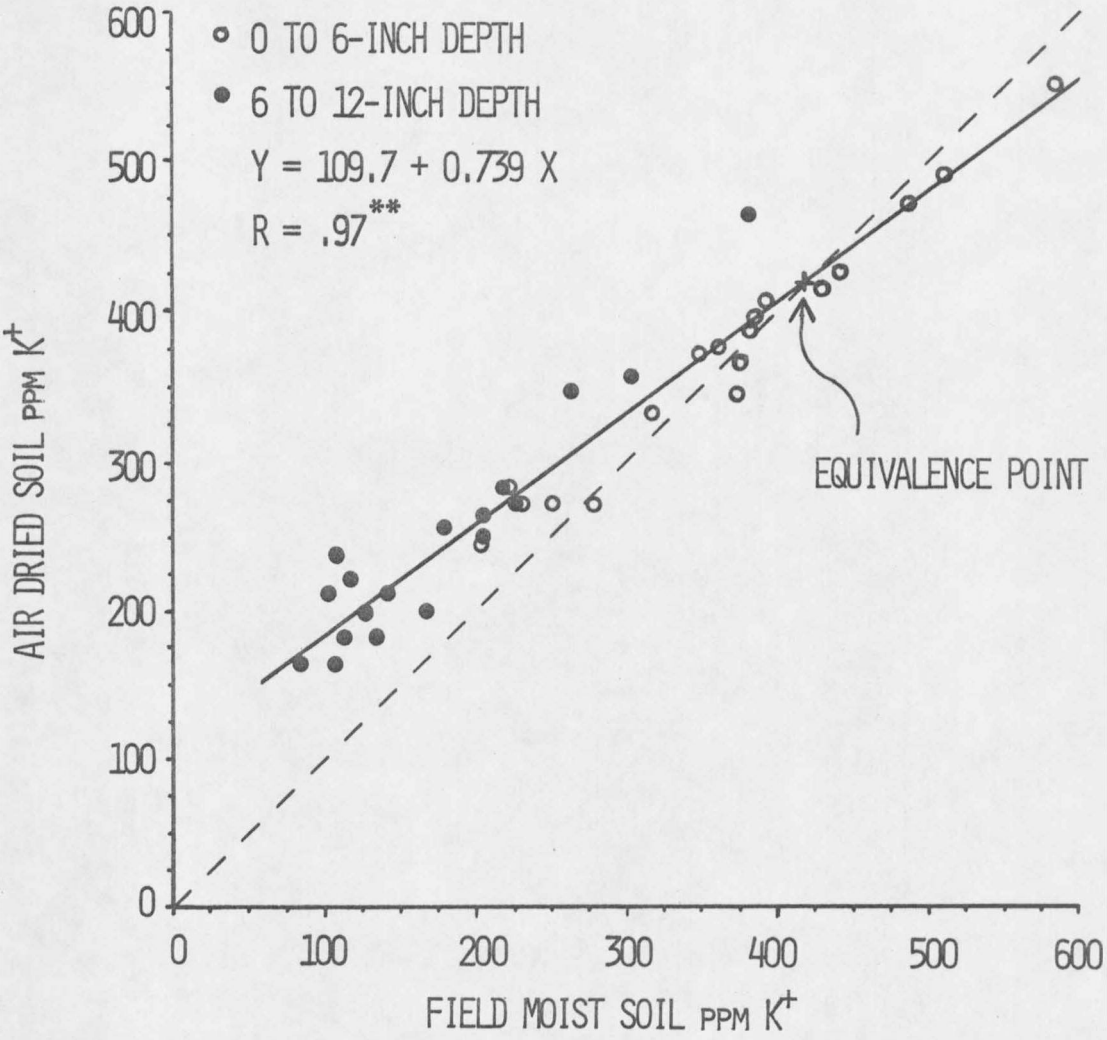


FIGURE 1. CORRELATION OF N NH_4OAc EXTRACTABLE K^+ FROM FIELD MOIST VS. AIR DRIED SOIL SAMPLES COLLECTED IN THE FALL OF 1972.

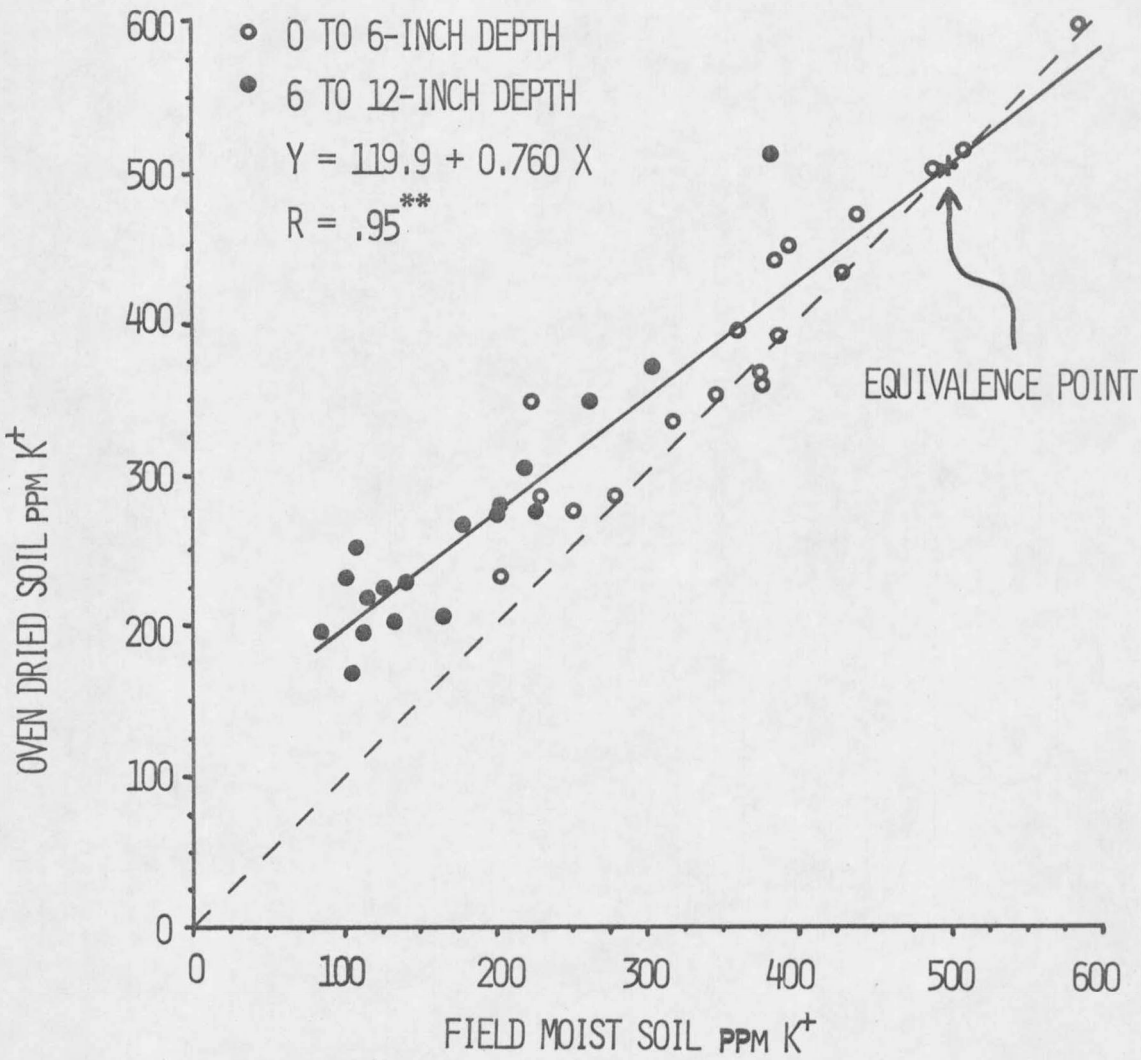


FIGURE 2. CORRELATION OF N NH_4OAc EXTRACTABLE K^+ FROM FIELD MOIST VS. OVEN DRIED (60 C) SOIL SAMPLES COLLECTED IN THE FALL OF 1972.

and 500 ppm K in the oven-dried soils the K content of the field-moist samples equaled that of the dried counterparts. Drying soils which had field-moist exchangeable K concentrations greater than these equivalence concentrations tended to effect fixation of exchangeable K. The work of Bray and DeTurk (1938) and others is in accord with these results. The fact that the equivalence point was at a higher concentration with oven-dried than with air-dried samples indicated that the slopes of these graphs were probably different. This was verified by the single degree of freedom F test, at the .01 probability level. The slope of Figure 2 is greater than that of Figure 1, and indicates that more severe drying temperatures caused greater release of K from these soils.

In Figure 1 the points which represent the 6 to 12-inch deep soils appear to have a greater slope than that for the combination of both depths or for the 0 to 6-inch depth separately. Separate correlations by individual depths revealed the slope for the 6 to 12-inch depth soils was .91 compared to .79 for the 0 to 6-inch depth samples. This suggests that the larger amount of clay in the 6 to 12-inch depth releases a greater concentration of K on drying.

Scott, et al. (1957) postulated that release of K on drying soils at 110 C or below may be due to an exchange of other ions for the fixed K during the drying process. I believe that the release of K from clay on drying may be due to the degree of edge separation or distortion of

the individual clay layers. The more severe the desiccation, the greater the separation and the larger the concentration of K which is exposed to exchange processes. Clays which fix or maintain a constant level of exchangeable K on drying, may contain sufficient quantities of this element to provide adequate bonding to hold the clay layers together, or even cause them to collapse tighter on drying.

Analytical results for the four cations with the five different soil treatments are presented in appendix Table 2. Table 3 presents results of paired t tests performed on the data in appendix Table 2. By this test there was no significant difference between the means of exchangeable K in field moist vs. air dried soils, or in 60 C dried soils ground finer than 20 mesh vs. unground soils from the surface 6-inch depth. Drying and grinding caused significant increases ($p = .05$) in exchangeable K in the 6 to 12-inch depth when compared to the field moist K content. Rehydration for 15 hours at 40% water appeared to have little effect on exchangeable soil K (Appendix Table 2).

The paired t test revealed some significant mean differences by sample treatment for Ca, Mg, and Na. However, the t test is a liberal test which will indicate differences when a more conservative multiple comparison method may not. The Newman-Keuls test (Snedecor and Cochran, 1967) was conducted on all comparisons which were found to be significant by the paired t test. By this test there were no significant differences between Ca or Mg levels at either depth for any sample

Table 3. Statistical analysis (paired t) of cations in soils analyzed (1) field moist, (2) air dried, < 20-mesh, (3) oven dried (60 C), < 20-mesh, (4) oven dried (60 C) unground, and (5) oven dried (60 C), < 20-mesh and rehydrated for 15 hours at 40% water.

Correlation	Depth	Potassium					Calcium				
		$\bar{d}$ 1/	S_d 2/	df 3/	t 4/	$S_{\bar{d}}$ 5/	$\bar{d}$	S_d	df	t	$S_{\bar{d}}$
Field Moist vs Air Dry (25 C)	0-6	-5.89	26.12	17	-.96	6.16	2.08	1.75	16	4.90*	0.42
	6-12	-71.94	24.68	17	-12.36*	5.82	2.61	4.08	15	2.56*	1.02
Air Dry vs 60 C dried, < 20 mesh	0-6	-16.33	23.46	17	-2.95*	5.53	-0.81	1.47	16	-2.28*	.36
	6-12	-15.50	12.34	17	-5.33*	6.21	-2.12	1.75	13	-4.54*	.47
60 C dried, < 20 mesh vs 60 C dried, unground	0-6	10.29	25.62	16	1.66	6.21	.20	1.37	15	.58	.34
	6-12	17.50	10.79	17	6.88*	2.54	.41	1.72	13	.90	.46
Field Moist vs 60 C dried, < 20 mesh, 40% water	0-6	-32.56	17.17	17	-8.04*	4.05	3.22	7.08	16	1.88	1.72
	6-12	-77.17	29.29	17	-11.18*	6.90	.21	2.82	13	.27	.75
Field Moist vs 60 C, < 20 mesh	0-6	-22.22	34.04	17	-2.77*	8.02	1.27	.93	16	5.65*	.22
	6-12	-87.44	28.01	17	-34.24*	6.60	-.60	3.10	13	-.73	.83

Correlation	Depth	Magnesium					Sodium				
		$\bar{d}$	S_d	df	t	$S_{\bar{d}}$	$\bar{d}$	S_d	df	t	$S_{\bar{d}}$
Field Moist vs Air Dry (25 C)	0-6	.78	.50	17	6.65*	.12	.22	.20	17	4.76*	.05
	6-12	1.37	.54	17	10.82*	.13	.15	.15	17	4.15*	.04
Air Dry vs 60 C dried, < 20 mesh	0-6	-.45	.41	17	-4.72*	.10	-.26	.10	17	-11.72*	.02
	6-12	-.77	.27	17	-12.04*	.06	-.24	.13	17	-7.66*	.03
60 C dried, < 20 mesh vs 60 C dried, unground	0-6	.08	.18	16	1.89	.04	.02	.06	16	1.03	.02
	6-12	.11	.21	17	2.21*	.05	.03	.08	17	1.55	.02
Field Moist vs 60 C dried, < 20 mesh 40% water	0-6	-.08	.21	17	-1.69	.05	.30	.19	17	6.61*	.05
	6-12	-.02	.50	17	-.16	.12	.25	.08	17	13.93*	.02
Field Moist vs 60 C, < 20 mesh	0-6	.33	.24	17	5.88*	.06	-.04	.17	17	1.01	.04
	6-12	.60	.50	17	5.11*	.12	-.09	.10	17	-3.73*	.02

1/ Sample mean difference

2/ Standard deviation of differences

3/ Degrees of freedom

4/ $\bar{d}/S_{\bar{d}}$

5/ Standard error of mean differences

* Sign. p is 0.05 or better

treatment. Comparisons were not made on Na. There was no significant difference in extractable K content of the 0 to 6-inch depth from any treatment. There were significant mean differences ($p = .05$) in the 6 to 12-inch depth between field moist versus oven dried soil K, field moist versus air dried soil K, field moist soil K versus K in oven dried, unground soils, and field moist soil K versus K in oven dried, ground and rehydrated soils. The existence of significant mean differences in the 6 to 12-inch but not in the 0 to 6-inch depth was probably the result of clay accumulation in the 6 to 12-inch depth.

An initial rehydration study was made to determine the K fixation properties of the 0 to 6 and 6 to 12-inch depths of ten selected soils. One set of subsamples was air dried (25 C) and another set was oven dried (60 C) prior to rehydration. Potassium determinations were made at weekly intervals on the moist samples. This was initially designed to be a time of rehydration study, but due to evaporation from the plastic snap-cap vials, some moisture was lost from the samples. Table 4 displays results of multiple regression analyses of the dependent variable (field moist soil K)/(K at given moisture), (Y_1) versus percentage moisture (X_1) in soils at the time the analyses were made, rehydration time in weeks (X_2), and ppm K measured (X_3) in these 0 to 6-inch depth samples at the specified moisture and rehydration time. The percentage moisture in soils at the time of analysis had a highly significant relationship with Y_1 in all regressions. The

Table 4. Multiple regression of rehydrated samples to determine the effect of percentage soil moisture (X1), rehydration time in weeks (X2), and ppm K measured (X3) on (field moist K)/(K at given moisture) (Y1). Data represent 0 to 6-inch soil depths.

Variables (indep.)	Mean	Part. Corr.	Reg. Coeff.	Standard Error of Reg.Coeff.	Comp. t	Inter-cept	R^2	Std. Error	F Value	Reg. df	Resid. df	Signif. F .01	Signif. t .01
X_1	23.37	-.607	-.0041	.00069	-5.96	.987	.368	.068	35.54	1	61	7.08	2.66
X_2	4.0	.426	.017	.0045	3.67	.825	.181	.072	13.50	1	61	7.08	2.66
X_3	415	.374	.00025	.00008	3.15	.788	.140	.074	9.91	1	61	7.08	2.66
X_1	23.37	-.497	-.0053	.0012	-4.43	1.05	.383	.063	18.63	2	60	4.98	2.66
X_2	4.0	-.154	-.0083	.0069	-1.21								
X_1	23.37	-.701	-.0044	.00058	-7.61	0.87	.562	.053	38.50	2	60	4.98	2.66
X_3	415	.554	.0003	.00006	-5.16								
X_2	4.0	.517	.019	.0041	4.68	0.69	.370	.064	17.59	2	60	4.98	2.66
X_3	415	.480	.0029	.00007	4.24								
X_1	23.37	-.563	-.0053	.001	-5.24	0.92	.570	.053	26.03	3	59	4.13	2.66
X_2	4.0	-.132	-.0060	.0058	-1.02								
X_3	415	.550	-.00029	.00006	5.06								

same was true for measured K, but this should have been expected, as K measured was a factor in computing the dependent variable. When rehydration time was regressed singly it also had a highly significant relationship with Y_1, but when included in a multiple regression this relationship appeared to be masked by soil moisture and ppm K measured.

Fine, et al. (1942) observed a reduction of exchangeable K following freezing of soils having high levels of exchangeable K. An experiment based on this information was devised to test the idea that the exchangeable K content of air-dried soils might be forced back to the level at which it existed prior to drying. A second rehydration experiment was conducted, similar to the first, but included freezing the 40% rehydrated soil samples at -29 C for 15 hours, followed by thawing, then air drying these samples at 12 hour intervals from 0 to 48-hours.

Table 5 contains results of the moisture and exchangeable K contents of 10 soils treated as described above. A paired t comparison revealed that the mean of the original field moist soil exchangeable K and the mean of exchangeable K in treated soils which had air dried for 48 hours were significantly different at the .05 level of confidence. This shows that exchangeable K in soils treated in this manner and dried for 48 hours will not revert to the field-moist concentration. However, a paired t comparison of the exchangeable K in the original field moist soil, with exchangeable K in selected 48-hour

Table 5. Potassium and moisture contents of ten soils which were air dried, rehydrated to 40% water, frozen for 15 hours at -29 C, thawed and allowed to air dry at 12-hour intervals from 0 to 48-hours. Values are averages of duplicate analyses.

Soil	Drying time hrs.	48	36	24	12	0	Original field moist	Air dry
Unknown	% moisture	4.46	7.66	19.69	29.65	35.47	14.55	
	ppm K	583	589	576	632	663	586	552
Evanston clay loam	% moisture	2.63	4.46	18.39	26.42	35.09	10.78	
	ppm K	369	374	375	398	420	375	347
Gerber clay loam	% moisture	11.28	16.14	29.30	33.32	39.80	15.76	
	ppm K	548	525	539	558	597	490	472
Chanta or Attewan loam	% moisture	0.61	3.91	12.88	25.01	40.76	10.82	
	ppm K	228	247	238	264	289	204	245
Fort Collins sandy loam	% moisture	1.44	1.67	11.02	25.76	39.72	8.97	
	ppm K	268	278	278	299	354	251	273
Williams clay loam	% moisture	1.44	4.93	16.99	27.72	40.69	10.89	
	ppm K	403	409	421	445	512	385	387
Cherry Silty clay loam	% moisture	11.31	19.93	26.23	32.82	41.94	12.66	
	ppm K	452	436	462	491	530	443	426
Cherry Silty clay loam	% moisture	10.74	18.97	25.94	32.05	42.72	15.26	
	ppm K	436	410	441	457	496	395	407
Martinsdale sandy clay loam	% moisture	1.88	3.24	15.60	25.36	39.20	13.90	
	ppm K	261	254	266	286	311	231	273
Absarokee clay loam	% moisture	1.02	1.91	15.47	26.06	38.85	-	
	ppm K	396	391	417	439	475	-	449

dried soils which contained less than five percent water, revealed that the means were similar when compared at the .05 level of confidence. From these tests it may be concluded that rehydration and freezing, followed by air drying to less than five percent water, but not completely dry, will cause exchangeable K in soils which had been air dried, to revert to the approximate content of the original field moist soils. If exchangeable K must be extracted from moist soils in the future, this reversion process could be used to bring the K content of soils which had been air dried, back to that of the original field moist condition.

Nine of these 10 soils showed significant correlations between exchangeable K and moisture content following the rehydration and freezing treatment (Table 6). It may be theorized that the rehydrated silicate clay layers were further expanded by the freeze treatment. Upon thawing, interlayer K was more susceptible to extraction for a variable period of time. This susceptible period appeared to be directly related to the moisture content. Subsequent gentle desiccation rendered the interlayer K less susceptible to extraction as the silicate layers collapsed. Severe desiccation would probably cause this fixed K to be released again. A graph of the relationship of soil moisture to exchangeable K in the Absarokee clay loam is shown in Figure 3. In this graph soil K appears to be directly related to the soil moisture content.

Table 6. Individual correlation coefficients for soils which were 40% moisture rehydrated, frozen at -29 C for 15 hours and dried at 12-hour intervals from 0 to 48-hours.

Percentage soil moisture versus soil K in ppm.

Soil	r	r^2	β	α	$\bar{X}$	$\bar{Y}$	Significance level .01	Significance level .05	d.f. [1]
Unknown	.853	.728	2.43	560	18.58	605		X	4
Evanston, clay loam	.920	.847	1.42	363	17.40	387	X		4
Gerber, clay loam	.729	.532	1.67	510	25.97	553			4
Chanta or Attewan loam	.945	.893	1.38	230	16.63	253	X		4
Fort Collins sandy loam	.940	.883	1.96	264	15.92	295	X		4
Williams clay loam	.944	.892	2.58	391	18.35	438	X		4
Cherry silty clay loam	.895	.801	2.82	400	26.45	474		X	4
Cherry silty clay loam	.843	.710	2.19	391	26.08	448		X	4
Martinsdale sandy clay loam	.970	.941	1.43	251	17.06	276	X		4
Absarokee clay loam	.991	.981	2.11	388	16.66	424	X		3

[1] With 4 degrees of freedom (d.f.) significance values are .917 .811
" 3 " " " " " " " .959 .878

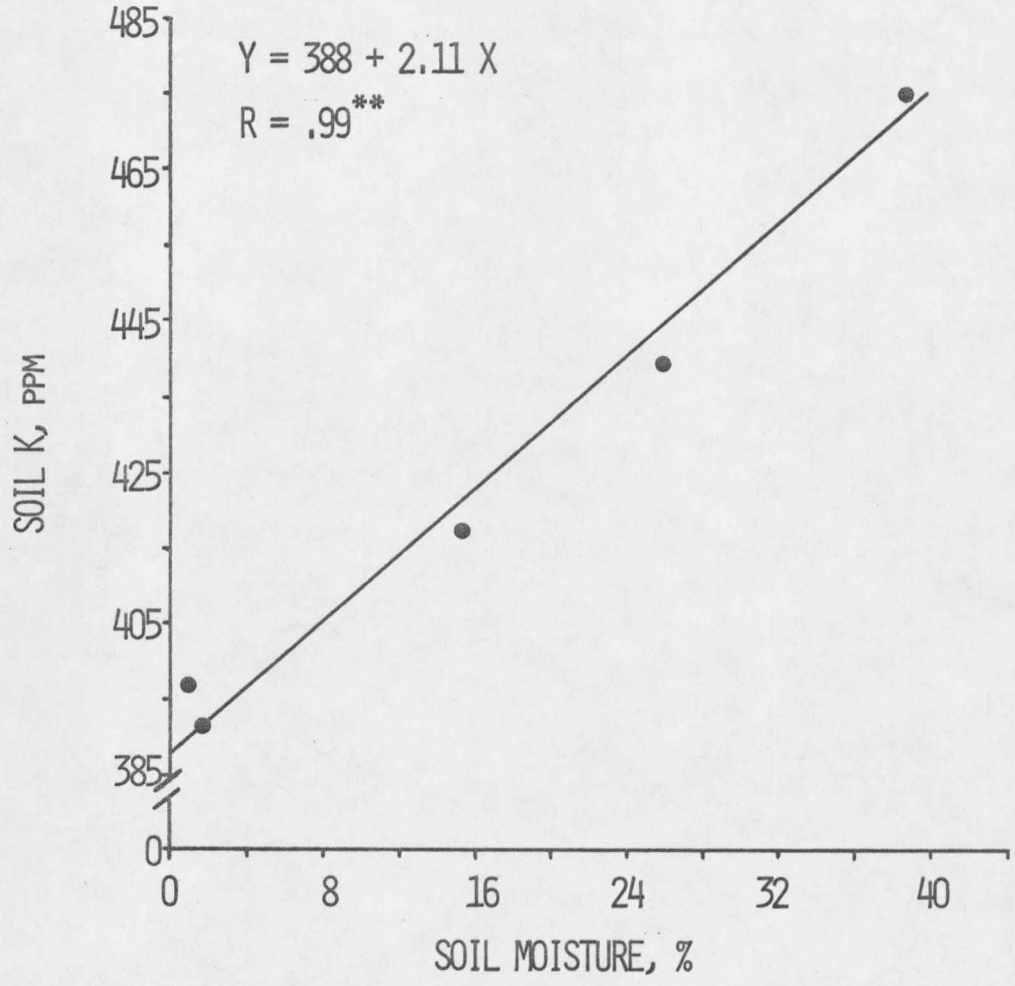


FIGURE 3. THE CORRELATION OF EXCHANGEABLE SOIL POTASSIUM WITH MOISTURE CONTENT OF AN ABSAROKEE 6-INCH SURFACE SOIL WHICH HAD BEEN REHYDRATED TO 40% WATER, FROZEN, AND DRIED TO THE ABOVE MOISTURE CONTENTS.

Extraction methods and calibrations, 1967 through 1971 soils.

The N NH_4OAc extractable K content of Montana soils is rated as very low, low, medium, and high for 0 to 75, 75 to 125, 125 to 250, and > 250 ppm respectively in the 0 to 6-inch depth. The probability of crop response to fertilizer K has been considered good in the very low and low categories. The medium K level has been considered a region of uncertainty, whereas crops growing in soils containing high levels of K supposedly will not respond to K application. However, as indicated earlier, this probability of crop response has not consistently been correct. Research results of attempts to calibrate the N NH_4OAc K technique and other extraction methods with crop response will be discussed below.

One normal ammonium acetate potassium extraction method. Analysis of dried soil samples from selected fertilizer experiments in 1967 through 1971 for available K by the N NH_4OAc extraction procedure, demonstrated a fallacy in this soil K rating system. These soils contained from 198 to 890 ppm K with an average of 408 ppm in the surface 6-inches of soil. The average yield increase due to K fertilization was 1.6 bu of winter wheat per acre with the greatest increase being 4.5 bu. The maximum yield depression was 1.68 bu per acre. This low magnitude of crop response to K may be one reason why it is difficult to calibrate a soil test for K in Montana. The yields and K test values for these 17 sites are shown in Table 7. Appendix Table 13

Table 7. Yields and K soil test results for the 1967 through 1971 K fertilizer trial sites.

Cooperator	Site year	Fert. K lbs/Ac	N NH_4OAc K, ppm		Response to K Bu/A	% Yield Response
			0-6 inch	6-12 inch		
Bates	1971	25	625	318	2.65	5.69
Bramlette	1967	25	545	427	-1.68	-4.39
Carter	1969	25	295	178	-1.06	-2.86
Dahlman	1967	25	214	184	1.50	3.61
Dahlman	1969	25	269	220	3.66	8.01
Dyk	1971	25	429	293	1.95	6.17
Fadhl	1967	25	219	110	1.48	5.31
Gagnon	1967	25	452	365	1.11	3.21
Goodan	1967	25	890	917	4.46	13.21
Hanser	1967	25	413	309	1.06	1.94
Holland	1971	100	317	198	-1.42	-3.09
Iverson	1967	25	420	239	1.01	3.19
O'Conner	1969	25	198	189	2.21	8.90
Ross	1967	25	300	223	4.03	12.86
Schultz	1967	25	324	149	-0.01	-0.05
Torski	1971	25	661	444	3.10	5.52
Walker	1969	25	368	188	-0.36	-0.85

describes these sites by county, soil type, crop variety, rainfall, and available soil moisture when these factors were available.

The data in Table 7 infer that N NH_4OAc extractable soil K is not sufficient by itself to predict response of winter wheat to K fertilization. For example, the Carter site soil contained 295 ppm K, yet K fertilization decreased the yield below the check. The Goodan site soil contained 890 ppm K but the yield was increased due to applied K after N had decreased yields below the check. These research results indicate that the soil test for K in Montana soils needs improvement.

Table 8 contains the mean values and standard deviations along with the units for variables used with each extraction technique attempted on the 1967 through the 1971 site soil samples.

Table 9 contains multiple linear regression equations, squared regression coefficients, and correlation coefficients relating percentage yield response (PYR) of winter wheat to N NH_4OAc K in the surface 6-inches and in the 6 to 12-inch depths. Although some of the equations shown in this and succeeding tables of regression results may not have been statistically significant, it is imperative that their R^2 values be discussed when comparing extraction methods. Table 9 illustrates that only 5% of the yield variation could be explained by soil test K in the surface 6 inches. Nearly 23% could be explained by including the 6 to 12-inch depth K, but 32% of this variation in yield response was accounted for by including fertilizer K in addition

Table 8. Mean and standard deviation of variables used for predicting percentage yield response of winter wheat from the 1967 through 1971 sites.

Variable	Units		Mean	Std. Dev.
K treatment yield	lbs/A		2429	539
Control yield	lbs/A		2345	533
Percentage yield response			3.91	5.16
Average K rate,	lbs/A		1/ 29.41	18.19
One N NH_4OAc extractable K	ppm	a	408	184
		b	291	187
		c	350	181
Saturated paste extraction, soluble K	ppm	a	24.2	14.7
		b	13.8	16.7
		c	19.0	15.5
$RT\ln[K]/[Ca]^{\frac{1}{2}}$	cal.	a	-2458	278
		b	-2841	374
		c	-2610	292
$RT\ln[K]/[Ca+Mg]^{\frac{1}{2}}$	cal.	a	-2659	257
		b	-3053	364
		c	-2818	280
$RT\ln[K]/[Mg]^{\frac{1}{2}}$	cal.	a	-2441	250
		b	-2844	363
		c	-2607	280
Dilute cation solution extraction, solution K	ppm	a	20.52	7.11
		b	14.56	8.69
		c	17.26	7.78
$RT\ln[K]/[Ca]^{\frac{1}{2}}$		a	-2925	186
		b	-3157	238
		c	-3027	201
$RT\ln[K]/[Ca+Mg]^{\frac{1}{2}}$	cal.	a	-3002	180
		b	-3239	231
		c	-3106	196
$RT\ln[K]/[Mg]^{\frac{1}{2}}$	cal.	a	-2558	176
		b	-2812	220
		c	-2667	190
Dilute K solution extraction, solution K	ppm	a	9.17	2.26
		b	7.71	2.76
		c	8.44	2.47
$RT\ln[K]/[Ca]^{\frac{1}{2}}$	cal.	a	-2458	206
		b	-2663	221
		c	-2566	197
$RT\ln[K]/[Ca+Mg]^{\frac{1}{2}}$	cal.	a	-2588	190
		b	-2761	211
		c	-2664	186
$RT\ln[K]/[Mg]^{\frac{1}{2}}$	cal.	a	-2176	170
		b	-2375	207
		c	-2278	178
DTPA extractable K	ppm	a	193	98
		b	128	107
		c	161	101
HEDTA extractable K	ppm	a	270	135
		b	176	142
		c	223	133
Resin plus NH_4OAc extractable K	ppm	a	576	225
		b	417	231
		c	497	222
Moderately available K [(resin + NH_4OAc) - NH_4OAc]	ppm	a	186	55
		b	134	54
		c	160	51
Resin-thimble extraction	ppm	a	132	65
		b	89	74
		c	111	69

1/ a = 0 to 6-inch depth; b = 6 to 12-inch depth; c = average of 0 to 6 and 6 to 12-inch depths.

Table 9. Multiple linear regression equations and correlations relating winter wheat percentage yield response to K applied and N NH_4OAc extractable soil K, 1967 to 1971 data.

Equation	F 1/	SE 2/	R^2
1. Y = 4.65 - .093 x 1 + .0049 x 2	1.27	5.07	.154
2. Y = 6.76 - .090 x 1 - .02 x 2 + .027 x 3	2.08	4.70	.324
3. Y = 3.94 - .090 x 1 + .0075 x 4	1.66	4.96	.191
4. Y = 1.43 + .0061 x 2	.74	5.20	.047
5. Y = 3.72 - .019 x 2 + .027# x 3	2.04	4.85	.226
6. Y = 0.88 + .0087 x 4	1.53	5.07	.092

Correlation Coefficients:

	Variables			
	1 K Appl.	2 0-6 K	3 6-12 K	4 Aver K
K treatment yield	.117	.387	.250	.326
Control yield		.323	.161	.248
Yield response, %	-.351	.217	.376	.304

1/ F ratio due to regression; n = 17.

2/ Standard error of the estimate

sign. p = 0.10

to the K extracted from these two soil depths. The latter regression also gave the lowest standard error of the estimate. When the K extracted from the 0 to 6 and 6 to 12-inch depths was averaged, and, along with K applied was regressed on PYR, the predictive power of the N NH_4OAc K test decreased to 19%. However, the analysis of variance (ANOV) F was not significantly different from the value in the "F" Table at the .05 confidence level. The information presented by Skogley (1971) agrees with these results.

Yeast cell potassium extraction method. The pH in a yeast cell suspension (3.8) probably approximates the pH of the soil in close proximity to an active plant root.

Results of the initial experiment to determine the absorption of K by yeast cells are presented in Figure 4. This experiment determined that the uptake of K, as a percentage of that added, became constant between 48 and 80 ppm K added. This verifies the results reported by Leggett, Olsen, and Spangler (1962). This constant percentage uptake of K lead to the idea that yeast cells might act as a sink for K in a manner similar to an ion exchange resin. If this were true, a resin would serve as a much less complicated sink to use for K exchange from soils. In addition, the process of growing the yeast cells in a K free medium to dilute their original K concentration to an acceptable level was considered too tedious for use as a routine soil test method. Also the cells were difficultly soluble in soluene-

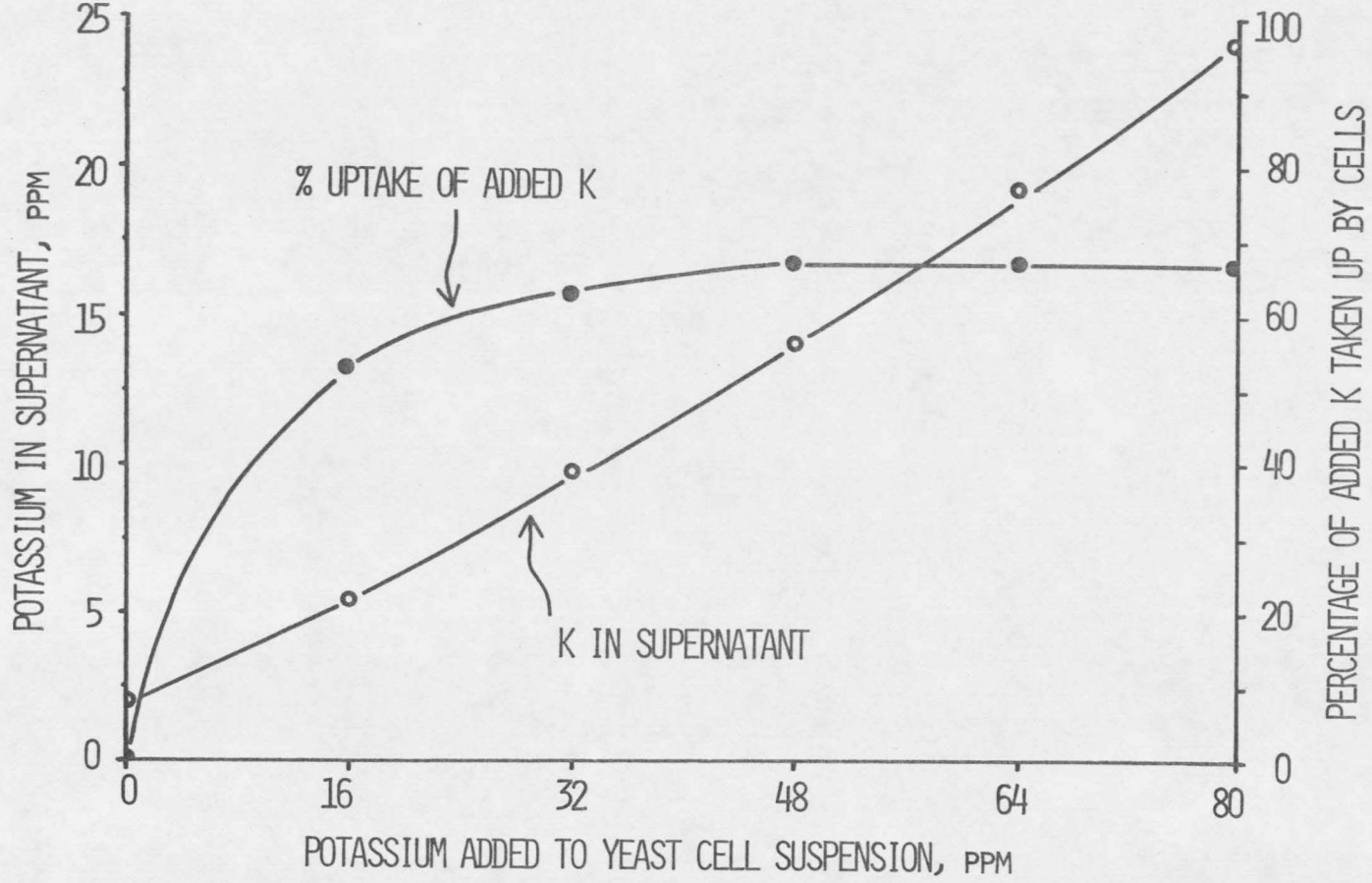


FIGURE 4. POTASSIUM IN SUPERNATANT AND PERCENTAGE OF ADDED K TAKEN UP BY CELLS VS. POTASSIUM ADDED TO YEAST CELL SUSPENSION.

100. These findings and problems lead to the abandonment of the yeast cell K extraction idea.

Saturated paste (soluble) K extraction method. At the initiation of this research it could not be determined whether to use percentage yield response from all treatments in an experiment, the average response for all treatments, or a specific treatment from a given experiment for correlation and regression analyses. Therefore, three regression analyses were computed using percentage yield response from data handled by the above methods versus soil K extracted by the saturated paste method. An R^2 of .11 and a standard error of 3.84 were generated by the regression of applied K and indigenous soil K in the 0 to 6 and 6 to 12-inch depths versus PYR. For the same regression but using the average percent yield response as the dependent variable the R^2 and standard error values were .26 and 4.76, respectively. When percent yield response from one selected K treatment within each experimental site was used as the dependent variable the R^2 and standard error values generated were .35 and 4.63, respectively. The largest R^2 was obtained by regression against the PYR from one selected K treatment from each site. The lowest standard error of the estimate (SE) was obtained when the PYR from all treatments was used in the regression. Despite this lower SE it was felt that the greater variation explanatory power should be the overriding factor. The PYR from the one selected K treatment was used in succeeding regression analyses

throughout this thesis.

The possibility that N NH_4OAc may be too harsh an extractant for K availability in Montana soils lead to this attempt to relate water soluble K to crop response. The saturated paste extraction technique was used on the 1967 through 1971 site soil samples. Appendix table 3 shows results of Ca, Mg, and K concentrations in the 0 to 6 and 6 to 12-inch soil depths by saturated paste extraction. The predictive ability of this method was only a slight improvement over that of N NH_4OAc, accounting for 34.5% of the variation in PYR when fertilizer K and 0 to 6 and 6 to 12-inch depth K were regressed over PYR (Table 10). In all cases, regressions one, two, and three which included applied K as a variable, produced higher R^2 values than their counterparts four, five, and six which did not include applied K. The ANOV F test indicated that regression equations three, four, and six were significant at the .10 level. The coefficients from the correlation of K applied versus K treatment yield and versus PYR were .12 and -.35, respectively. These are nonsignificant and will remain the same regardless of the soil extraction method used on these same samples. The relation of the 6 to 12-inch depth soluble K versus PYR was the only statistically significant correlation obtained by use of the saturated paste extraction technique. The computation of PYR changed the sign on the coefficient to positive when reasoning suggests it should probably have been negative.

Table 10. Multiple linear regression equations and correlations relating winter wheat percentage yield response to K applied and saturated paste soil K, 1967 to 1971 data.

	Equation	F 1/	SE 2/	R^2
1.	Y = 3.19 - .089 x 1 + .138 x 2	2.69	4.68	.278
2.	Y = 6.22 - .091 x 1 -.124 x 2 + .244 x 3	2.28	4.63	.345
3.	Y = 3.78 - .089 x 1 + .145# x 4	3.16#	4.57	.311
4.	Y = .320 + .149# x 2	3.30#	4.82	.180
5.	Y = 3.16 - .102 x 2 + .234 x 3	2.24	4.80	.242
6.	Y = .993 + .154# x 4	4.08#	4.72	.213

Correlation coefficients:

	Variables 1 K Appl.	2 ppm K(0-6)	3 ppm K(6-12)	4 ppm K(Aver.)
K treatment yield	.117	-.110	-.042	-.076
Control yield		-.190	-.140	-.167
Yield response, %	-.351	.425	.483*	.462

1/ F ratio due to regression; n = 17

2/ Standard error of the estimate

Sign. p = 0.10
* Sign. p = 0.05

Tables 11, 12, and 13 present regression and correlation results for free energy of K exchange (G_K)[15/] computations based on the respective ratios $[K]/[Ca]^{\frac{1}{2}}$, $[K]/[Ca+Mg]^{\frac{1}{2}}$, and $[K]/[Mg]^{\frac{1}{2}}$ from cations extracted by the saturated soil paste method. Free energy calculated from the ratio $[K]/[Ca]^{\frac{1}{2}}$ (Table 11) produced the only significant F value (.10 level) based on the ANOV for the regression of PYR versus applied K, and 0 to 6 and 6 to 12-inch depth G_K, or from the same regression without the applied K variable. The single degree of freedom F test revealed that there was significant variation (.10 level) in the effect of G_K from the 0 to 6 and from the 6 to 12-inch depths on yield response in equations one and five, respectively. This contributed toward the significant F. When PYR was regressed over the 0 to 6-inch soil K as the independent variable, the soil K provided significant variation on yield response at the .10 level (Table 10).

The mean K values from the seventeen 1967 through 1971 site soils by N NH_4OAc extraction were 408 ppm in the 0 to 6 and 291 ppm in the 6 to 12-inch depths. For these same depths, the soluble K content by saturated paste extraction was 24 and 14 ppm, respectively. In general, the water soluble K levels in Montana's cultivated small grain cropped

15/ Woodruff's original notation for energy of exchange was F. Baker's notation was E_K. However, current physical chemistry texts are using G. In an effort to avoid duplication of terminology with the chemistry profession, G_K will be used in this thesis to refer to the free energy of K exchange from the ratio of K to Ca and/or Mg.

Table 11. Multiple linear regression equations and correlations relating winter wheat percentage yield response to K applied and the free energy of exchange, $RT\ln[K]/[Ca]^{\frac{1}{2}}$, by saturated paste soil extraction. Brackets denote conc in moles per liter, 1967 to 1971 data.

	Equation	F 1/	SE 2/	R^2
1.	$Y = 15.72 - .097 \times 1 + .0036 \times 5$	1.35	5.05	.162
2.	$Y = 17.84 - .084 \times 1 - .0075^{*} \times 5 + .011 \times 6$	2.65#	4.51	.379
3.	$Y = 22.14 - .092 \times 1 + .006 \times 7$	2.17	4.82	.236
4.	$Y = 13.67 + .004 \times 5$	.71	5.20	.046
5.	$Y = 16.23 - .0079 \times 5 + .011^{*} \times 6$	2.91#	4.63	.294
6.	$Y = 20.70 + .0064 \times 7$	2.30	4.96	.133

Correlation coefficients:

	Variables 1 K Appl.	5 G_K(0-6)	6 G_K(6-12)	7 G_K(Aver.)
K treatment yield	.117	-.037	-.026	-.022
Control yield		-.076	-.123	-.094
Yield response, %	-.351	.214	.474	.365

1/ F ratio due to regression; n = 17

2/ Standard error of the estimate

\# Sign. p = 0.10

* Sign. p = 0.05

Table 12. Multiple linear regression equations and correlations relating winter wheat percentage yield response to K applied and the free energy of exchange, $RT\ln[K]/[Ca+Mg]^{\frac{1}{2}}$, by saturated paste soil extraction. Brackets denote conc in moles per liter, 1967 to 1971 data.

Equation	F 1/	SE 2/	R^2
1. $Y = 15.2 - .097 \times 1 + .0032 \times 8$	1.22	5.09	.149
2. $Y = 15.4 - .089 \times 1 - .0092 \times 8 + .011^{\#} \times 9$	2.43	4.58	.359
3. $Y = 21.99 - .093 \times 1 + .0055 \times 10$	1.87	4.90	.211
4. $Y = 13.56 + .0036 \times 8$	.51	5.24	.034
5. $Y = 13.9 - .0093 \times 8 + .011^{\#} \times 9$	2.49	4.73	.262
6. $Y = 20.67 + .0059 \times 10$	1.75	5.04	.104

Correlation coefficients:

	Variables			
	1	8	9	10
	K Appl.	G_K(0-6)	G_K(6-12)	G_K(Aver.)
K treatment yield	.117	-.060	-.020	-.032
Control yield		-.089	-.106	-.094
Yield response, %	-.351	.181	.431	.324

1/ F ratio due to regression; n = 17

2/ Standard error of the estimate

Sign. p = 0.10

Table 13. Multiple linear regression equations and correlations relating winter wheat percentage yield response to K applied and the free energy of exchange, $RT\ln[K]/[Mg]^{\frac{1}{2}}$, by saturated paste soil extraction. Brackets denote conc in moles per liter, 1967 to 1971 data.

	Equation	F 1/	SE 2/	R^2
1.	$Y = 12.72 - .097 \times 1 + .0024 \times 11$	1.11	5.12	.137
2.	$Y = 12.21 - .094 \times 1 - .0104 \times 11 + .0109^{\#} \times 12$	2.18	4.66	.335
3.	$Y = 18.52 - .094 \times 1 + .0046 \times 13$	1.58	4.98	.184
4.	$Y = 11.41 + .0031 \times 11$	.34	5.26	.022
5.	$Y = 10.92 - .0010 \times 11 + .011^{\#} \times 12$	2.03	4.85	.225
6.	$Y = 17.11 + .0051 \times 13$	1.23	5.12	.076

Correlation coefficients:

	Variables			
	1	11	12	13
	K Appl.	G_K(0-6)	G_K(6-12)	G_K(Aver.)
K treatment yield	.117	-.078	-.009	-.027
Control yield		.099	-.085	-.077
Yield response, %	-.3513	.149	.382	.276

1/ F due to regression; n = 17

2/ Standard error of the estimate

\# Sign p = 0.10

soils amount to 5.9 and 4.6% of the N NH_4OAc extractable K in the 0 to 6 and 6 to 12-inch depths, respectively.

Dilute Ca, Mg, and K solution equilibration method. Multiple linear regression results from extraction of the 1967 through 1971 experimental site soil samples by the dilute cation method of Baker (1971) are reported in tables 14 through 17. Appendix Table 4 reports the concentrations of Ca, Mg, and K in these solutions following equilibration with the soil samples.

Four computation methods were tried in regressions on these data. Tables 14, 15, 16, and 17 represent regressions of solution K and G_K from $[K]/[Ca]^{\frac{1}{2}}$, $[K]/[Ca+Mg]^{\frac{1}{2}}$, and $[K]/[Mg]^{\frac{1}{2}}$, respectively. Regression of PYR versus solution K or free energy in both the 0 to 6 and 6 to 12-inch depths with or without applied fertilizer K (equations two and five, respectively), produced F values which indicate that at least one regression coefficient was different from zero at the .05 level of confidence. The single degree of freedom "F" test indicated that there was significant variation, at the .05 level, in the effect of solution K or G_K from the 0 to 6-inch depth, and at the .01 level in the effect of solution K or G_K from the 6 to 12-inch depth in both equations from these tables. Regression of PYR versus the 0 to 6 or the average of the 0 to 6 and 6 to 12-inch depth solution K or G_K, with or without applied fertilizer K failed to produce significant relationships.

Comparisons of the R^2 values from the statistically significant

Table 14. Multiple linear regression equations and correlations relating winter wheat percentage yield response to K applied and solution K by dilute cation extract (Baker, 1971), 1967 to 1971 data.

Equation	F 1/	SE 2/	R^2
1. Y = 3.30 - .093 x 1 + .162 x 2	1.46	5.01	.173
2. Y = 10.5 - .093 x 1 - .806* x 2 + .869** x 3	4.93*	3.91	.532
3. Y = 2.68 - .090 x 1 + .225 x 4	2.19	4.81	.238
4. Y = .048 + .188 x 2	1.08	5.14	.067
5. Y = 7.25 - .780* x 2 + .869** x 3	5.21*	4.17	.423
6. Y = -.325 + .245 x 4	2.39	4.95	.137

Correlation coefficients:

	Variables			
	1 K Appl.	2 ppm K(0-6)	3 ppm K(6-12)	4 ppm K(Aver.)
K treatment yield	.117	.123	.008	.092
Control yield		.063	-.092	.011
Yield response, %	-.351	.260	.482*	.370

1/ F due to regression; n = 17

2/ Standard error of the estimate

* Sign. p = 0.05
** Sign. p = 0.01

Table 15. Multiple linear regression equations and correlations relating winter wheat percentage yield response to K applied and free energy of exchange, $RT\ln[K]/[Ca]^{\frac{1}{2}}$, by dilute cation extraction (Baker, 1971), 1967 through 1971 data. Brackets denote conc in moles per liter.

	Equation	F [1/]	SE [2/]	R^2
1.	Y = 18.8 - .096 x 1 + .0041 x 5	1.19	5.09	.146
2.	Y = 17.78 - .082 x 1 .025* x 5 + .026** x 6	5.24*	3.85	.547
3.	Y = 30.99 - .090 x 1 + .0081 x 7	1.99	4.86	.222
4.	Y = 18.45 + .005 x 5	.50	5.24	.032
5.	Y = 17.43 - .025* x 5 + .027** x 6	6.08*	4.03	.465
6.	Y = 30.99 + .0089 x 7	2.08	4.99	.122

Correlation coefficients:

	Variables			
	1 K Appl.	5 G_K(0-6)	6 G_K(6-12)	7 G_K(Aver.)
K treatment yield	.117	.120	.046	.127
Control yield		.154	-.059	.049
Yield response, %	-.351	.179	.496*	.349

1/ F due to regression; n = 17

2/ Standard error of the estimate

* Sign. p = 0.05
** Sign. p = 0.01

Table 16. Multiple linear regression equations and correlations relating winter wheat percentage yield response to K applied and free energy of exchange, $RT\ln[K]/[Ca+Mg]^{\frac{1}{2}}$, by dilute cation extraction (Baker, 1971), 1967 through 1971 data. Brackets denote conc in moles per liter.

Equation	F [1/]	SE [2/]	R^2
1. $Y = 17.38 - .096 \times 1 + .0035 \times 8$	1.13	5.12	.139
2. $Y = 16.23 - .084 \times 1 - .026^* \times 8 + .027^{**} \times 9$	5.07*	3.88	.539
3. $Y = 30.21 - .090 \times 1 + .0076 \times 10$	1.82	4.91	.206
4. $Y = 17.31 + .0045 \times 8$	.37	5.26	.024
5. $Y = 16.13 - .026^* \times 8 + .028^{**} \times 9$	5.77*	4.08	.452
6. $Y = 30.46 + .0085 \times 10$	1.77	5.04	.105

Correlation coefficients:

	Variables 1 K Appl.	8 G_K(0-6)	9 G_K(6-12)	10 G_K(Aver.)
K treatment yield	.117	.178	.027	.118
Control yield		.138	-.072	.046
Yield response, %	-.351	.156	.474	.325

1/ F due to regression; n = 17

2/ Standard error of the estimate

* Sign p = 0.05

** Sign p = 0.01

Table 17. Multiple linear regression equations and correlations relating winter wheat percentage yield response to K applied and free energy of exchange, $RT\ln[K]/[Mg]^{\frac{1}{2}}$, by dilute cation extraction (Baker, 1971), 1967 through 1971 data. Brackets denote conc in moles per liter.

Equation	F 1/	SE 2/	R^2
1. $Y = 9.51 - .098 \times 1 + .0011 \times 11$	1.00	5.16	.125
2. $Y = 11.79 - .094 \times 1 - .028^{*} \times 11 + .027^{**} \times 12$	4.19*	4.08	.491
3. $Y = 20.75 - .093 \times 1 + .0053 \times 13$	1.34	5.05	.161
4. $Y = 9.71 + .0023 \times 11$	.091	5.31	.006
5. $Y = 12.01 - .027^{*} \times 11 + .028^{**} \times 12$	4.35*	4.33	.383
6. $Y = 21.00 + .0064 \times 13$	.89	5.17	.056

Correlation coefficient:

	Variables			
	1	11	12	13
	K Appl.	G_K(0-6)	G_K(6-12)	G_K(Aver.)
K treatment yield	.117	.089	-.037	.076
Control yield		.071	-.113	.026
Yield response, %	-.351	.077	.385	.236

1/ F due to regression n = 17.

2/ Standard error of the estimate

* Sign p = 0.05

** Sign p = 0.01

equations reveals that the regression including applied fertilizer K and the 0 to 6 and 6 to 12-inch depth solution K or G_K by any computation method, explained more of the variation in PYR than did the regression which did not include fertilizer K. Calculation of adjusted R^2 values by the method of Yamane (1967)[16/] reveals that this explanatory power holds true despite the addition of one more variable in equation two compared to five. The adjusted R^2 for equation two was .42 compared to .34 for equation five. This dilute cation equilibration procedure is simple and reproducible. The cation concentration keeps the soil sufficiently flocculated for clear filtration through Whatman No. 1 paper. A computer is desirable to calculate the G_K values. However, it is possible to use only the solution K concentrations following equilibration of this solution with soils. The R^2 for solution K by equation 2 was .53 (Table 14) compared to .55 from the comparable equation for G_K calculated from the ratio $[K]/[Ca]^{\frac{1}{2}}$ (Table 15).

16/ Adj. $R^2 = 1 - \frac{(\text{S.S. residual})}{(\text{S.S. total})} \times \frac{(n-1)}{(n-q-1)}$ or $1 - (1-R^2) \times \frac{(n-1)}{(n-q-1)}$,

where q = the number of variables fitted.
The difference between R^2 and adjusted R^2 is an estimation process which attempts to eliminate the amount of variation which occurs just because another variable is entered, no matter what the other variable is.

Dilute potassium solution equilibration method. The soil samples from the 1967 through 1971 experimental sites were equilibrated with a 0.00024 M solution of KCl (9.4 ppm K). Theoretically, if the soil was K deficient it would remove K from this solution. If the soil contained an excess of K, it would release K to the solution. Comparison of the equilibrium K values in Appendix Table 5 and the response to K application shown in Table 7 reveals that each depth of soil from the Goodan site released about 7 ppm K to the equilibrating solution. Winter wheat yields were increased 4.46 bu/acre by the addition of 25 lbs K/acre. This same K rate decreased winter wheat yield on the Bramlette site by 1.68 bu/acre even though the soil took K from solution.

Results of regression analyses for the dilute K equilibration method are reported in Tables 18 through 21. Equilibrium solution K and G_K from the ratio $[K]/[Mg]^{\frac{1}{2}}$ failed to produce statistically significant regressions (Tables 18 and 21). In Tables 19 and 20 the regressions of PYR versus applied fertilizer K and the 0 to 6-inch depth G_K from the ratios $[K]/[Ca]^{\frac{1}{2}}$ and $[K]/[Ca+Mg]^{\frac{1}{2}}$, respectively, were significant at the .10 level. The single degree of freedom F test (.05 level) indicates that the 6 to 12-inch depth G_K was the main contributing variable in these regressions. Equation five in Table 19 produced an ANOV F which was significant at the .05 level compared to the .10 level for the related equation in Table 20. Applied K and G_K from

Table 18. Multiple linear regression equations and correlations relating winter wheat percentage yield response to K applied and solution K by dilute K extraction of the 1967 through 1971 site soils.

Equation	F 1/	SE 2/	R^2
1. Y = 0.48 - .085 x 1 + .647 x 2	1.76	4.93	.201
2. Y = 1.73 - .090 x 1 + .213 x 2 + .372 x 3	1.12	5.10	.205
3. Y = 1.42 - .089 x 1 + .605 x 4	1.81	4.91	.206
4. Y = - 3.14 + .769 x 2	1.92	5.01	.113
5. Y = - 3.18 + .785 x 2 - .014 x 3	.89	5.19	.113
6. Y = - 1.92 + .691 x 4	1.84	5.02	.109

Correlation coefficients:

	Variables 1	2	3	4
	K Appl.	ppmK(0-6)	ppmK(6-12)	ppmK(Aver.)
K treatment yield	.117	.0046	-.112	-.060
Control yield		-.064	-.171	-.125
Yield response, %	-.351	.337	.316	.331

1/ F due to regression; n = 17

2/ Standard error of the estimate.

Table 19. Multiple linear regression equations and correlations relating winter wheat percentage yield response to K applied and free energy of exchange, $RT\ln[K]/[Ca]^{\frac{1}{2}}$, by dilute K solution equilibration. Brackets denote conc in moles per liter, 1967 through 1971 data.

Equation	F 1/	SE 2/	R^2
1. Y = 13.16 - .099 x 1 + .0026 x 5	1.08	5.13	.134
2. Y = 26.93 - .077 x 1 - .012 x 5 + .019* x 6	3.31#	4.31	.433
3. Y = 30.40 - .089 x 1 + .0093 x 7	2.31	4.78	.248
4. Y = 10.89 + .0028 x 5	0.20	5.29	.013
5. Y = 26.2 - .013 x 5 + .020* x 6	4.00*	4.40	.363
6. Y = 29.88 + .010 x 7	2.64	4.91	.150

Correlation coefficients:

	Variables 1 K Appl.	5 G_K(0-6)	6 G_K(6-12)	7 G_K(Aver.)
K treatment yield	.117	.065	-.029	.042
Control yield		.042	-.127	-.037
Yield response, %	-.351	.114	.492*	.387

1/ F due to regression n = 17

2/ Standard error of the estimate

\# Sign. p = 0.10

* Sign. p = 0.05

Table 20. Multiple linear regressions and correlations relating winter wheat percentage yield response to K applied and free energy of exchange, $RT\ln[K]/[Ca+Mg]^{\frac{1}{2}}$, by dilute K solution equilibration. Brackets denote conc in moles per liter, 1967 through 1971 data.

	Equation	F 1/	SE 2/	R^2
1.	Y = 12.79 - .099 x 1 + .0023 x 8	1.05	5.14	.131
2.	Y = 24.85 - .077 x 1 - .012 x 8 + .018* x 9	2.70#	4.49	.384
3.	Y = 29.99 - .090 x 1 + .0088 x 10	2.00	4.86	.223
4.	Y = 10.58 + .0026 x 8	.139	5.30	.009
5.	Y = 24.17 - .013 x 8 + .020* x 9	3.19#	4.57	.313
6.	Y = 29.83 + .0097 x 10	2.10	4.99	.123

Correlation coefficients:

	Variables			
	1 K Appl.	8 G_K(0-6)	9 G_K(6-12)	10 G_K(Aver.)
K treatment yield	.117	.042	-.060	.010
Control yield		.024	-.146	-.060
Yield response, %	-.351	.096	.447	.350

1/ F due to regression n = 17

2/ Standard error of the estimate

\# Sign. p = 0.10

* Sign. p = 0.05

Table 21. Multiple linear regressions and correlations relating winter wheat percentage yield response to K applied and free energy of exchange, $RT\ln[K]/[Mg]^{\frac{1}{2}}$, by dilute K solution equilibration. Brackets denote conc in moles per liter; 1967 through 1971 data.

	Equation	F 1/	SE 2/	R^2
1.	Y = 9.78 - .099 x 1 + .0014 x 11	1.00	5.15	.125
2.	Y = 13.67 - .082 x 1 - .012 x 11 + .014 x 12	1.43	4.96	.248
3.	Y = 19.56 - .093 x 1 + .0057 x 13	1.34	5.05	.161
4.	Y = 7.88 + .0018 x 11	.542	5.31	.004
5.	Y = 12.69 - .0135 x 11 + .016 x 12	1.41	5.03	.167
6.	Y = 19.53 + .0069 x 13	.89	5.17	.056

Correlation coefficients:

	Variables			
	1	11	12	13
	K Appl.	G_K(0-6)	G_K(6-12)	G_K(Aver.)
K treatment yield	.117	-.035	-.123	-.072
Control yield		-.041	-.174	-.113
Yield response, %	-.351	.060	.300	.236

1/ F due to regression n = 17

2/ Standard error of the estimate.

the ratio $[K]/[Ca]^{\frac{1}{2}}$ in the 0 to 6 and 6 to 12-inch depths accounted for 43% of the variation in PYR.

Correlations were run on G_K computed from six different K to Ca, Mg, and Na ratios on the 0 to 6-inch depth soil samples to determine which of these ratios were similar. The ratios were $[K]/[Ca]^{\frac{1}{2}}$, $[K]/[Ca+Mg]^{\frac{1}{2}}$, $[K]/[Mg]^{\frac{1}{2}}$, $[K]/[Ca+Mg^{\frac{1}{2}}+[Na]$, $[K]/[Ca+Mg/2]^{\frac{1}{2}}+[Na]$, and $[K]/[Ca+Mg/2]^{\frac{1}{2}}$ (Table 22). The r value from the table for significance at the .01 level with 17 degrees of freedom is .58. All the G_K values by any computation method were correlated at the .01 level. Observation of correlations one through five reveals that G_K from the ratio $[K]/[Ca]^{\frac{1}{2}}$ explains only 72% of the variation in the G_K from the ratio $[K]/[Mg]^{\frac{1}{2}}$. Consideration of correlations six through nine indicates that G_K from the ratio $[K]/[Mg]^{\frac{1}{2}}$ is not as good a predictor of G_K from $[K]/[Ca+Mg]^{\frac{1}{2}}$ as are the G_K values from the other three ratios. From these results the only ratios which need be used to compute G_K in future work are $[K]/[Ca]^{\frac{1}{2}}$, $[K]/[Ca+Mg]^{\frac{1}{2}}$, and $[K]/[Mg]^{\frac{1}{2}}$. Even G_K values from the ratios $[K]/[Ca]^{\frac{1}{2}}$ and $[K]/[Ca+Mg]^{\frac{1}{2}}$ are essentially the same in these soils.

One additional problem with this dilute potassium equilibration technique is the fact that the clay remained too dispersed. A clear filtrate could only be obtained by centrifugation.

Diethylene triamine pentaacetic acid-triethanolamine extractable K. Sodium saturated diethylene triamine pentaacetic acid-

Table 22. Correlations from comparison of the free energy values computed from the ratio of $[K]^*$ to $[Ca]^{\frac{1}{2}}$, $[Ca+Mg]^{\frac{1}{2}}$, $[Mg]^{\frac{1}{2}}$, $[Ca+Mg/2]^{\frac{1}{2}}$, $[Ca+Mg/2]^{\frac{1}{2}} + [Na]$, and $[Ca+Mg]^{\frac{1}{2}} + [Na]$. n = 19

No.	Correlation	r	r^2
1.	$[K]/[Ca]^{\frac{1}{2}}$ vs. $[K]/[Ca+Mg]^{\frac{1}{2}}$	.991**	.982
2.	" " $[K]/[Mg]^{\frac{1}{2}}$	.846**	.716
3.	" " $[K]/[Ca+Mg]^{\frac{1}{2}} + [Na]$	.991**	.982
4.	" " $[K]/[Ca+Mg/2]^{\frac{1}{2}}$	.992**	.984
5.	" " $[K]/[Ca+Mg/2]^{\frac{1}{2}} + [Na]$	.990**	.980
6.	$[K]/[Ca+Mg]^{\frac{1}{2}}$ vs $[K]/[Mg]^{\frac{1}{2}}$	.908**	.824
7.	" " " $[K]/[Ca+Mg]^{\frac{1}{2}} + [Na]$	1.00**	1.00
8.	" " " $[K]/[Ca+Mg/2]^{\frac{1}{2}}$	1.00**	1.00
9.	" " " $[K]/[Ca+Mg/2]^{\frac{1}{2}} + [Na]$	1.00**	1.00
10.	$[K]/[Mg]^{\frac{1}{2}}$ vs $[K]/[Ca+Mg]^{\frac{1}{2}} + [Na]$	.911**	.830
11.	" " $[K]/[Ca+Mg/2]^{\frac{1}{2}}$	.908**	.824
12.	" " $[K]/[Ca+Mg/2]^{\frac{1}{2}} + [Na]$	.912**	.832
13.	$[K]/[Ca+Mg]^{\frac{1}{2}} + [Na]$ vs $[K]/[Ca+Mg/2]^{\frac{1}{2}}$	.727**	.529
14.	" " " $[K]/[Ca+Mg/2]^{\frac{1}{2}} + [Na]$	.728**	.530
15.	$[K]/[Ca+Mg/2]^{\frac{1}{2}}$ vs $[K]/[Ca+Mg/2] + [Na]$	1.00**	1.00

* [ ] denote concentration in moles per liter.

** Sign. p = 0.99

triethanolamine (DTPA) buffered at pH 7.3 is a sodium chelate currently used in many western states for extraction of the micronutrients iron, zinc, copper, and manganese from soils. This solution also contains calcium, but is essentially devoid of K and Mg. Regression results from DTPA analysis of the 1967 through 1971 soils are shown in Table 23. Extractable Mg and K values are reported in Appendix Table 6. The DTPA extractable K in the surface 6-inch depth did not provide a significant ANOV F value (Equation 4, Table 23). However, when PYR was regressed over the 0 to 6 and 6 to 12-inch depth K, a significant relationship was obtained. Applied K along with soil K in both depths also produced a significant regression (Equation 2). This regression explained 47% of the variation in the PYR. It should be realized that the extraction of soil K by DTPA is probably not a chelation process. The reaction could be a simple exchange process whereby the Na and Ca in the DTPA solution exchange K from the clay. Calcium saturated DTPA becomes the major species above pH 7.5. The K - O.M. affinity research conducted by McGeorge (1931), Mehlich (1946), and Spencer (1954) indicates that the stability of K with chelates may be fairly low.

The extraction of plant available soil K by the DTPA method would simplify lab work in the respect that this is also the routine test method for iron, zinc, copper, and manganese. A very minor problem with the technique is that soils having very high clay content will absorb all of the DTPA solution at the 1:2 soil to solution ratio.

Table 23. Multiple linear regressions and correlations relating winter wheat percentage yield response to K applied and soil K by DTPA extraction, 1967 through 1971 data.

Equation	F 1/	SE 2/	R^2
1. Y = 4.05 - .093 x 1 + .013 x 2	1.62	4.97	.188
2. Y = 8.69 - .092 x 1 - .056* x 2 + .069* x 3	3.85*	4.16	.470
3. Y = 3.63 - .090 x 1 + .018 x 4	2.31	4.78	.248
4. Y = 1.00 + .015 x 2	1.34	5.10	.082
5. Y = 5.66 - .055 x 2 + .069* x 3	4.02*	4.39	.365
6. Y = .733 + .018 x 4	2.61	4.91	.148

Correlation coefficients:

	Variables			
	1 K Appl.	2 ppm K(0-6)	3 ppm K(6-12)	4 ppm K(Aver.)
K treatment yield	.117	.139	.075	.107
Control yield		.074	-.024	.022
Yield response, %	-.351	.286	.464	.385

1/ F due to regression; n = 17

2/ Standard error of the estimate

* Sign. p = 0.05

However, this usually occurs only with samples from the B_t or other illuvial horizons.

Hydrogen EDTA, resin plus NH_4OAc, and moderately available K methods. Tables 24, 25, and 26 present regression equations relating PYR to applied K and 0 to 6 and 6 to 12-inch depth K by extraction of soils with HEDTA, resin plus N NH_4OAc, and resin by the [(resin plus N NH_4OAc) minus N NH_4OAc] methods respectively. Appendix Table 7 illustrates the results of chemical analysis of the 1967 through 1971 experimental soils. No significant relationships between PYR versus fertilizer and soil K were developed by these test methods. However, research to modify the resin-NH_4OAc K extraction method of Barber and Matthews (1962), provided some insight into the use of the Dowex 50X8-50 resin for K extraction from soils. This will be considered in detail later in the thesis.

Resin-thimble potassium extraction method. Multiple linear regressions and correlations relating winter wheat response to K applied and the 0 to 6 and 6 to 12-inch depth extractable soil K by the resin-thimble method are exhibited in Table 27. In both equations two and five resin extractable soil K contributed toward the significant ANOV F. In equation two fertilizer K applied, 0 to 6-inch soil K, and 6 to 12-inch soil K were related to PYR at the .10, .05, and .01 levels, respectively. The R^2 value for equation two indicates that 56% of the variation in PYR on these sites is explainable by fertilizer

Table 24. Multiple linear regressions and correlations relating winter wheat percentage yield response to K applied and soil K by HEDTA extraction, 1967 through 1971 data.

	Equation	F 1/	SE 2/	R^2
1.	Y = 4.15 - .097 x 1 + .0096 x 2	1.61	4.97	.187
2.	Y = 5.37 - .089 x 1 - .011 x 2 + .023 x 3	1.93	4.76	.308
3.	Y = 3.70 - .093 x 1 + .013 x 4	2.22	4.80	.241
4.	Y = 1.16 + .0102 x 2	1.15	5.13	.071
5.	Y = 2.74 - .012 x 2 + .025 x 3	1.87	4.90	.211
6.	Y = 0.77 + .0141 x 4	2.29	4.96	.132

Correlation coefficients:

	Variables			
	1 K Appl.	2 ppm K(0-6)	3 ppm K(6-12)	4 ppm K(Aver.)
K treatment yield	.117	.208	.154	.188
Control yield		.140	.061	.104
Yield response, %	-.351	.267	.427	.364

1/ F due to regression; n = 17

2/ Standard error of the estimate

Table 25. Multiple linear regressions and correlations relating winter wheat percentage yield response to K applied and moderately available + exchangeable soil K by resin + N NH_4OAc extraction, 1967 through 1971 data.

Equation	F 1/	SE 2/	R^2
1. $Y = 4.45 - .092 \times 1 + .0038 \times 2$	1.23	5.08	.150
2. $Y = 6.64 - .092 \times 1 - .014 \times 2 + .020 \times 3$	1.91	4.76	.306
3. $Y = 3.58 - .089 \times 1 + .0059 \times 4$	1.60	4.97	.186
4. $Y = 1.07 + .0049 \times 2$	0.73	5.20	.046
5. $Y = 3.28 - .013 \times 2 + .020 \times 3$	1.79	4.92	.204
6. $Y = 0.42 + .0070 \times 4$	1.50	5.08	.091

Correlation coefficients:

	Variables			
	1 K Appl	2 ppm K(0-6)	3 ppm K(6-12)	4 ppm K(Aver.)
K treatment yield	.117	.397	.262	.338
Control yield		.334	.175	.260
Yield response, %	-.351	.215	.370	.302

1/ F due to regression n = 17

2/ Standard error of the estimate.

Table 26. Multiple linear regressions and correlations relating winter wheat response to K applied and moderately available soil K by resin [(resin + N NH_4OAc) - N NH_4OAc] extraction, 1967 through 1971 data.

Equation	F 1/	SE 2/	R^2
1. Y = 3.40 - .091 x 1 + .017 x 2	1.29	5.07	.155
2. Y = 3.71 - .082 x 1 - .021 x 2 + .049 x 3	1.42	4.96	.247
3. Y = 2.1 - .085 x 1 + .027 x 4	1.67	4.95	.193
4. Y = - 0.23 + .022 x 2	0.88	5.17	.056
5. Y = 0.48 - .020 x 2 + .054 x 3	1.39	5.03	.166
6. Y = - 1.32 + .033 x 4	1.78	5.03	.106

Correlation coefficients:

	Variables			
	1	2	3	4
	K Appl.	ppm K(0-6)	ppm K(6-12)	ppm K(Aver.)
K treatment yield	.117	.417	.327	.394
Control yield		.352	.235	.312
Yield response, %	-.351	.236	.387	.326

1/ F due to regression; n = 17

2/ Standard error of the estimate

Table 27. Multiple linear regressions and correlations relating winter wheat response to K applied and extractable soil K by the thimble-resin extraction technique, 1967 through 1971 data.

Equation	F 1/	SE 2/	R^2
1. Y = 3.78 - .087 x 1 + .020 x 2	1.63	4.96	.189
2. Y = 11.54 - .108# x 1 - .124* x 2 + .133** x 3	5.44*	3.81	.557
3. Y = 3.44 - .085 x 1 + .027 x 4	2.33	4.77	.250
4. Y = 0.68 + .025 x 2	1.60	5.06	.097
5. Y = 7.17 - .108* x 2 + .123* x 3	5.00*	4.21	.417
6. Y = 0.58 + .030 x 4	2.89	4.88	.161

Correlation coefficients:

	Variables			
	1	2	3	4
	K Appl.	ppm K(0-6)	ppm K(6-12)	ppm K(Aver.)
K treatment yield	.117	.135	.032	.080
Control yield		.065	-.068	-.007
Yield response, %	-.351	.311	.475	.402

1/ F due to regression; n = 17

2/ Standard error of the estimate

\# Sign. p = 0.10
* Sign. p = 0.05
** Sign. p = 0.01

K applied and resin extractable K in the two soil depths. The remaining variation in PYR must be due to other soil and crop properties and to climatic variables. Appendix Table 8 contains the resin extractable K values from the 1967 through 1971 site soils.

Table 28 is a summary of the standard error and R^2 values for the K extraction methods tried on the 1967 through 1971 experimental site soil samples. This table displays that the dilute cation solution, DTPA, and resin-thimble extraction for K were the only methods which produced significant ANOV F values for regression equations using extracted soil K and/or applied fertilizer K variables vs. PYR. Although the resin-thimble procedure explained the greatest amount of error, the precision between duplicate sample analyses was not good. The free energy calculated from the ratio $[K]/[Ca]^{\frac{1}{2}}$ in the dilute cation solution extraction method explained slightly less variation in PYR but was a very precise extraction method. These methods were tested on a second set of experimental site soil samples.

Extraction methods and calibrations, 1973 experimental soils.

Preferred extraction methods, including N NH_4OAc as a reference procedure, were tested with soils from selected 1973 winter wheat experimental sites. The N NH_4OAc K extraction procedure was also tried on soils from sugar beet, barley, and spring and winter wheat experiments. Appendix Table 14 describes these sites by county, soil

Table 28. An abstract of R^2 and standard error of the estimate values for the regression of percentage yield response versus applied K, and 0 to 6 and 6 to 12-inch indigenous soil K extracted, or free energy of exchange from the seventeen 1967 through 1971 soils by the various extraction techniques.

Extraction technique	Std. Error	R^2
1 N Ammonium acetate extraction	4.70	.324
Saturated paste extraction		
Soluble soil K	4.63	.345
$RT\ln[K]/[Ca]^{\frac{1}{2}}$	4.51	.379
$RT\ln[K]/[Ca+Mg]^{\frac{1}{2}}$	4.58	.359
$RT\ln[K]/[Mg]^{\frac{1}{2}}$	4.66	.335
Dilute cation solution extraction		
Solution K	3.91	.532*
$RT\ln[K]/[Ca]^{\frac{1}{2}}$	3.85	.547*
$RT\ln[K]/[Ca+Mg]^{\frac{1}{2}}$	3.88	.539*
$RT\ln[K]/[Mg]^{\frac{1}{2}}$	4.08	.491*
Dilute K solution extraction		
Solution K	5.10	.205
$RT\ln[K]/[Ca]^{\frac{1}{2}}$	4.31	.433
$RT\ln[K]/[Ca+Mg]^{\frac{1}{2}}$	4.49	.384
$RT\ln[K]/[Mg]^{\frac{1}{2}}$	4.96	.284
DTPA Extraction	4.16	.470*
HEDTA	4.76	.308
Moderately available + N NH_4OAc extractable K	4.76	.306
Moderately available K by $[(\text{resin} + NH_4OAc) - NH_4OAc]$	4.96	.247
Resin - thimble extraction	3.81	.557*

* ANOV F indicates regression coefficients were different at the .05 confidence level.

type, crop variety, rainfall, and available soil moisture when these factors were available. These experiments were done to gain additional evidence in favor of the predictability of a particular K extraction method and to determine the advantage of analyzing field moist or air dried soil samples. Climatic data were obtained from seven winter wheat experimental sites and used in a stepwise regression program to predict potential yield (PY), control yield (CY), and K fertilizer rate (FR).

One N NH_4OAc K extraction method. The N NH_4OAc extraction method for soil K was tried on sugar beets, barley, and spring and winter wheat. Appendix Tables 9 and 10 include data on K fertilizer rate, N NH_4OAc extractable K and selected physical and chemical properties of soils from the 1973 experimental sites. Table 29 represents results of multiple linear regression equations and correlations relating total sugar yield differences to N NH_4OAc extractable K in field moist and air-dried samples. No significant relationships were produced from these data even though the extractable K levels ranged from 102 to 565 ppm in the surface 6-inch depth. The K treatment yields remained essentially the same as the control yields. All the beet experiments were irrigated. According to Van der Paauw (1958) and Barber (1959) the response of wheat, potatoes, and canary grass to fertilizer K is inversely related to the amount of seasonal rainfall. One could then theorize that crops would respond to K less when adequately

Table 29. Multiple linear regression equations and correlations relating total sugar yield difference† to N NH_4OAc extractable K in field moist and air-dried samples, 1973 data.

	Equation	F 1/	SE 2/	R^2
	Field Moist			
1.	Y = 731 - 2.25 x 4	1.19	714.6	.230
2.	Y = -94.99 + .103 x 5	0.00	814	.000
3.	Y = 361 - 3.64 x 4 + 3.62 x 5	0.91	741	.378
	Air Dried			
4.	Y = 83.61 - .477 x 6	0.05	809	.014
5.	Y = - 56.92 - .0517 x 7	0.00	814	.000
6.	Y = - 547.8 - 2.82 x 6 + 5.29 x 7	0.12	904	.076

Correlation coefficients:

	Variables: Field Moist		Air Dry	
	4 ppm K(0-6)	5 ppm K(6-12)	6 ppm K(0-6)	7 ppm K(6-12)
K treatment yield	-.283	-.536	-.359	-.313
Control yield	-.131	-.564	-.335	-.325
Yield difference	-.479	.014	-.116	-.006

1/ F due to regression; n = 6

2/ Standard error of the estimate

†Yield difference = K treatment yields - Control yield

irrigated than when produced under water stress. This would probably be due to increased K diffusion to roots when moisture is in adequate supply. Though nonsignificant, the R^2 values for K extracted from field moist soils explained more of the variation in sugar yield differences than did this parameter for air dried soils.

Table 30 presents results of multiple linear regression equations and correlations relating spring wheat yield response in bu/acre to N NH_4OAc extractable K in field moist and air dried soil samples. Field moist soil K in the 6 to 12-inch depth was the only variable which contributed toward an ANOV-F value which was significant at the .05 level. Again, field moist soil analysis explained more variation in yield response than did air dried soil analysis. Though nonsignificant, a larger R^2 value is generated when 0 to 6 and 6 to 12-inch depth K results are regressed over yield response than when the 0 to 6-inch soil K is the only independent variable.

When barley and spring and winter wheat experimental site soil K and yield responses are pooled, no significant relationships could be obtained from N NH_4OAc extractable K vs. yield response. The regressions and correlations are presented in Table 31. The range of conditions under which these three crops are grown probably contributed sufficient variation to cause these nonsignificant regression equations.

The stepwise multiple regression program of Dixon (1970) was utilized on data from the 1973 winter wheat sites. This effort

Table 30. Multiple linear regression equations and correlations relating spring wheat yield response in bu/Acre to N NH_4OAc extractable K in field moist and air-dried samples, 1973 data.

	Equation	F 1/	SE 2/	R^2
	Field Moist			
1.	$Y = 1.46 + .0047 \times 4$	1.18	1.23	.283
2.	$Y = 0.46 + .016^* \times 5$	19.61*	0.53	.867
3.	$Y = 0.42 + .0002 \times 4 + .016 \times 5$	6.55	0.65	.868
	Air Dried			
4.	$Y = 1.53 + .0045 \times 6$	0.89	1.27	.228
5.	$Y = - 0.56 + .019 \times 7$	3.61	0.98	.546
6.	$Y = - 0.56 - .0002 \times 6 + .019 \times 7$	1.20	1.20	.546

Correlation coefficients:

	Variables			
	Field Moist		Air Dry	
	4 ppm K(0-6)	5 ppm K(6-12)	6 ppm K(0-6)	7 ppm K(6-12)
K treatment yield	-.558	-.888*	-.496	-.870
Control yield	-.570	-.924*	-.508	-.870
Yield response	.532	.931*	.478	.739

1/ F due to regression; n = 5

2/ Standard error of the estimate

* Sign . p = 0.05

Table 31. Multiple linear regression equations and correlations relating yield response of barley and spring and winter wheat in bu/Acre to N NH_4OAc extractable K in field moist and air dried samples, 1973 data.

Equation	F [1]	SE [2]	R^2
Field Moist			
1. $Y = 172.0 + .069 \times 4$	0.15	231	.001
2. $Y = 161.6 + .216 \times 5$	0.07	230	.005
3. $Y = 169.9 - .041 \times 4 + .254 \times 5$	0.03	239	.005
Air Dried			
4. $Y = 140.8 + .154 \times 6$	0.06	230	.005
5. $Y = 90.75 + .524 \times 7$	0.31	228	.024
6. $Y = 108.3 - .100 \times 6 + .617 \times 7$	0.15	237	.025

Correlation coefficients:

	Variables			
	Field Moist		Air Dry	
	4 ppm K(0-6)	5 ppm K(6-12)	6 ppm K(0-6)	7 ppm K(6-12)
K treatment yield	-.182	-.106	-.209	.033
Control yield	-.205	-.138	-.245	-.019
Yield response, %	.034	.072	.068	.153

1/ F due to regression; n = 15

2/ Standard error of the estimate

attempted to determine the effect of soil K and climatic variables on potential yield, control yield and the K fertilizer rate for these experimental sites. The means and standard deviations for these variables are presented in Table 32. The variables are assigned a number preceded by an "x". These numbers refer to different variables than those used with the 1967 through 1971 samples. Frequent reference to Table 32 may need to be made in the ensuing discussion of the stepwise regressions because the variable numbers preceded by "x" will be used in regression equations. The "x" refers to the multiplication of the variable by its constant (regression coefficient).

Tables 33, 34, and 35 contain stepwise multiple regression equations and correlations relating potential yield, control yield, and K fertilizer rate, respectively, to climatic factors and N NH_4OAc extractable K in air dried and moist soils from seven 1973 winter wheat experimental sites.

In Table 33, equation one for both the air dry and moist soil analyses, the K in the 0 to 6-inch depth was the first variable entered in the stepwise regression. Though nonsignificant, the slightly larger F value and the R^2 value for equation one from moist, compared to dry soil analysis, indicate that when NH_4OAc is the K extractant, moist soils should be analyzed. This is especially true when subsurface depths are analyzed for K and included in the regression such as in step five of the air dried and moist soil equations. A significant

Table 32. Mean and standard deviation of variables used for predicting potential yield, K fertilizer rate, and control yield from the 1973 K fertilizer trials on winter wheat. Seven sites.

No.	Variable				Units	Mean	Std. Dev.
x1	Fertilizer rate				lbs/acre	34.29	22.25
x2	K treatment yield (Potential Yield)				Bu/acre	47.00	7.60
x3	Control yield				Bu/acre	43.36	5.36
x4	Average soil temp at 50 cm 5/16-30 to 6/25-8/9)				°C	16.93	2.12
x5	Available soil water (5/16-30)				inches	4.81	2.99
x6	Rainfall (5/16-30 to 6/25-8/9)				inches	4.22	1.32
x7	Evaporation rate (5/16-30 to 6/25-8/9)				cm/day	0.44	0.11
	Ammonium acetate (1 N) extractable K						
x9	Dry soil	0-6 inch depth			ppm	367	95
x10		6-12 " "			"	221	81
x11	Moist soil	0-6 " "			"	364	108
x12		6-12 " "			"	180	87
	Resin - thimble extractable K						
x13	Dry soil	0-6 inch depth			ppm	105.1	27.1
x14		6-12 " "			"	56.4	14.7
x15	Moist soil	0-6 " "			"	109.0	33.2
x16		6-12 " "			"	43.0	21.6
	Resin plus N ammonium acetate extractable K						
x17	Dry soil	0-6 inch depth			ppm	581	157
x18		6-12 " "			"	375	118
x19	Moist soil	0-6 " "			"	515	143
x20		6-12 " "			"	321	113
	Moderately available K [(resin +NH_4OAc) - NH_4OAc]						
x21	Dry soil	0-6 inch depth			ppm	214	79.0
x22		6-12 " "			"	154	48.2
x23	Moist soil	0-6 " "			"	151	68.5
x24		6-12 " "			"	140	44.9
	Percent K saturation of exchange complex						
x25	Moist soil	0-6 inch depth			%	5.38	0.53
x26		6-12 " "			%	2.95	0.41
	Dilute cation solution extractable K						
x27	K in solution	Dry soil	0-6		ppm	20.14	2.54
x28			6-12		"	13.86	2.48
x29	$RT\ln[K]/[Ca]^{\frac{1}{2}}$	" "	0-6	ΔG_K	Cal.	-2866	80
x30			6-12	"	"	-3106	102
x31	$RT\ln[K]/[Ca+Mg]^{\frac{1}{2}}$	Dry soil	0-6	"	"	-2950	79
x32			6-12	"	"	-3193	102
x33	$RT\ln[K]/[Mg]^{\frac{1}{2}}$	" "	0-6	"	"	-2539	77
x34			6-12	"	"	-2785	110
	Specific soil chemical and physical properties						
x35	Cation Exchange Capacity		0-6		meq/100g	17.29	3.45
x36			6-12		"	18.86	4.71
x37	Percentage clay		0-6		%	24.71	7.80
x38			6-12		%	28.86	11.23
x39	Percentage silt		0-6		%	34.43	7.59
x40			6-12		%	33.00	5.72
x41	Percentage organic matter		0-6		%	1.73	0.58
x42			6-12		%	1.26	0.59

ΔG_K = Gibbs free energy of K exchange from $RT\ln[K]/[Ca \text{ and/or } Mg]$ where R = 1.987 calories/mole degree and T = absolute temperature

Table 33. Stepwise regression equations and correlations relating potential yield in Bu/acre to climatic factors and N NH_4OAc extractable K in air dried and moist soils from seven 1973 winter wheat experimental sites.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Air Dried				
1.	Y=58.11-0.030x9	0.83	7.71	.142	
2.	Y=52.84-0.043x9+22.28x7	0.56	8.22	.220	
3.	Y=139.51-0.151x9+113.39x7-5.15x4	0.93	7.74	.482	
4.	Y=258.10-0.313x9+209.28x7-9.48x4-6.63x6	33.39*	1.60	.985	.96
5.	Y=251.16-0.317x9+209.13x7-9.35x4-6.04x6+0.017x10	32.23	1.46	.994	.99
	Moist				
1.	Y=57.51-.029x11	1.01	7.59	.168	
2.	Y=51.48-.039x11+22.26x7	0.66	8.07	.248	
3.	Y=128.31-.125x11+104.39x7-4.83x4	1.06	7.48	.516	.03
4.	Y=212.14-.231x11+169.35x7-7.75x4-5.76x6	8.11	3.17	.942	.83
5.	Y=210.45-.262x11+182.08x7-8.07x4-4.76x6+.045x12	171.48#	0.64	.999	.99

Correlation coefficients:

	Variable No.						
	x4	x6	x7	x9	x10	x11	x12
Air Dried, x2	.226	.062	.061	-.377	-.132		
Moist, x2	.226	.062	.061			-.410	-.235

1/ F ratio due to regression

2/ Standard error of the estimate

Sign. p = 0.10

* Sign. p = 0.05

Table 34. Stepwise regression equations and correlations relating control yield in Bu/acre to climatic factors and N NH_4OAc extractable K in air dried and moist soils from seven 1973 winter wheat experimental sites.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Air Dried				
1.	Y=52.74-0.026x9	1.28	5.24	.204	.04
2.	Y=81.44-0.041x9-1.37x4	1.48	4.97	.425	.14
3.	Y=145.13-0.132x9-5.35x4+84.66x7	4.11	3.35	.804	.61
4.	Y=154.13-0.177x9-5.99x4+105.22x7+0.042x10	10.52#	1.98	.955	.87
5.	Y=174.97-0.196x9-6.66x4+118.21x7+0.030x10-1.31x6	10.64	1.78	.982	.89
	Moist				
1.	Y=51.66-0.023x11	1.33	5.21	.211	.05
2.	Y=80.57-0.037x11-1.41x4	1.59	4.90	.443	.16
3.	Y=129.25-0.102x11-4.70x4+69.86x7	3.09	3.75	.756	.51
4.	Y=144.20-0.158x11-5.65x4+97.69x7+0.053x12	8.38	2.20	.944	.83
5.	Y=131.20-0.159x11-5.04x4+99.43x7+0.090x12-0.964x5	4.79	2.63	.960	.76

Correlation coefficients:

	Variable No.						
	x4	x6	x7	x9	x10	x11	x12
Air Dried, x3	-.186	.324	-.374	-.452	-.158		
Moist, x3	-.186	.324	-.374			-.459	-.226

1/ F ratio due to regression

2/ Standard error of the estimate

Sign. p = 0.10

Table 35. Stepwise regression equations and correlations relating K fertilizer rate in pounds/acre to climatic factors and N NH_4OAc extractable K in air dried and moist soils from seven 1973 winter wheat experimental sites.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Air Dried				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=-102.57+2.07x2+67.63x7+2.04x5	2.21	17.56	.689	.38
4.	Y=-149.62+1.95x2+20.95x7+3.00x5+4.04x4	1.86	17.74	.788	.36
5.	Y=-144.04+1.90x2+19.79x7+2.57x5+4.44x4-1.78x6	0.77	24.71	.795	
	Moist				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=-102.57+2.07x2+67.63x7+2.04x5	2.21	17.56	.689	.38
4.	Y=-149.62+1.95x2+20.95x7+3.00x5+4.04x4	1.86	17.74	.788	.36
5.	Y=-225.52+1.70x2+24.30x7-2.73x5+8.31x4+0.230x12	0.88	23.42	.815	

Correlation coefficients:

	Variable No.					
	x2	x4	x5	x6	x7	x12
Air Dried, x1	.654	.540	.232	-.121	.493	
Moist, x1	.654	.540	.232		.493	.038

1/ F ratio due to regression

2/ Standard error of the estimate

ANOV F (.10 level) was generated when the 6 to 12-inch depth moist soil K was introduced at step five of the moist soil equations. The standard error is also lower from this equation than from the same equation with the air dried soils. These and previous data presented in this thesis support the analysis of moist subsurface soils when they are analyzed along with the surface soils by N NH_4OAc in an attempt to improve the prediction of K fertilizer needs. The work of Luebs, et al. (1956), Hanway, et al. (1961 and 1962), and Schulte and Corey (1965) support this conclusion. It must be remembered that, according to Luebs, et al. (1956), in the midwestern United States, exchangeable K at a particular depth remained nearly constant below the surface one-inch layer of soil due to more constant moisture levels.

Caution must be exercised when the R^2 values are used to judge how well these regression equations account for variation in potential yield. There are only five allowable degrees of freedom. In step five for the air dried soil analysis the F from the ANOV for this regression equation is statistically nonsignificant. Thus, despite the fact that the R^2, verified by the adjusted R^2, indicates that 99% of the variation in potential yield is explained by the regression equation, this equation must be considered as having little interpretive value.

The regression equations developed at step four from air dried

soil analysis effectively predict potential yields and control yields as shown in Tables 33 and 34 at the .05 and .10 levels of significance, respectively. Both equations utilized soil K in the surface 6-inch depth, evaporation rate, and average soil temperature at 50 cm as the first three variables entering the equation. Rainfall was entered at step four of the potential yield equation. The control yield equation (Table 34) entered the 6 to 12-inch depth K at step four. The reason this occurred is probably due to the potential yield sites receiving an adequate supply of K fertilizer prior to cropping. Therefore, rainfall was considered more important than subsurface soil K.

The NH_4OAc extractable K and climatic factors were ineffective in predicting the K fertilizer rate as is shown in Table 35. No significant relationships were developed despite the fact that all five allowable degrees of freedom were utilized.

Resin-thimble potassium extraction method. The first K extraction of the 1973 winter wheat site soils by the resin-thimble method was done on the less than 2 mm diameter particles using unselected thimbles and measured quantities of resin. Results of the stepwise regression equations and correlations relating potential yield, control yield, and K fertilizer rate to climatic factors and resin-thimble extractable K in air dry and moist soils from these experimental sites are presented in Tables 36, 37, and 38, respectively.

Step four for air dried soils in Table 36 reveals that the resin

Table 36. Stepwise regression equations and correlations relating potential yield in Bu/acre to climatic factors and resin (thimble method) extractable K in air dried and moist soils from seven 1973 winter wheat experimental sites using 2 mm soil, unselected thimbles, and measured resin.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Air Dried				
1.	Y=62.94-1.66x13	3.59	6.35	.418	.30
2.	Y=60.75-0.305x13+0.316x14	3.08	5.84	.606	.41
3.	Y=49.87-0.384x13+0.387x14+34.08x7	3.99	4.81	.800	.60
4.	Y=92.43-0.485x13+0.304x14+70.32x7-2.64x4	13.03#	2.53	.963	.89
5.	Y=110.70-0.474x13+0.141x14+72.99x7-2.91x4-1.85x6	13.30	2.27	.985	.91
	Moist				
1.	Y=53.62-0.061x15	0.38	8.03	.070	
2.	Y=75.42-0.152x15-2.79x6	0.34	8.60	.146	
3.	Y=77.17-0.222x15-3.95x6+24.19x7	0.31	9.40	.235	
4.	Y=143.84-0.472x15-6.87x6+75.19x7-2.93x4	0.27	10.59	.353	
5.	Y=283.79-2.22x15-3.51x6+310.85x7-12.25x4+2.11x16	0.62	9.19	.756	

Correlation coefficients:

	Variable No.						
	x4	x6	x7	x13	x14	x15	x16
Air Dried, x2	.226	.062	.061	-.646	-.234		
Moist, x2	.226	.062	.061			-.265	-.213

1/ F ratio due to regression

2/ Standard error of the estimate

Sign. p = 0.10

Table 37. Stepwise regression equations and correlations relating control yield in Bu/acre to climatic factors and resin (thimble method) extractable K in air dried and moist soils from seven 1973 winter wheat sites, using 2 mm soil, unselected thimbles, and measured resin.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Air Dried				
1.	Y=54.72-0.118x13	3.72	4.44	.427	.31
2.	Y=85.85-0.169x13-1.55x4	5.26#	3.44	.724	.59
3.	Y=105.14-0.271x13-3.08x4+37.33x7	12.32*	2.08	.925	.85
4.	Y=110.44-0.319x13-3.28x4+36.69x7+0.623x5	32.68*	1.14	.985	.96
5.	Y=108.88-0.315x13-3.32x4+36.41x7+0.691x5+0.385x6	19.81	1.31	.990	.94
	Moist				
1.	Y=46.66-0.684x5	0.86	5.42	.146	
2.	Y=51.27-0.484x5-12.63x7	0.50	5.87	.200	
3.	Y=47.27-0.256x5-14.00x7+0.827x6	0.29	6.66	.227	
4.	Y=23.21-1.23x5-5.51x7+3.88x6+0.282x16	0.19	7.91	.273	
5.	Y=-11.25-2.95x5+31.94x7+8.78x6+1.11x16-0.276x15	0.11	10.51	.359	

Correlation coefficients:

	Variable No.						
	x4	x5	x6	x7	x13	x15	x16
Air Dried, x3	-.186	-.382	.324	-.374	-.653		
Moist, x3	-.186	-.382	.324	-.374		-.363	-.302

1/ F ratio due to regression

2/ Standard error of the estimate

* Sign. p = 0.05

Table 38. Stepwise regression equations and correlations relating K fertilizer rate in pounds/acre to climatic factors and resin (thimble method) extractable K in air dried and moist soils from seven 1973 winter wheat experimental sites using 2 mm soil, unselected thimbles, and measured resin.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Air Dried				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=-102.57+2.07x2+67.63x7+2.04x5	2.21	17.56	.689	.38
4.	Y=-34.15+1.08x2+97.01x7+3.99x5-0.461x13	1.88	17.66	.790	.37
5.	Y=84.06-2.20x2+283.28x7-3.60x5-1.93x13+2.68x14	2.41	15.10	.923	.52
	Moist				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=-102.57+2.07x2+67.63x7+2.04x5	2.21	17.56	.689	.38
4.	Y=-149.62+1.95x2+20.95x7+3.00x5+4.04x4	1.86	17.74	.788	.36
5.	Y=-233.95+1.99x2-40.94x7+0.522x5+8.39x4+.442x16	1.06	21.72	.841	.05

Correlation coefficients:

	Variable No.						
	x2	x4	x5	x7	x13	x14	x16
Air Dried, x1	.654		.232	.493	-.310	.023	
Moist, x1	.654	.540	.232	.493			.072

1/ F ratio due to regression

2/ Standard error of the estimate

exchangeable K in the 0 to 6 and 6 to 12-inch depths combined with the evaporation rate and average soil temperature to provide a potential yield equation which was significant at the .10 level. These variables explained at least 89% of the variation in potential yield. Moist soil analysis did not contribute toward a significant relationship.

This resin technique was more effective in developing statistically significant regression equations for predicting control yields as shown in steps two, three, and four (air dried) of Table 37. The combination of resin extractable soil K in the surface 6-inch depth of air dry soils and average soil temperature was significantly related, at the .10 level, with control yield. Inclusion of evaporation rate and/or available soil water increased the significance to the .05 level and accounted for at least 85 and 96%, respectively, of the variation in the control yield.

By observation of the regression ANOV F values in Table 38, one can ascertain that this technique did not adequately predict the K fertilizer rate from analysis of either air dry or moist soils.

No significant relationships for control yield were found when moist soils were analyzed. Results in Tables 36 and 37 indicate that the resin-thimble extractable K method predicted PY, CY, and FR more effectively when air dry soils were analyzed. Thus, future testing of this method was done only on air dry soils.

Duplicate sample analysis of the 1967 through 1971 and the 1973

site samples revealed that the resin-thimble K extraction procedure lacked precision. Observation of the thimbles revealed that their bases were not uniform in thickness. Also the inside diameter and wall thickness varied among thimbles. It was thought that thimbles selected for uniformity might provide greater precision. A batch of uniform thimbles was selected by visual inspection of the amount of light entering through the base, and sizing of the thimbles for uniform wall thickness and inside diameter. These were used to repeat the extraction of the 1973 site soil samples for K by the resin-thimble procedure using measured quantities of resin. The precision between duplicate 6-inch depth samples improved from an average standard deviation of 11.86 ppm when using unselected thimbles to 7.29 ppm from use of these selected thimbles. However, a standard deviation of 7.29 ppm should still be improved if the procedure is to be sufficiently precise for soil analysis.

A sufficient number of thimbles was selected to allow for two additional sets of analyses of the 1973 site samples. In both runs the soil samples were ground finer than 0.5 mm and five grams of cation resin were weighed into each extraction beaker. The average standard deviation was reduced to 1.72 and 5.72 ppm for these two runs. The human eye must be considered insufficiently accurate for thimble selection as all the thimbles for both runs were selected by the same criteria but the average standard deviations differed by 4 ppm. Perhaps

an instrument could be designed on the principle of a colorimeter to electronically select those thimbles allowing a certain quantity of light to pass through the base of the thimble. A caliper could be used to ascertain the correct inside diameter and wall thickness.

Machine made thimbles having a length of 80 mm by 20 mm diameter were provided by Reeve Angel, Inc., 9 Bridgewell Place, Clifton, New Jersey, to evaluate their precision for K extraction by the resin method. The 50 x 10 mm thimbles were hand made. The average standard deviations for two extractions using these machine made thimbles were 17.86 and 45.36 ppm, much worse than the unselected 50 x 10 mm thimbles. However, the 22 cm diameter of these thimbles allowed more soil to be in closer proximity to the resin. This allowed the resin to extract a greater concentration of K. The results of duplicate sample analyses for each resin-thimble technique variation attempted are shown in Appendix Table 11.

Tables 39, 40, and 41 show the stepwise regression equations and correlations relating potential yield, control yield, and K fertilizer rate to climatic factors and resin (thimble method) extractable soil K in air dried soils from seven 1973 winter wheat sites, with (1) 2 mm soil, selected thimbles, and measured volumes of resin, (2) 0.5 mm soil, selected thimbles and weighed resin, and (3) a repeat of (2), respectively. Use of selected thimbles with 2 mm soil and measured resin failed to show improvement in predicting potential yield over

Table 39. Stepwise regression equations and correlations relating potential yield, control yield, and K fertilizer rate to climatic factors and resin (thimble method) extractable soil K in air dried soils from seven 1973 winter wheat experimental sites. This is a rerun of the resin (thimble) procedure using 2 mm soil, selected thimbles and measured resin.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Potential yield				
1.	Y=59.10-0.121x13	2.23	6.93	.308	.17
2.	Y=48.23-0.200x13+42.79x7	2.43	6.25	.549	.32
3.	Y=69.03-0.314x13+58.30x7-3.84x6	4.30	4.67	.811	.62
4.	Y=70.98-0.302x13+61.76x7-4.33x6-0.547x5	2.54	5.34	.835	.51
5.	Y=39.99-0.508x13+113.61x7-4.71x6-4.44x5+0.882x14	72.95#	0.97	.997	.98
	Control yield				
1.	Y=56.71-0.133x13	15.28*	2.91	.753	.70
2.	Y=63.97-0.158x13-1.13x6	8.23*	2.90	.805	.71
3.	Y=62.52-0.200x13-1.60x6+17.61x7	7.18#	2.65	.878	.76
4.	Y=72.78-0.212x13-1.08x6+29.22x7-0.972x4	14.27#	1.71	.966	.90
5.	Y=70.26-0.228x13-0.910x6+30.69x7-0.969x4+0.049x14	7.71	2.09	.975	.85
	K fertilizer rate				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=-102.57+2.07x2+67.63x7+2.04x5	2.21	17.56	.689	.38
4.	Y=-22.97+1.57x2+37.16x7+9.18x5-1.38x14	2.35	16.15	.824	.47
5.	Y=-70.41+1.47x2-7.00x7+9.92x5-1.35x14+3.89x4	2.20	15.72	.917	.50

Correlation coefficients:

	Variable No						
	x2	x4	x5	x6	x7	x13	x14
Potential yield, x2			-.264	.062	.061	-.555	-.418
Control yield, x3		-.186		.324	-.374	-.868	-.554
K fertilizer rate, x1	.654	.540	.232		.493		-.095

1/F ratio due to regression

2/Standard error of the estimate

Sign. p = 0.10

* Sign. p = 0.05

Table 40. Stepwise regression equations and correlations relating potential yield, control yield, and K fertilizer rate to climatic factors and resin (thimble method) extractable soil K in air dried soils from seven 1973 winter wheat experimental sites. This is a rerun of the resin (thimble) procedure using 0.5 mm soil, selected thimbles and weighed amounts of resin.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Potential yield				
1.	Y=68.74-0.207x13	5.96#	5.62	.544	.45
2.	Y=59.48-0.289x13+40.71x7	7.83*	4.20	.797	.70
3.	Y=88.11-0.378x13+68.30x7-1.86x4	14.72*	2.71	.936	.87
4.	Y=91.91-0.397x13+64.71x7-1.47x4-1.59x6	58.37*	1.21	.992	.98
5.	Y=92.86-0.389x13+66.90x7-1.48x4-1.88x6-0.313x5	257.86*	0.52	.999	.998
	Control yield				
1.	Y=59.91-0.157x13	8.66*	3.55	.634	.56
2.	Y=78.05-0.174x13-0.966x4	6.81#	3.12	.773	.66
3.	Y=88.34-0.250x13-1.87x4+29.69x7	11.63*	2.13	.921	.84
4.	Y=86.65-0.242x13-2.05x4+31.29x7+0.707x6	8.25	2.22	.943	.83
5.	Y=73.80-0.243x13-1.75x4+29.18x7+1.48x6+0.100x14	3.95	2.88	.952	.71
	K fertilizer rate				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=-102.57+2.07x2+67.63x7+2.04x5	2.21	17.56	.689	.38
4.	Y=-149.62+1.95x2+20.95x7+3.00x5+4.04x4	1.86	17.74	.788	.36
5.	Y=-283.54+3.41x2-84.01x7+2.78x5+6.98x4+0.599x13	0.83	24.07	.805	

Correlation coefficients:

	Variable No.						
	x2	x4	x5	x6	x7	x13	x14
Potential yield, x2		.226	-.264	.062	.061	-.737	
Control yield, x3		-.186		.324	-.374	-.796	-.185
K fertilizer rate, x1	.654	.540	.232		.493	-.275	

1/F ratio due to regression

2/Standard error of the estimate

\# Sign. p = 0.10

* Sign. p = 0.05

Table 41. Stepwise regression equations and correlations relating potential yield, control yield, and K fertilizer rate to climatic factors and resin (thimble method) extractable soil K in air dried soils from seven 1973 winter wheat experimental sites. This is the second rerun of the resin (thimble) procedure using 0.5 mm soil, selected thimbles, and weighed amounts of resin.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Potential yield				
1.	Y=66.40-0.165x13	2.65	6.73	.346	.22
2.	Y=59.38-0.254x13+39.86x7	2.65	6.11	.570	.36
3.	Y=90.19-0.420x13+55.95x7-4.34x6	7.79#	3.63	.886	.77
4.	Y=115.71-0.505x13+82.91x7-4.13x6-1.67x4	31.00*	1.65	.984	.95
5.	Y=130.83-0.509x13+86.31x7-5.11x6-1.97x4-0.100x14	38.09	1.35	.995	.97
	Control yield				
1.	Y=60.66-0.147x13	6.21#	3.92	.554	.46
2.	Y=78.77-0.164x13-0.951x4	4.42#	3.66	.688	.53
3.	Y=95.54-0.275x13-2.20x4+39.51x7	8.92#	2.41	.899	.80
4.	Y=100.55-0.304x13-2.15x4+41.74x7-0.815x6	5.87	2.60	.921	.76
5.	Y=100.33-0.308x13-2.15x4+40.88x7-0.701x6+0.145x5	2.46	3.60	.925	.55
	K fertilizer rate				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=-102.57+2.07x2+67.63x7+2.04x5	2.21	17.56	.689	.38
4.	Y=-149.62+1.95x2+20.95x7+3.00x5+4.04x4	1.86	17.74	.788	.36
5.	Y=-222.17+2.57x2-41.40x7+2.48x5+5.94x4+0.350x13	0.84	23.90	.808	

Correlation coefficients:

	Variable No.						
	x2	x4	x5	x6	x7	x13	x14
Potential yield, x2		.226		.062	.061	-.589	-.119
Control yield, x3		-.186	-.382	.324	-.374	-.744	
K fertilizer rate, x1	.654	.540	.232		.493	-.117	

1/F ratio due to regression

2/Standard error of the estimate

\# Sign. p = 0.10
* Sign. p = 0.05

use of unselected thimbles (Table 39). The equation for step five was significant at the .10 level. Prediction of the control plot yields became significant at the .05 level in steps one and two. However, prediction of the K fertilizer rate remained insignificant.

The potential yield predictive equations were much improved when the average standard deviation was reduced to 1.71 by analysis of 0.5 mm soil using selected thimbles and weighed resin as shown in Table 40. The step one equation was almost significant at the .05 level. If these results could be reproduced consistently, the resin-thimble method would be the best of the procedures tried. However, an exact rerun of this technique revealed a higher average standard deviation of 5.72 and a lower level of potential yield explanatory power (Table 41). Also, different variables were entered in steps three, four, and five.

Resin extraction of soils for "plant available" K appears to have possibilities for predicting potential yield, but a more uniform soil sample container, which still allows for K diffusion, is needed.

Appendix Table 12 contains results of extraction of the 1973 experimental site soils for K, percentage K saturation of the CEC, and free energy by the methods to be discussed below.

Resin plus ammonium acetate K extraction method. The concentration of K extracted by the H-resin plus that amount extracted by N NH_4OAc failed to predict potential yield or the K fertilizer rate

required for that potential yield by extraction of moist or dry samples as shown in Tables 42 and 44. This combination of extraction methods did, however, predict yields from the control plots at a .10 level of significance by analysis of both moist and air dried samples (Table 43). Potassium in the 0 to 6-inch depth was injected into the regression equation at step one and accounted for 48 and 54% of the variation in control yield for air dried and moist soil extraction, respectively. Subsequent introduction of soil temperature and evaporation rate into the stepwise regression equations at steps two and three maintained the .10 level of significance while improving the explanatory power of the control yield prediction. Further improvement in the prediction of control plot yields occurred only at step five of the regression using moist soil K analysis. Additional climatic factors inserted into this equation were rainfall (step four) and stored available soil water at step five. A .05 level of significance was obtained with a variability explanatory power of 99.9%. Caution should be exercised in the application of this equation due to the limited degrees of freedom compared to the number of variables involved.

These results are supported by those of Barber and Matthews (1962) who reported having accounted for 56% of the variability of the average yield increase for corn, wheat, oats, and potatoes. They related response of these crops to moderately available K and resin plus N NH_4OAc K by a multiple quadratic regression method.

Table 42. Stepwise regression equations and correlations relating potential yield in B$/ acre to climatic factors and resin plus N NH_4OAc extractable K in air dried and moist soils from seven 1973 winter wheat experimental sites.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Air Dried				
1.	Y=62.42-0.027x17	2.16	6.96	.301	.16
2.	Y=92.81-0.050x17-3.93x6	2.24	6.39	.528	.29
3.	Y=90.03-0.065x17-4.80x6+33.80x7	2.50	5.75	.714	.43
4.	Y=123.31-0.085x17-5.01x6+62.34x7-1.98x4	2.54	5.34	.836	.51
5.	Y=137.11-0.088x17-6.67x6+81.78x7-2.37x4-1.39x5	44.61	1.24	.996	.98
	Moist				
1.	Y=60.36-0.026x19	1.57	7.26	.239	.09
2.	Y=53.02-0.039x19+31.87x7	1.26	7.29	.387	.08
3.	Y=84.13-0.077x19+50.66x7-4.74x6	2.31	5.91	.698	.40
4.	Y=92.40-0.079x19+65.29x7-6.46x6-1.34x5	2.83	5.10	.850	.55
5.	Y=118.45-0.095x19+93.98x7-6.69x6-1.55x5-1.66x4	3.43	4.37	.945	.67

Correlation coefficients:

	Variable No.					
	x4	x5	x6	x7	x17	x19
Air Dried, x2	.226	-.264	.062	.061	-.549	
Moist, x2	.226	-.264	.062	.061		-.489

1/ F ratio due to regression

2/ Standard error of the estimate

Table 43. Stepwise regression equations and correlations relating control yield in Bu/ acre to climatic factors and resin plus N NH_4OAc extractable K in air dried and moist soils from seven 1973 winter wheat experimental sites.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Air Dried				
1.	Y=57.04-0.024x17	4.56#	4.24	.477	.37
2.	Y=84.42-0.031x17-1.37x4	5.27#	3.44	.725	.59
3.	Y=97.78-0.045x17-2.44x4+28.86x7	6.23#	2.82	.862	.72
4.	Y=110.64-0.056x17-2.52x4+33.52x7-1.63x6	7.27	2.35	.936	.81
5.	Y=132.98-0.056x17-2.73x4+34.80x7-3.75x6-0.028x18	23.60	1.20	.992	.95
	Moist				
1.	Y=57.57-0.028x19	5.96#	3.96	.544	.45
2.	Y=75.90-0.031x19-0.976x4	4.34#	3.69	.684	.53
3.	Y=88.78-0.049x19-2.09x4+35.12x7	6.23#	2.82	.862	.72
4.	Y=99.17-0.062x19-2.08x4+41.29x7-1.62x6	7.10	2.38	.934	.80
5.	Y=105.90-0.065x19-2.27x4+51.21x7-2.42x6-0.632x5	772.23*	0.21	.9997	.998

Correlation coefficients:

		Variable No.						
		x4	x5	x6	x7	x17	x18	x19
Air dried,	x3	-.186	-.382	-.324	-.374	-.691	-.365	
Moist,	x3	-.186	-.382	-.324	-.374			-.737

1/ F ratio due to regression

2/ Standard error of the estimate

Sign. p = 0.10

* Sign. p = 0.05

Table 44. Stepwise regression equations and correlations relating K fertilizer rate in pounds/acre to climatic factors and resin plus N NH_4OAc extractable K in air dried and moist soils from seven 1973 winter wheat experimental sites.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Air Dried				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=-102.57+2.07x2+67.63x7+2.04x5	2.21	17.56	.689	.38
4.	Y=-149.62+1.95x2+20.95x7+3.00x5+4.04x4	1.86	17.74	.788	.36
5.	Y=-144.04+1.90x2+19.79x7+2.57x5+4.44x4-1.78x6	0.77	24.71	.795	
	Moist				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=-102.57+2.07x2+67.63x7+2.04x5	2.21	17.56	.689	.378
4.	Y=-149.62+1.95x2+20.95x7+3.00x5+4.04x4	1.86	17.74	.788	.36
5.	Y=-144.04+1.90x2+19.79x7+2.57x5+4.44x4-1.78x6	0.77	24.71	.795	

Correlation coefficients:

		Variable No.				
		x2	x4	x5	x6	x7
Air dried,	x1	.654	.540	.232	-.121	.493
Moist,	x1	.654	.540	.232	-.121	.493

1/ F ratio due to regression

2/ Standard error of the estimate

Moderately available K by resin extraction. Moderately available soil K was calculated from extraction of the 1973 experimental site soil samples by subtracting the N NH_4OAc extractable K from that K extracted by the resin plus N NH_4OAc method. Results of equations from stepwise regression and correlations relating potential yield, control yield and K fertilizer rate with climatic factors and moderately available soil K in air dried and moist soils are illustrated in Tables 45, 46, and 47, respectively.

In Table 45, regression steps one, two, and three entered moderately available air dried soil K in the surface 6-inch depth, rainfall, and available soil water, respectively. None of these equations significantly predicted potential yield. However, at step four evaporation rate was entered into the equation, causing the prediction of potential yield to become significant at the .05 level, and accounting for at least 97% of the variability in potential yield. Moderately available soil K in the 6 to 12-inch depth was entered into the equation at step five. The ANOV F for this equation was highly significant. All of the variability in potential yield was accounted for as indicated by the R^2 of 1.0 and the negligible standard error. Control yield was predicted at various levels of significance by combinations of soil temperature, available soil water, and rainfall with moderately available, air dry soil K in the surface 6-inch depth (Table 46). Similar results were obtained when the moderately available K was

Table 45. Stepwise regression equations and correlations relating potential yield in Bu/acre to climatic factors and moderately available soil K[(resin K+NH_4OAc K)-NH_4OAc K] in air dried and moist soils from seven 1973 winter wheat experimental sites.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Air Dried				
1.	$\hat{Y}$=60.15-0.062x21	3.46	6.40	.409	.29
2.	$\hat{Y}$=81.57-0.097x21-3.30x6	3.08	5.84	.606	.41
3.	$\hat{Y}$=98.24-0.105x21-5.31x6-1.30x5	3.52	5.05	.779	.56
4.	$\hat{Y}$=94.17-0.123x21-6.53x6-2.09x5+37.34x7	43.65*	1.40	.989	.97
5.	$\hat{Y}$=84.08-0.135x21-5.61x6-2.25x5+42.39x7+0.049x22	71279.31**	0.03	1.000	1.0
	Moist				
1.	$\hat{Y}$=53.32-0.042x23	0.83	7.71	.142	
2.	$\hat{Y}$=33.00-0.053x23+1.30x4	0.72	7.99	.264	
3.	$\hat{Y}$=33.83-0.078x23+2.08x4-2.41x6	0.59	8.53	.370	
4.	$\hat{Y}$=49.08-0.111x23+2.91x4-6.00x6-1.91x5	1.30	7.29	.693	.08
5.	$\hat{Y}$=53.70-0.135x23+2.24x4-6.77x6-2.78x5+40.38x7	1.15	7.16	.852	.11

Correlation coefficients:

	Variable No.						
	x4	x5	x6	x7	x21	x22	x23
Air dried, x2		-.264	.062	.061	-.640	-.344	
Moist, x2	.226	-.264	.062	.061			.043

1/ F ratio due to regression

2/ Standard error of the estimate

* Sign. p = 0.05

** Sign. p = 0.01

Table 46. Stepwise regression equations and correlations relating control yield in Bu/acre to climatic factors and moderately available soil K[(resin K+NH_4OAc K)-NH_4OAc K] in air dried and moist soils from seven 1973 winter wheat experimental sites.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Air Dried				
1.	Y=55.42-0.056x21	11.26*	3.25	.693	.63
2.	Y=71.67-0.061x21-0.902x4	8.83*	2.82	.815	.72
3.	Y=73.25-0.058x21-0.932x4-0.370x5	5.91#	2.88	.855	.71
4.	Y=82.98-0.075x21-0.626x4-0.775x5-2.18x6	12.69#	1.81	.962	.89
5.	Y=91.51-0.064x21-0.454x4-0.729x5-3.53x6-0.055x22	53.71	0.80	.996	.98
	Moist				
1.	Y=53.05-0.064x23	10.27*	3.36	.673	.61
2.	Y=56.14-0.064x23-0.658x5	8.40*	2.88	.808	.71
3.	Y=65.87-0.074x23-1.03x5-1.50x6	7.39#	2.62	.881	.76
4.	Y=65.56-0.091x23-1.50x5-2.23x6+18.67x7	11.39#	1.90	.958	.87
5.	Y=58.25-0.103x23-1.69x5-1.68x6+23.67x7+0.038x24	30.26	1.06	.993	.96

Correlation coefficients:

		Variable No.							
		x4	x5	x6	x7	x21	x22	x23	x24
Air dried,	x3	-.186	-.382	.324		-.832*	-.624		
Moist,	x3		-.382	.324	-.374			-.820*	-.398

1/ F ratio due to regression

2/ Standard error of the estimate

Sign. p = 0.10

* Sign. p = 0.05

Table 47. Stepwise regression equations and correlations relating K fertilizer rate in pounds/ acre to climatic factors and moderately available soil K[(resin K+NH_4OAc K)-NH_4OAc K] in air dried and moist soils from seven 1973 winter wheat experimental sites.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Air dried				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=-102.57+2.07x2+67.63x7+2.05x5	2.21	17.56	.689	.38
4.	Y=-149.62+1.95x2+20.95x7+3.00x5+4.04x4	1.86	17.74	.788	.36
5.	Y=-144.04+1.90x2+19.79x7+2.57x5+4.44x4-1.78x6	0.77	24.71	.795	
	Moist				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.76+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=-102.57+2.07x2+67.63x7+2.05x5	2.21	17.56	.689	.38
4.	Y=-149.62+1.95x2+20.95x7+3.00x5+4.04x4	1.86	17.74	.788	.36
5.	Y=-151.11+2.02x2+8.58x7+3.72x5+4.61x4-0.067x24	0.80	24.38	.800	

Correlation coefficients:

		Variable No.					
		x2	x4	x5	x6	x7	x24
Air dried,	x1	.654	.540	.232	-.121	.493	
Moist,	x1	.654	.540	.232		.493	.189

1/ F ratio due to regression

2/ Standard error of the estimate

determined in field moist soils, except that evaporation rate, which is an integrator of climatic variables, was entered instead of the average soil temperature. Results in Table 46 again point to the analysis of air dried soils for K when the H-resin is used as the extractant. The ANOV F values in Table 47 indicate that moderately available K did not effectively predict the K fertilizer rate.

Percentage potassium saturation of the cation exchange complex (PKS). The percentage of K on the cation exchange complex was determined on soils from the 1973 winter wheat experimental sites, and along with climatic factors was used in an attempt to predict potential yield, control yield, and the K fertilizer rate. The regression equations in Table 48 indicate an agreement with those of Stewart and Volk (1946) and Hossner and Doll (1970) who found that PKS of the CEC was not related to crop response from applied K. The PKS of the CEC in the 0 to 6-inch depth entered the potential yield predictive equation at step one, but was not significantly related to potential yield and explained only 8% of its variability. A combination of PKS, evaporation rate, average soil temperature, and available soil water, in that order, was needed to develop a significant (.10 level) predictive equation for potential yield. If soils release moderately available K to plants as soluble and exchangeable K are depleted, this could indicate why PKS is not related to crop response.

A highly significant (.01 level) predictive equation for the K

Table 48. Stepwise regression equations and correlations relating potential yield, control yield, and K fertilizer rate to climatic factors and percent K saturation of the exchange complex in soils from seven 1973 winter wheat experimental sites.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Potential yield				
1.	Y=68.69-4.03x25	0.43	7.99	.080	
2.	Y=139.47-27.56x25+126.68x7	3.80	5.47	.655	.48
3.	Y=215.92-40.95x25+206.93x7-2.35x4	5.33	4.27	.842	.68
4.	Y=258.80-52.44x25+244.75x7-2.57x4+1.27x5	10.70#	2.78	.955	.87
5.	Y=266.97-54.86x25+256.49x7-2.92x4+1.58x5+0.967x6	6.47	3.22	.970	.82
	Control yield				
1.	Y=73.18-5.54x25	2.17	4.90	.303	.16
2.	Y=92.92-12.10x25+35.34x7	1.29	5.11	.393	.09
3.	Y=152.81-22.60x25+98.21x7-1.84x4	1.66	4.65	.624	.25
4.	Y=149.77-22.10x25+101.83x7-2.25x4+1.34x6	1.20	5.03	.706	.12
5.	Y=142.48-29.10x25+143.28x7-3.19x4+3.97x6+10.73x26	13.38	1.59	.985	.91
	K fertilizer rate				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=-152.52+1.84x2+88.36x7+20.86x26	3.63	14.62	.784	.57
4.	Y=-232.10+1.05x2+165.81x7+60.18x26-6.92x5	3.72	13.28	.881	.64
5.	Y=-349.53+0.704x2+199.76x7+91.47x26-9.02x5+8.64x6	8104.74**	0.27	1.000	1.0

Correlation coefficients:

	Variable No.						
	x2	x4	x5	x6	x7	x25	x26
Potential yield, x2		.226	-.264	.062	.061	-.282	
Control yield, x3		-.186		.324	-.374	-.550	-.082
K fertilizer rate, x1	.654		.232	-.121	.493		.414

1/F ratio due to regression

2/Standard error of the estimate

Sign. p = 0.10
**Sign. p = 0.01

fertilizer rate was produced utilizing K treatment yield, evaporation rate, PKS in the 6 to 12-inch depth, available soil water, and rainfall. The standard error of this prediction was very low and 100% of the variability was accounted for. Which of these variables was of greatest importance in developing this highly significant predictive equation is difficult to determine. The single degree of freedom F test was not computed on these data. One could only guess that rainfall played a very important role here because no statistically significant relationship existed prior to its entering the equation. Again, caution should be exercised when interpreting these data due to the high ratio of variables to degrees of freedom.

Dilute cation solution equilibration method. Baker's (1971) dilute cation equilibration method was tried on the 1973 site soils because it had been one of the best tests on the 1967 through 1971 soil samples. Tables 49, 50, 51, and 52 contain regression equations and correlations relating potential yield, control yield and K fertilizer rate to climatic factors and solution K and G_K's from $[K]/[Ca]^{\frac{1}{2}}$, $[K]/[Ca+Mg]^{\frac{1}{2}}$, and $[K]/[Mg]^{\frac{1}{2}}$, respectively.

Solution K (Table 49) by itself was not effective in predicting potential yield but did predict control yield at the .10 level of significance. A highly significant prediction of potential yield was developed when rainfall was entered into the equation along with the 0 to 6-inch depth solution K and evaporation rate. At step four,

Table 49. Stepwise regression equations and correlations relating potential yield, control yield, and K fertilizer rate to climatic factors and K in solution after extracting soils from seven 1973 winter wheat experimental sites with 50 ml of a dilute cation solution (Baker, 1971).

Step	Equation	F [1]	SE [2]	R^2	Adj R^2
	Potential yield				
1.	Y=76.23-1.45x27	1.55	7.28	.236	.08
2.	Y=81.10-2.66x27+44.06x7	1.78	6.77	.471	.21
3.	Y=157.69-5.96x27+82.92x7-6.43x6	36.14**	1.76	.973	.95
4.	Y=170.65-6.29x27+94.15x7-6.32x6-0.697x4	73.94*	1.08	.993	.98
5.	Y=172.75-6.47x27+94.03x7-6.24x6-0.698x4+0.243x5	79.09#	0.93	.998	.99
	Control yield				
1.	Y=75.32-1.59x27	6.58#	3.86	.568	.48
2.	Y=87.61-1.64x27-0.661x4	3.50	3.96	.636	.45
3.	Y=110.33-2.75x27-1.66x4+37.40x7	4.60	3.20	.821	.64
4.	Y=133.86-3.79x27-1.57x4+48.70x7-2.14x6	6.93	2.41	.933	.80
5.	Y=133.13-4.47x27-1.78x4+67.31x7-2.28x6+0.749x28	81.45#	0.65	.998	.99
	K fertilizer rate				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=-211.47+2.49x2+135.49x7+4.97x28	5.27	12.57	.841	.68
4.	Y=-358.83+2.71x2+284.15x7+12.48x28-6.78x5	17.01#	6.51	.971	.91
5.	Y=-366.15+2.71x2+313.24x7+13.78x28-8.68x5-3.33x6	31.85	4.31	.994	.964

Correlation coefficients:

	Variable No. x2	x4	x5	x6	x7	x27	x28
Potential yield, x2		.226	-.264	.062	.061	-.486	
Control yield, x3		-.186		.324	-.374	-.754*	-.116
K fertilizer rate, x1	.654		.232	-.121	.493		-.078

[1]/F ratio due to regression

[2]/Standard error of the estimate

\# Sign. p = 0.10
* Sign. p = 0.05
** Sign. p = 0.01

Table 50. Stepwise regression equations and correlations relating potential yield, control yield, and K fertilizer rate to climatic factors and free energy of K exchange, $RT\ln[K]/[Ca]^{\frac{1}{2}}$, after extracting soils from seven 1973 winter wheat experimental sites with 50 ml of a dilute cation solution (Baker, 1971).

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Potential yield				
1.	Y=-76.21-0.040x30	1.96	7.05	.282	.14
2.	Y=-154.96-0.037x30-0.031x29	1.25	7.30	.385	.08
3.	Y=-563.68-0.080x30-0.121x29+3.31x5	2.52	5.73	.716	.43
4.	Y=-676.68-0.090x30-0.154x29+3.42x5-3.08x6	3.55	4.63	.877	.63
5.	Y=-749.15-0.048x30-0.220x29+2.45x5-5.12x6+66.31x7	9.20	2.72	.977	.86
	Control yield				
1.	Y=-85.19-0.045x29	4.07#	4.36	.449	.34
2.	Y=-142.84-0.064x29+0.650x5	2.00	4.64	.500	.25
3.	Y=-357.81-0.098x29+2.01x5-0.036x30	2.63	3.98	.724	.45
4.	Y=-374.11-0.102x29+2.14x5-0.041x30-0.843x4	2.41	3.85	.828	.48
5.	Y=-392.96-0.143x29+1.46x5-0.009x30-1.93x4+54.54x7	1.62	4.35	.890	.34
	K fertilizer rate				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=266.64+2.76x2+139.48x7+0.136x30	6.23#	11.70	.862	.72
4.	Y=741.09+3.23x2+271.77x7+0.306x30-5.99x5	30.02*	4.93	.984	.95
5.	Y=963.39+3.56x2+344.92x7+0.377x30-8.39x5-2.22x4	84.20#	2.65	.998	.99

Correlation coefficients:

	Variable No.						
	x2	x4	x5	x6	x7	x29	x30
Potential yield, x2			-.264	.062	.061	-.387	-.531
Control yield, x3		-.186	-.382		-.374	-.670	-.258
K fertilizer rate, x1	.654	.540	.232		.493		-.147

1/ F ratio due to regression

2/ Standard error of the estimate

Sign. p = 0.10

* Sign. p = 0.05

Table 51. Stepwise regression equations and correlations relating potential yield, control yield, and K fertilizer rate to climatic factors and free energy of K exchange, $RT\ln[K]/[Ca+Mg]^{\frac{1}{2}}$, after extracting soils from seven 1973 winter wheat sites with 50 ml of a dilute cation solution (Baker, 1971).

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Potential yield				
1.	Y=-56.33-0.032x32	1.15	7.50	.187	.02
2.	Y=-153.76-0.031x32-0.035x31	0.94	7.68	.319	
3.	Y=684.49-0.088x32-0.147x31+3.95x5	2.23	5.98	.691	.38
4.	Y=-801.56-0.097x32-0.180x31+4.08x5-2.90x6	2.54	5.34	.836	.51
5.	Y=-806.40-0.050x32-0.228x31+2.69x5-4.84x6+65.56x7	2.93	4.71	.936	.62
	Control Yield				
1.	Y=-88.09-0.045x31	3.83	4.42	.434	.32
2.	Y=-81.42-0.046x31-0.590x4	1.91	4.69	.488	.23
3.	Y=-243.28-0.101x31-1.95x4+52.16x7	2.64	3.97	.726	.45
4.	Y=-415.53-0.156x31-2.33x4+70.05x7+1.26x5	4.10	3.06	.891	.67
5.	Y=-516.59-0.191x31-2.39x4+85.83x7+1.28x5-1.77x6	6.13	2.33	.968	.81
	K fertilizer rate				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=253.43+2.52x2+139.52x7+0.125x32	5.54#	12.31	.847	.69
4.	Y=743.29+2.72x2+277.90x7+0.291x32-6.14x5	14.24#	7.10	.966	.90
5.	Y=896.22+2.73x2+318.16x7+0.336x32-8.63x5-4.17x6	361.69*	1.28	.9994	.996

Correlation coefficients:

	Variable No.						
	x2	x4	x5	x6	x7	x31	x32
Potential yield, x2			-.264	.062	.061	-.388	-.433
Control yield, x3		-.186	-.382	.324	-.374	-.659	
K fertilizer rate, x1	.654		.232	-.121	.493		-.090

1/ F ratio due to regression

2/ Standard error of the estimate

Sign. p = 0.10

* Sign. p = 0.05

Table 52. Stepwise regression equations and correlations relating potential yield, control yield, and K fertilizer rate to climatic factors and free energy of K exchange, $RT\ln[K]/[Mg]^{\frac{1}{2}}$, after extracting soils from seven winter wheat experimental sites with 50 ml of a dilute cation solution (Baker, 1971).

Step	Equation	F [1]	SE [2]	R^2	Adj R^2
	Potential yield				
1.	Y=-49.17-0.038x33	0.87	7.69	.148	
2.	Y=-208.76-0.092x33+51.92x7	1.35	7.20	.402	.10
3.	Y=-408.45-0.172x33+86.16x7-4.49x6	2.29	5.93	.696	.39
4.	Y=-571.57-0.243x33+144.24x7-4.82x6-2.45x4	3.20	4.84	.865	.60
5.	Y=626.19-0.298x33+192.87x7-5.38x6-3.17x4+0.033x34	120.17#	0.76	.998	.99
	Control yield				
1.	Y=-64.31-0.042x33	2.96	4.65	.372	.25
2.	Y=-58.40-0.044x33-0.650x4	1.56	4.92	.437	.16
3.	Y=-231.07-0.113x33-2.36x4+61.22x7	2.34	4.15	.701	.40
4.	Y=-255.41-0.15x33-2.96x4+100.30x7+0.030x34	6.22	2.53	.926	.78
5.	Y=-332.02-0.186x33-3.13x4+118.21x7+0.033x34-1.53x6	21.81	1.25	.991	.95
	K fertilizer rate				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=138.29+2.00x2+133.77x7+0.092x34	3.97	14.12	.799	.60
4.	Y=119.36+1.83x2+109.00x7+0.098x34+3.18x4	3.26	14.05	.867	.60
5.	Y=106.36+1.80x2+91.68x7+0.092x34+4.23x4-3.20x6	1.68	17.78	.894	.36

Correlation coefficients:

		Variable No.						
		x2	x4	x5	x6	x7	x33	x34
Potential yield,	x2		.226		.062	.061	-.384	-.149
Control yield,	x3		-.186		.324	-.374	-.610	.219
K fertilizer rate,	x1	.654	.540		-.121	.493		.065

[1] F ratio due to regression

[2] Standard error of the estimate

Sign. p = 0.10

average soil temperature, and at step five, available soil water entered the potential yield equation but reduced the significance level of the prediction at the 90% level in equations five and four, respectively.

Free energy of exchange in the 0 to 6 and 6 to 12-inch depth, computed from the ratio $[K]/[Ca]^{\frac{1}{2}}$ or from $[K]/[Ca+Mg]^{\frac{1}{2}}$, along with available soil water, rainfall, and evaporation rate failed to predict potential yield (Tables 50 and 51, respectively). Control yield was predicted at the .10 level of significance by G_K from $[K]/[Ca]^{\frac{1}{2}}$ (Table 50). The K fertilizer rate was predicted with varying levels of significance by combinations of the 6 to 12-inch depth G_K from $[K]/[Ca]^{\frac{1}{2}}$, available soil water and average soil temperature along with potential yield and evaporation rate (Table 50). Similar equations at varying significance levels were developed to predict K fertilizer rate when G_K from the ratio $[K]/[Ca+Mg]^{\frac{1}{2}}$ in the 6 to 12-inch depth, available soil water, and rainfall were combined with potential yield and evaporation rate (Table 51).

The only predictive equation of statistical significance (.10 level) in Table 52 was developed by a combination of G_K from $[K]/[Mg]^{\frac{1}{2}}$ in the 0 to 6 and 6 to 12-inch depths and evaporation rate, rainfall, and average soil temperature. This equation predicted potential yield with a standard error of 0.76 and explained at least 99% of the variability in potential yield.

Effect of soil chemical and physical factors on crop response calibrations. All regression equations predicting potential yield, control yield, and K fertilizer rate were significant at the .10 level or greater when the computer was allowed to select the independent variables from specific soil chemical and physical properties, in addition to climatic variables and resin-thimble extractable soil K (Table 53). Certain of these relationships must be considered empirical at this time. It is difficult to theorize how soil properties such as percentage silt in the 6 to 12 or 0 to 6-inch depth should be related to potential yield. These two variables entered the predictive equation for potential yield at steps one and four, respectively. According to Decker (1972) only 0.6% of the extractable K by N NH_4OAc is accounted for by the total silt fraction. Only 6.3% of the stored soil water at field capacity was related to this same soil separate. The correlation coefficients for percentage silt in the 0 to 6 and 6 to 12-inch depths vs. potential yield are negative. This indicates that as the percentage silt increases, the potential yield decreases. If the percentage sand remained constant when silt increased, there would be less clay in this soil to supply K to the plants. At this point it could be argued that the K supply may not have been a factor. The computer was allowed to select over variables which included fertilizer K, but it did not choose this as one of the five allowed variables. Additional research is needed to resolve the relation of

Table 53. Stepwise regression equations and correlations relating potential yield, control yield, and K fertilizer rate to climatic factors, percent organic matter, percent silt, percent clay, cation exchange capacity, and resin (thimble method -2mm soil, weighed resin, selected thimbles) extractable K in soils from seven 1973 winter wheat experimental sites.

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Potential yield				
1.	Y=80.46-1.01x40	6.94*	5.39	.581	.50
2.	Y=83.65-0.692x40-0.131x13	5.76#	4.72	.742	.61
3.	Y=97.00-0.883x40-0.409x13+17.56x42	7.21#	3.75	.878	.76
4.	Y=112.86-2.59x40-0.538x13+21.91x42+1.42x39	20.53*	2.03	.976	.93
5.	Y=101.18-2.07x40-0.556x13+20.28x42+1.15x39+16.89x7	11110.53**	0.08	1.000	1.00
	Control yield				
1.	Y=59.91-0.157x13	8.66*	3.55	.634	.60
2.	Y=63.23-0.377x13+11.47x41	15.69*	2.21	.887	.83
3.	Y=70.15-0.319x13+10.34x41-0.337x40	46.79*	1.10	.979	.96
4.	Y=73.98-0.331x13+12.30x41-0.390x40-0.074x14	667.78**	0.25	.999	.99
5.	Y=73.65-0.332x13+12.81x41-0.265x40-0.087x14-0.113x39	7029.61**	0.07	1.000	1.00
	K fertilizer rate				
1.	Y=135.31-3.06x40	8.09*	15.06	.618	.54
2.	Y=53.04-2.77x40+4.29x4	7.06*	12.81	.779	.67
3.	Y=60.98-2.89x40+5.84x4-7.15x6	14.39*	8.02	.935	.87
4.	Y=80.13-6.07x40+5.80x4-6.94x6-2.48x39	33.54*	4.67	.985	.96
5.	Y=93.86-7.45x40+6.81x4-7.92x6-3.50x39-36.20x7	102.01#	2.41	.998	.99

Correlation coefficients:

	Variable No.								
	x4	x6	x7	x13	x14	x39	x40	x41	x42
Potential yield, x2			.061	-.737		-.742	-.762*		-.621
Control yield, x3				-.796	-.185	-.737	-.737	-.518	
K fertilizer rate, x1	.540	-.121	.493			-.693	-.786*		

1/ F ratio due to regression

2/ Standard error of the estimate

\# Sign. p = 0.10

* Sign. p = 0.05

** Sign. p = 0.01

soil silt to potential yield.

Another puzzling variable which entered the potential yield predictive equation at step three was soil organic matter (O.M.) in the 6 to 12-inch depth. An average of 1.27% O.M. was found in this depth, A negative, though insignificant correlation coefficient was generated for potential yield vs. soil O.M. in the 6 to 12-inch soil depth. According to Mehlich (1946) and Spencer (1954) K is loosely retained by the negative sites on O.M.

Both potential yield and control yield were very adequately predicted by the respective regression equations at step five. The standard error was insignificant and 100% of the variability in each yield prediction was accounted for as indicated by R^2. Despite the fact that the adjusted R^2 equalled 1.0, caution should be used when attempting to apply this equation because of the low number of experimental sites.

The combination of percentage silt in the 0 to 6 and 6 to 12-inch depths and average soil temperature, rainfall, and evaporation rate provided one of the best predictions of the K fertilizer rate for these soils. The fact that soil K did not enter into this equation may be due to the problem which initiated this research - apparent adequate K in these soils. This equation is of little value for determining the response of crops to K, but it may provide some good leads to future understanding of the answers to this K soil test problem.

Importance of climatic variables. The computer, by means of stepwise regression, was allowed to determine the order of importance of the climatic factors when soil test K was prohibited from entering the equation (Table 54). For potential yield the order of selection was available soil water, average soil temperature, rainfall, and evaporation rate. For the control yield prediction, available soil water was again chosen first, followed by evaporation rate, rainfall, and average soil temperature. All of these climatic variables together were not able to develop a predictive equation which was statistically significant. The standard error was increased with the addition of each variable after step one.

The prediction of the K fertilizer rate was also nonsignificant. The standard error began to increase with the addition of available soil water at step three. Notice the negative correlation between standard error and the adjusted R^2. As standard error decreases, the adjusted R^2 increases. When standard error begins to increase, the adjusted R^2 decreases. Both these statistics attempt to explain the variation in response, but the approach is different. As the standard error decreases it indicates that more of the variation in response is explainable. An increasing R^2 indicates that a greater percentage of the variation in response is being explained by the fitted variables.

Table 55 is a summary of the standard error and R^2 values for the K extraction methods tried on the 1973 experimental site soil samples

Table 54. Stepwise regression equations and correlations relating potential yield, control yield, and K fertilizer rate to climatic factors in soils from seven 1973 winter wheat experimental sites. (Soil test K locked out)

Step	Equation	F 1/	SE 2/	R^2	Adj R^2
	Potential yield				
1.	Y=50.22-0.669x5	0.37	8.03	.070	
2.	Y=37.81-0.616x5+0.718x4	0.25	8.78	.109	
3.	Y=40.92-0.961x5+0.995x4-1.46x6	0.17	9.93	.147	
4.	Y=41.48-1.09x5+0.776x4-1.41x6+8.14x7	0.09	12.11	.154	
	Control yield				
1.	Y=46.66-0.684x5	0.86	5.42	.146	
2.	Y=51.27-0.484x5-12.63x7	0.50	5.87	.200	
3.	Y=47.27-0.256x5-14.00x7+0.827x6	0.29	6.66	.227	
4.	Y=53.51-0.320x5-7.22x7+1.18x6-0.61x4	0.18	7.97	.262	
	K fertilizer rate				
1.	Y=-55.76+1.92x2	3.74	18.44	.428	.31
2.	Y=-92.96+1.83x2+92.99x7	3.46	16.49	.634	.45
3.	Y=-102.57+2.07x2+67.63x7+2.04x5	2.21	17.56	.689	.38
4.	Y=-149.62+1.95x2+20.95x7+3.00x5+4.04x4	1.86	17.74	.788	.36
5.	Y=-144.04+1.90x2+19.79x7+2.57x5+4.44x4-1.78x6	0.77	24.71	.795	

Correlation coefficients:

	Variable No.				
	x2	x4	x5	x6	x7
Potential yield, x2		.226	-.264	.062	.061
Control yield, x3		-.186	-.382	.324	-.374
K fertilizer rate, x1	.654	.540	.232	-.121	.493

1/ F ratio due to regression

2/ Standard error of the estimate

Table 55. A compendium of R^2 and standard error of the estimate values for step one of the stepwise regression of potential yield versus soil K and climatic variables on both moist and air dried soil samples from seven 1973 winter wheat experimental sites.

Extraction technique	Variable entered	Std. Error	R^2
1 N Ammonium acetate extraction			
Moist soil	0 to 6-inch K	7.59	.168
Dried soil	0 to 6-inch K	7.71	.142
Resin-thimble extraction,			
2mm moist soil, measured resin, unselected thimbles	0 to 6-inch K	8.03	.070
2mm dried soil, measured resin, unselected thimbles	0 to 6-inch K	6.35	.417
2mm dried soil, measured resin, visually selected thimbles	0 to 6-inch K	6.93	.308
0.5mm dried soil, weighed resin, visually selected thimbles	0 to 6-inch K	5.62	.543
0.5mm dried soil, weighed resin, visually selected thimbles	0 to 6-inch K	6.73	.347
Resin plus N NH_4OAc extraction			
Moist soil	0 to 6-inch K	7.29	.387
Dry soil	0 to 6-inch K	6.96	.301
Moderately available K extraction, $[(\text{resin} + NH_4OAc)-NH_4OAc]$			
Moist soil	0 to 6-inch K	7.71	.142
Dry soil	0 to 6-inch K	6.40	.410
Percent saturation of exchange complex	0 to 6-inch %	7.99	.080
Resin-thimble extraction plus climatic and soil physical and chemical variables	6 to 12-inch % silt	5.37	.582
Soil climatic variables only	Available soil water	8.03	.070
Dilute cation solution extraction			
Dry soils: solution K	0 to 6-inch K	7.28	.236
$RT\ln[K]/[Ca]^{\frac{1}{2}}$	6 to 12-inch	7.05	.282
$RT\ln[K]/[Ca+Mg]^{\frac{1}{2}}$	6 to 12-inch	7.50	.187
$RT\ln[K]/[Mg]^{\frac{1}{2}}$	0 to 6-inch	7.69	.147

at step one of the stepwise regression. It is a facsimile of Table 28. Results of Table 28 indicated that the two soil K extraction methods which were most highly related to percentage yield response were the resin-thimble procedure ($R^2 = 0.56$) and the dilute cation solution equilibration procedure with G_K computed from $[K]/[Ca]^{\frac{1}{2}}$ ($R^2 = 0.55$). Only the resin-thimble K extraction method, tested on the 1973 experimental site soil samples provided a significant prediction of potential yield when 0 to 6-inch depth K was entered at step one as the only independent variable. The largest R^2 value was .54. This value was achieved when a very uniform set of selected thimbles, 0.5 mm soil samples, and accurately weighed resin were combined in the resin-thimble procedure to allow an average standard deviation of 1.72 ppm K between duplicate samples. (With only one degree of freedom, this standard error simplifies to the deviation of the duplicate K results from their mean.) Reruns of this procedure by various modifications in technique consistently provided R^2 values above 0.30.

The dilute cation procedure of Baker (1971) produced a high R^2 value of .28 when the 6 to 12-inch depth G_K from $[K]/[Ca]^{\frac{1}{2}}$ entered the equation at step one. The standard error was 7.05, greater than any produced by variations in the resin-thimble technique used to analyze air dry samples. Moderately available K by the [(resin + N NH_4OAc) minus N NH_4OAc] extraction method was one of the better extraction methods employed on the 1973 samples. When used on air dried

soils it generated an R^2 of .41 at step one of the stepwise regression procedure. The standard error was 6.4 and was lower than that of any other extraction method.

This research has not solved the problem of developing and calibrating the one best soil analysis procedure for K. Rather, it has unearthed additional opportunities to be researched and possibly pointed out some directions which may be taken in future research on the subject.

A resin procedure holds promise of being developed into the best method to extract soil K and relate this to crop yields. As has been in the past, the dilemma of how to separate the resin from the soil remains. The thimble placed research somewhat closer to accomplishing this separation. If a very uniform soil container could be developed the procedure used in this research would work. However, as reported earlier, machine manufactured thimbles are less uniform than the hand made thimbles. Some other type of soil container should be tried.

This research did not reveal a procedure which, only by extracting K from the soil, could predict the K fertilizer requirement for winter wheat response. To predict winter wheat and other dry land crop's response to K fertilizer, extensive research, evaluating all tangible growth promoting factors of these plants, must be conducted. The ideas of Collis-George and Davey (1960) and the work of Laird and Cady (1969) and Voss et al. (1970) along with results in this thesis

indicate possible avenues future K soil test calibration research should take.

Development of the resin procedures for K extraction.

Resin-thimble procedure. The idea of a resin-thimble procedure for extraction of available K from soil was a remnant of the attempt to develop the yeast cell K extraction technique. The resin was substituted for the yeast cells. Use of a strongly acid cation resin was suggested.[17]

Williams and Jenny (1952) reported that H^+ is a better extractant than Na^+, Li^+, Ca^{++}, Mg^{++}, or NH_4^+. Theoretically, the strongly acid cation resin will exchange H^+ for soil cations in a manner similar to the action of plant roots. The Dowex resin was selected because of its greater stability in solutions, and spherical design which provides greater surface area.[18] The 20 to 50-mesh resin was chosen to provide for ease of separation of the resin from the soil, had this been necessary. The decision to use approximately 5 g of resin to extract 2 g of soil in the initial resin-thimble procedure development was

17/ Earl Skogley, Montana Agricultural Experiment Station, Bozeman, Montana. Personal communication.

18/ Gary Strobel, Montana Agricultural Experiment Station, Bozeman, Montana. Personal communication.

based on the need for an exchanger CEC at least 10 times greater than that of the soil. Thirty-one meq/100 g was the highest CEC found in any of the soils initially tested in this research. Therefore, the CEC of two g of resin (1.7 meq/g) was actually 15 times in excess of that in any soil sample studied.

Initial results of duplicate sample analysis for K by the resin-thimble method indicated that this procedure lacked precision. A randomized, complete block experiment was designed to determine the precision of this extraction technique. Results of this experiment are shown in Table 56. Careful examination of these data revealed that frequently one K value out of three was completely out of line. Thus, analysis of the error among the three replications was unnecessary. Without improvement in the precision of this procedure, it could not be used as a valid test for extractable soil K.

An attempt to determine the cause of this variability revealed that the base of the thimbles varied in thickness. This would allow exchange of K to occur much more easily due to the proximity of the soil to the resin. Following this discovery attempts were made to find more uniform thimbles.

Moderately available soil potassium by resin extraction. The resin-ammonium acetate K extraction technique reported by Barber and Matthews (1962) required 48 hours to remove the moderately available K from soil samples. This is too long for routine soil testing. To

Table 56. Results of K extraction by the resin-thimble procedure to check its precision using three different soils screened to three particle sizes, and extracted for six time periods, using triplicate analysis.

Time Hrs	Soil Texture	1 to 2 mm			0.5 to 1 mm			less than 0.5 mm		
		K, ppm								
2	Sl*	24.19	22.22	18.52	15.98	13.32	29.27	17.93	15.27	19.57
	Cl	30.22	34.57	28.27	48.13	31.10	39.27	33.78	46.61	48.26
	C	17.32	52.88	22.12	35.89	30.52	29.95	31.51	34.31	31.65
4	Sl	19.05	13.33	23.56	15.69	24.12	14.71	18.59	18.38	16.36
	Cl	145.83	32.02	31.40	51.34	48.08	63.38	68.27	52.63	39.47
	C	35.89	36.53	26.43	66.51	33.07	31.91	57.38	44.72	43.48
8	Sl	17.50	11.52	15.54	22.47	22.56	18.37	25.25	33.46	23.72
	Cl	75.34	74.63	75.98	63.75	109.59	76.35	93.75	98.62	88.24
	C	68.09	45.45	39.47	53.57	66.67	69.94	78.70	87.04	95.13
16	Sl	25.91	25.38	18.04	46.22	53.42	28.93	40.00	36.84	46.00
	Cl	181.16	123.32	77.67	127.27	140.19	136.56	300.63	167.97	224.72
	C	69.65	74.56	108.70	106.52	148.94	327.00	141.98	122.49	127.45
32	Sl	37.44	42.92	37.56	47.53	32.47	53.70	42.55	65.14	76.49
	Cl	147.58	131.94	159.62	217.82	271.89	251.05	357.95	253.23	241.77
	C	273.61	154.51	131.46	214.29	252.19	134.04	225.12	197.37	204.23
64	Sl	107.66	53.81	95.98	70.31	115.88	63.49	82.73	92.59	78.57
	Cl	310.15	299.30	285.87	248.84	275.82	410.80	333.97	346.96	362.15
	C	226.79	261.36	197.62	239.13	303.19	253.16	290.35	289.70	282.70

* Sl-sandy loam, Cl-clay loam, C-clay. Percentages of sand, silt, and clay and CEC previously shown in Table 2.

modify the technique we had to determine the amount of resin required to extract Montana soils.

Results of the experiments to determine the amount of resin to use in this procedure are shown in Tables 57 and 58. The results in Table 57 indicate that as the weight of resin was increased, the amount of K extracted from the three soils decreased. What probably occurred was that, as the amount of resin increased, the amount of K extracted from the soils also increased, but the NH_4^+ in 50 ml of N NH_4OAc (50 meq/l) was not sufficiently concentrated to remove all the K from the resin (CEC from 10 g of resin is 17.0 meq/100 g). The tenacity with which the resin held K against this constant concentration of NH_4^+ increased as the CEC of the resin increased when more resin was added to the soil.

Results of equilibration of 2 g of the soils described in Table 2 with one through 5 g of resin for 16 hours, followed by five, 50 ml N NH_4OAc extractions of the resin-soil slurry for $\frac{1}{2}$ hour each, do verify the above statement (Table 58). Except for the clay soil there was no increase in extractable plus moderately available soil K even when 5 g of resin were used. Three g of resin adequately extracted these same forms of K from the clay which had a CEC of 30.64 meq/100 g. A ratio of approximately 1 g of resin appears to be needed for each 10 meq CEC/100 g of soil. Two to 3 g of resin would be adequate along with N NH_4OAc to remove moderately available plus exchangeable K from

Table 57. Results of 16-hour equilibrium extraction of 2 g of soils, described in Table 2, by resin, followed by ammonium acetate extraction for ½ hour. (Duplicate analyses)

Resin Wt. g	2		4		6		8		10	
Texture	K, ppm									
Sl*	313	325	250	250	188	188	100	100	38	38
Cl	738	725	600	600	475	475	288	288	75	63
C	800	788	700	700	513	513	313	325	113	100

* Sl-sandy loam, Cl-clay loam, C-clay

Table 58. Results of 16-hour equilibrium extraction of 2 g of soils, described in Table 2, by resin, followed by five extractions each with 50 ml of N NH_4OAc for $\frac{1}{2}$ hour. (Duplicate analyses).

Resin Wt. g	1		2		3		4		5	
Texture										
Sl*	516	402	459	459	516	516	459	459	516	516
Cl	978	1036	1153	1094	1036	1094	1094	1270	1094	1211
C	1153	1094	1211	1153	1388	1329	1447	1270	1270	1329

* Sl-sandy loam, Cl-clay loam, C-clay

soils studied in this research.

Table 59 contains results of K removed from triplicate samples of three different soils, screened to three particle sizes, and extracted for seven time periods by the resin-N NH_4OAc procedure to determine its precision. Observations of replicate data for specific fractions of these soils revealed that there was frequently one result which differed by 13 ppm. This was probably caused by instrument noise which made the indicator needle vary by as much as $\pm$ 2% when analyzing K on the Model 290-B Perkin-Elmer atomic absorption spectrophotometer. If this problem could be eliminated the results shown in Table 59 would be in closer agreement. A 1% deviation on the instrument dial reading accounts for .25 ppm difference in solution K between samples when the instrument is calibrated with a 0 to 25 ppm K standard curve. However, because of a dilution factor of 50 this difference becomes 12.5 ppm K in the soil. Initial observations of the data in Table 59 show that soil texture influences the amount of K removed. More K is removed from soils having higher clay content. Also, increasing the resin-soil equilibration time accounts for removal of greater concentrations of K. Grinding the soils into three different size fractions does not influence the amount of K removed by this procedure. The analysis of variance for these data is shown in Table 60.

Grinding these soils into 1 to 2, $\frac{1}{2}$ to 1, and less than $\frac{1}{2}$ mm

Table 59. Results of K extraction by the resin - N NH_4OAc procedure to check its precision using three different soils screened to three particle sizes, and extracted for seven time periods using triplicate analysis. Time refers to resin equilibration only.

Time Hrs	Soil Texture	1 to 2 mm			0.5 to 1 mm			less than 0.5 mm		
		K, ppm								
0	Sl*	275	275	263	238	238	238	238	225	225
	Cl	575	575	575	588	575	550	575	588	588
	C	625	638	625	625	638	625	625	625	625
2	Sl	288	275	275	250	250	250	250	250	275
	Cl	663	663	638	663	663	663	625	613	613
	C	663	650	663	663	688	663	663	650	638
4	Sl	288	288	275	250	250	250	263	250	263
	Cl	650	650	650	650	663	650	625	613	613
	C	675	688	688	675	700	688	688	700	700
8	Sl	300	313	313	288	288	288	275	275	275
	Cl	713	700	713	713	713	738	675	663	663
	C	713	725	713	688	725	725	725	713	738
16	Sl	325	338	313	300	300	300	288	300	300
	Cl	725	750	763	750	750	738	688	713	700
	C	800	813	813	825	825	825	825	838	825
32	Sl	375	363	375	338	338	338	350	338	350
	Cl	813	788	813	813	788	800	775	763	763
	C	875	863	900	875	900	875	863	888	875
64	Sl	438	450	438	413	413	425	425	425	413
	Cl	888	888	925	913	913	938	888	888	888
	C	1013	988	1013	1025	1025	1025	1025	1038	1038

* Sl-sandy loam, Cl-clay loam, c-clay. Percentages of sand, silt, and clay and CEC were previously shown in Table 2.

Table 60. Multifactor analysis of variance of K extracted from soils by the resin-N NH_4OAc procedure (Table 59).

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F
Replication	2	11562.5	5781.3	
Texture	2	5964580.	2982290	453.00**
Replication x texture	4	274041	6851	
Time	6	805110	134185	27.31**
Replication x time	12	58964.5	4913.7	
Texture x time	12	3262910	271909	53.94**
Replication x texture x time	24	120985	5041	
Fraction	2	33649	168245	3.62
Replication x fraction	4	18586.9	4646.7	
Texture x fraction	4	13921.7	3480.4	0.79
Replication x texture x fraction	8	35211	4401.4	
Time x fraction	12	49092.1	4091	0.79
Replication x time x fraction	24	123862	5160.9	
Time x texture x fraction	24	127846	5326.9	1.03
Replication x time x texture x fraction	48	249344	5194.7	
Between cells	188			
Overall observations 189				

** Sign. p = .01

separates did not change the amount of K extracted by this resin-NH_4OAc procedure because the less than $\frac{1}{2}$ mm fraction probably contained the same proportion of silt and clay as did the other two sized separates. Observation of the soils following the filtration step revealed that all separates had been equally well dispersed. Therefore, the H^+ and NH_4^+ were allowed optimum contact with the soil particles in each separate and could extract equivalent concentrations of K.

Figure 5 illustrates the effect of time on the concentration of K extracted from the three soils described in Table 2 by the resin-N NH_4OAc procedure. Each point in this figure represents an average analysis of the three separates. The lines connecting K concentrations resemble crop response curves except that they do not reach a peak. Time zero represents the K extracted from these soils by N NH_4OAc. The difference between K removed at any extraction time beyond zero and by N NH_4OAc represents the K extracted by the hydrogen resin. Each of the curves appears to have two different slopes.

The amount of K removed by N NH_4OAc represents that which is soluble and easily exchangeable to NH_4^+. The rate of K removal decreased after 8 hours of resin-soil equilibration in sandy loam and clay loam and after 16 hours in clay. The concentration of resin extractable K at these points, less that which is extracted by NH_4OAc is moderately available K (Barber and Matthews, 1968). Beyond these points in each

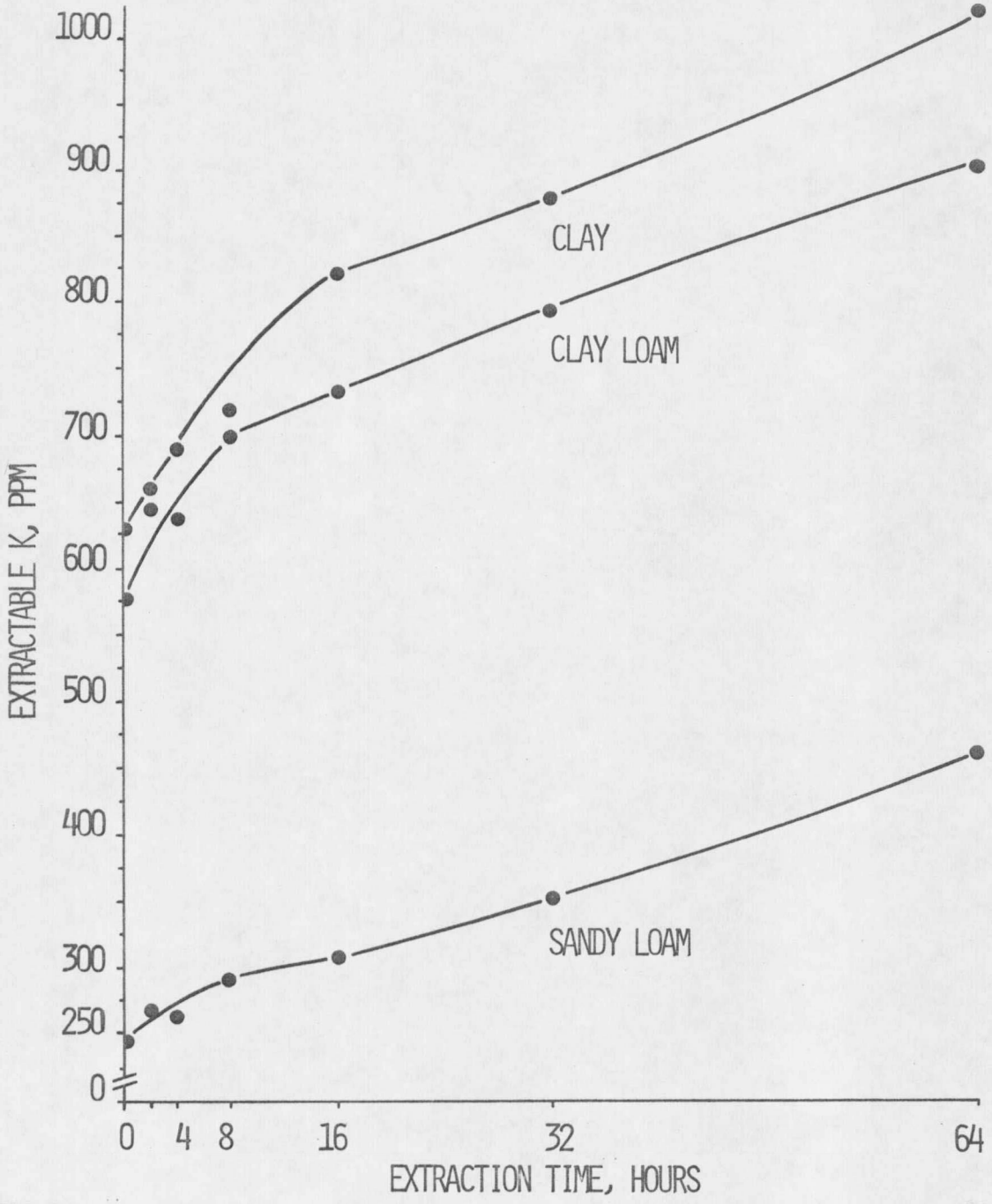


FIGURE 5. THE INFLUENCE OF TIME ON THE AMOUNT OF K EXTRACTED FROM THREE SOILS BY THE RESIN - N AMMONIUM ACETATE PROCEDURE.

soil the slope for resin extractable K becomes less steep but increases at a constant rate, indicating that the resin was extracting structural K from these soils. These observations were also made by Garman (1957) and Barber and Matthews (1962). According to Martin, et al. (1946), the pH at which the least K fixation occurs in soils is about 2.5. The pH in close proximity to these resin beads is 1.5. One could hypothesize that hydrolysis may be disintegrating the layer silicate minerals, causing release of structural K after the 16 hour equilibration time. Rich (1964) theorized that the lack of K fixation at low pH's is probably due to large numbers of hydronium ions and their ability to replace K effectively.

One additional observation may be made from Figure 5. The slopes of the lines after 16 hours are essentially the same. This could indicate that similar mineralogy and/or hydrolysis rate, or at least a similar K release mechanism is involved after 16 hours. The soils were taken from the Sidney, Huntley, and Edgar, Montana vicinities.

SUMMARY

The objectives of this research were to recalibrate the N NH_4OAc soil K extraction procedure, or to determine a better procedure for predicting crop response to applied K, including the evaluation of soil and climatic properties as they affect this prediction. Nine soil K extraction methods were evaluated to determine their ability to predict crop response on an initial set of 17 winter wheat research site soil samples from the years 1967 through 1971. These methods are listed as follows: (1) one N NH_4OAc; (2) saturated soil paste; (3) dilute cation solution; (4) dilute K solution; (5) DTPA solution; (6) hydrogen EDTA; (7) strongly acid cation resin plus NH_4OAc; (8) moderately available K; and (9) resin extractable K by the thimble method, developed by this research.

Multiple linear regression equations were utilized to evaluate data from 17 research sites in an attempt to predict percentage yield response to applied K fertilizer. The combination of K applied and 0 to 6 and 6 to 12-inch soil K by the three methods shown below, produced the only statistically significant (.05 level) relationships with percentage yield response.

Extraction method	Table No.	ANOV F	Std. Error	R^2
Dilute cation equilibration, (Baker,1971)	15	5.24	3.85	.55
DTPA, (Lindsay and Norvell, 1969)	23	3.85	4.16	.47
Resin-thimble method	27	5.44	3.81	.56

Although the resin-thimble procedure accounted for a slightly greater amount of error in predicting percentage yield response, the precision between duplicate sample analyses was not good. The free energy of K exchange calculated from the equation $RT\ln[K]/[Ca]^{\frac{1}{2}}$ in the dilute cation method was much more precise. The R^2 generated by the N NH_4OAc extraction method for available K was only .32.

The N NH_4OAc K extraction method was tested on soils from 1973 sugar beet, barley, spring wheat and winter wheat experimental sites to determine its yield predictive capabilities on these crops with other nutrients adequate. The total sugar yields from the K fertilized plots and the control plots were essentially the same even though the K concentrations in the soil varied from a low of 102 to a high of 565 ppm in the surface six inches. Thus no soil test relationship with sugar beets could be made. However, because the 12 to 18-inch depth samples from these sites contained about the same K or one level lower concentration than the surface samples, K in these deeper samples could explain the lack of predictive precision.

Spring wheat yield response was significantly related at the .05 probability level to the 6 to 12-inch soil K. Eighty-seven percent of the variation in yield response to K was attributed to this one factor. However, as this relationship was developed on data from only five sites, it should be used with caution.

The combination of barley, spring wheat, and winter wheat yield

responses failed to produce a significant relationship when regressed over N NH_4OAc extractable K in the 0 to 6 or 6 to 12-inch soil depth.

Selected K extraction methods some of which had been tested on the 1967 through 1971 site soils, were tested on seven soils from the 1973 winter wheat experimental sites. The dependent variables in the stepwise regression programs included potential yield of the site in bu/acre from K treated plots (x2), yield from control plots (x3), and the K fertilizer rate (x1). The independent variables included the appropriate variable presented above plus extractable K in the 0 to 6 and 6 to 12-inch soil depths (x varies by method used), stored available soil water (x5), average soil temperature at 50 cm (x4), growing season rainfall (x6), and evaporation rate from an open pan in cm/day (x7). Results for statistically significant potential yield predictions from these tests are shown on the next page. (Table 32 defines the variable numbering system used in the indicated tables.)

This list of regression results from potential yield predictive equations reveals that only the resin-thimble extractable K method was able to generate a statistically significant equation at step one, when K in the surface 6-inch depth was the variable entered. This resin-thimble technique utilized visually selected thimbles, one-half mm sized soil samples, and five grams of resin. The standard deviation between duplicate sample analyses was 1.72 ppm K. Inclusion of the climatic variables, along with extractable K in the 0 to 6 and 6

to 12-inch depths, generated statistically significant regression equations for predicting potential yield by use of the N NH_4OAc, resin-thimble, moderately available, percentage K saturation, and dilute cation solution K methods.

Extraction method	Table No.	Reg. Step	Signif. Level	Std. Error	R^2 Adj.
N NH_4OAc					
Air Dried Soil	33	4	.05	1.6	.96
Moist Soil	33	5	.10	0.6	.99
Resin-thimble (Best run)					
Air Dried Soil	40	1	.10	5.6	.45
"	40	2	.05	4.2	.70
"	40	3	.05	2.7	.87
"	40	4	.05	1.2	.98
"	40	5	.05	0.5	.998
Moderately available K					
Air Dried Soil	45	4	.05	1.4	.97
	45	5	.01	0.03	1.00
Percent K saturation	48	4	.10	2.78	.87
Dilute cation method (Baker, 1971)					
Solution K	49	3	.01	1.76	.95
	49	4	.05	1.08	.98

Analysis of the 0 to 6 and 6 to 12-inch depth moist soils by N NH_4OAc provided a better prediction of potential yield than analysis of air dried soils. All other statistically significant predictions of potential yield were developed from analysis of air dried soils.

Analysis of field moist soils by the other methods failed to generate statistically significant relationships.

When each K extraction method was evaluated at step one, the resin-thimble procedure explained the largest amount of variability in potential yield (R^2=.54) when 0 to 6-inch K entered the equation. The dilute cation procedure of Baker (1971) produced an R^2 of .28 when the 6 to 12-inch depth G_K from $[K]/[Ca]^{\frac{1}{2}}$ entered the equation at step 1. The standard error was 7.05, greater than any produced by variations in the resin-thimble technique. The moderately available extraction method $[(\text{resin} + N\ NH_4OAc) - N\ NH_4OAc]$ was one of the best tests employed on the 1973 samples. By this method an R^2 of .41 was generated when the 0 to 6-inch soil K was entered into the equation at step 1. The standard error was 6.4 and was lower than that of any other extraction method.

The order of importance of climatic factors for prediction of potential yield was (1) available soil water, (2) average soil temperature, (3) growing season rainfall, and (4) evaporation rate. No combination of these factors without soil test data could predict potential yield. Results of statistically significant K fertilizer rate predictions are presented on the following page.

This listing of regression results from these predictive equations indicates that, of all the methods evaluated in this research, the dilute cation method of Baker (1971) using G_K from $[K]/[Ca+Mg]^{+}$ may be

the best method for predicting the K fertilizer rate. The equation developed at step 5 included the variables: (x2) K treatment yield, (x7) evaporation rate, (x32) 6 to 12-inch G_K, (x5) available soil water, and (x6) rainfall. Caution must be exercised when predicting the K fertilizer rate by this method because the ratio of variables to degrees of freedom in this research was 1.0.

Extraction method	Table No.	Reg. Step	Signif. Level	Std. Error	R^2 Adj.
Percent K saturation	48	5	.01	0.27	1.00
Dilute cation method (Baker, 1971)					
Solution K	49	4	.10	6.51	.91
G_K from $[K]/[Ca]^{\frac{1}{2}}$	50	3	.10	11.70	.72
"	50	4	.05	4.93	.95
"	50	5	.10	2.65	.99
G_K from $[K]/[Ca+Mg]^{\frac{1}{2}}$	51	3	.10	12.31	.69
"	51	4	.10	7.10	.90
"	51	5	.05	1.28	.996

The order of importance of variables for predicting K fertilizer rate, as determined by the computer, was K treatment yield (x2), evaporation rate (x7), available soil water (x5), average soil temperature (x4), and rainfall (x6). No combination of these factors without soil test K could predict the K fertilizer rate.

This research determined that approximately one gram of strongly acid cation resin is needed to extract K from each 10 meq of soil CEC,

and that 16 hours at 160 cycles per minute is an adequate extraction time to remove moderately available K. The extraction time for the resin-thimble procedure was set at 15 hours. A longer extraction time would completely eliminate this method as a routine procedure. Additional research should be done on the soil container for the resin-thimble procedure.

This research has not solved the problem of developing and calibrating the one best soil extraction method for K. It has, however, indicated some directions future soil test K research might take. A multitude of field trials in which crop response to fertilizer K and its interactions with nitrogen and phosphorus is needed. To properly evaluate crop response to fertilizer K the research scientist should evaluate all possible factors which influence growth of the crop. The list of factors should include soil sampling and evaluation for physical and chemical properties in each plot or at least within each replicated treatment, analysis of subsurface samples, meteorological factors, past management and cropping practices, weed conditions, insect and disease damage, and the interactions among fertilizer nutrients and meteorological factors. The importance of some of these factors was shown by the equations developed in this research. Location and characterization of conditions at each potential experimental site should be done in sufficient time to allow selection of sites which have a wide range of soil and climatic variables.

An evaluation of the method of processing soil samples was made to determine the effect of drying and grinding on extractable soil K. Detectable changes in N NH_4OAc extractable K content between moist vs. dry soil analyses of the 0 to 6-inch depth were nonsignificant. Forty percent rehydration of air dried samples for 15 hours did not change extractable K. However, N NH_4OAc extractable K in soils which had been air dried was reverted to the original concentration in moist soils by 40% rehydration, freezing for 15 hours at -29C, and redrying to less than five percent moisture, but not quite to air dry. There was a statistically significant difference between field moist and air dry soil extractable K in the 6 to 12-inch depths. Generally, if the soil contained less than 420 ppm K, release of K occurred on drying. Above this level the soils fixed or maintained their extractable K level on drying. Surface soils usually contained more extractable K than subsoils. Grinding soils finer than 2 mm had no significant affect on NH_4OAc extractable K.

Resin extractable K from air dried soil samples provided a better calibration with potential yield than K from moist samples. Just the opposite was true when samples were extracted with N NH_4OAc.

A P P E N D I X

Appendix table 1. Culture technique for yeast cells (Saccharomyces cerevisiae).

Yeast Cell Preparation:

Ingredients: Fleischman's active dry yeast, reagent grade sucrose, distilled water.

Equipment: Water aspirator aerator, 2-liter Erlenmeyer flask, rubber tubing, 4-liter beaker, incubator, centrifuge and accessories.

Procedure: To 1 liter of distilled water at 30 C (see Source Yeast..., 1957) add 10 g of active dry yeast and swirl until it is dissolved. Add 20 g of sucrose and dissolve.
Place solution into a 30 C incubator and provide moderate aeration. After 2 hours centrifuge the cells, discard the supernatent, add 1 liter of 2% sucrose, provide aeration and incubate again for 2 hours.
Complete this process a total of three times, place the final cell sediment into 1 liter of 2% sucrose and the cells are ready to use. (The pH of the supernatant after each equilibration is 3.75 to 3.8. Four 8-hour equilibrations in sucrose deplete K more completely).

At this point 10 ml of cell suspension contain 100 mg of cells having a K content of 2.15 mg per liter.

A 40 ml aliquot of nutrient solution is added to 10 ml of yeast cell suspension for soil extraction. This nutrient solution was prepared according to specifications of Nosoh (1964), as follows: In a liter volumetric flask, place 24 g sucrose, 0.012 g inositol, 0.0053 g niacinamide, 0.0006 g calcium pantothenate, 0.00144 g pyridoxine and 0.00024 g biotin. Bring to volume with distilled water.

Appendix table 2. Normal ammonium acetate extraction of 1973 Fall soil samples for potassium, calcium, magnesium, and sodium after pretreatment as follows: (1) field condition, moist, (2) air dried, < 20-mesh, (3) 60 C dried, < 20-mesh, (4) 60 C dried, unground, and (5) 60 C, < 20-mesh, rehydrated for 15 hours at 40% water.

Soil Type	Depth	Moisture %	Wet Wt. Analyzed	Potassium, ppm					Calcium, meq/100g					Magnesium, meq/100g					Sodium, meq/100g				
				1*	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Chanta or	0-6	10.82	2.79	204	245	232	225	257	9.1	7.4	7.6	7.8	7.7	3.49	2.98	3.44	3.16	3.82	.57	.54	.74	.70	.51
Attewan loam	6-12	13.98	2.75	106	165	168	158	117	9.4	9.0	9.8	9.6	9.9	4.30	3.76	4.43	4.14	5.07	.65	.54	.72	.70	.40
Bozeman	0-6	20.64	2.78	224	284	348	282	293	22.0	19.4	20.4	18.0	20.6	5.24	4.40	4.67	4.84	5.28	.80	.61	.91	1.0	.40
silty clay loam	6-12	19.77	2.92	107	238	252	240	242	22.4	18.5	19.6	17.6	20.0	7.28	5.51	6.07	6.23	6.94	.75	.69	.83	1.0	.47
Martinsdale	0-6	13.90	2.71	231	273	286	263	278	12.1	10.4	11.4	9.2	10.9	4.00	3.63	3.85	3.57	4.20	.70	.61	.87	.78	.40
sandy clay loam	6-12	14.48	2.80	101	211	232	206	209	13.0	12.9	14.4	12.4	13.7	5.93	5.33	5.90	5.57	6.52	.66	.50	.89	.70	.37
Fort Collins	0-6	8.97	2.68	251	273	275	267	291	7.4	7.0	7.6	7.2	7.3	3.68	3.34	3.57	3.44	3.90	.63	.61	.74	.78	.34
sandy loam	6-12	11.22	2.75	113	183	195	176	187	12.6	11.4	12.0	12.0	11.7	4.58	3.91	4.26	4.00	4.69	.58	.72	.76	.74	.34
Edgar	0-6	20.06	2.72	279	273	286	275	287	11.4	8.8	9.8	8.4	11.5	4.97	3.84	4.18	4.14	4.61	1.37	.50	.87	.74	.40
loam	6-12	4.55	2.72	85	165	195	168	166	20.4	20.4	22.6	20.4	21.4	7.31	4.81	5.29	5.29	5.82	.59	.50	.87	.74	.40
Bainville	0-6	12.88	2.74	319	334	334	334	364	27.8	24.4	26.2	26.8	25.3	4.46	3.68	4.18	4.14	4.49	.69	.54	.70	.65	.33
clay loam	6-12	15.24	2.72	116	222	218	202	202		36.5				7.20	5.39	6.53	6.23	7.10	.76	.50	.72	.70	.51
Evanston	0-6	10.03	2.84	346	374	352	357	374	11.4	6.4	9.2	9.6	8.9	4.41	2.76	4.26	4.14	4.53	.60	.54	.70	.74	.47
clay loam	6-12	10.16	2.78	227	273	275	252	286	13.3	11.2	12.4	12.0	12.1	4.76	3.84	4.43	4.14	4.78	.61	.54	.74	.78	.40
Telstad	0-6	12.17	2.73	361	376	394	348	404	12.2	10.6	11.6	9.4	11.1	3.36	2.91	3.16	2.79	3.32	.64	.44	.76	.78	.50
sandy clay loam	6-12	11.87	2.69	167	200	206	161	194	22.5	20.8	24.4	24.0	22.4	3.50	3.05	3.31	2.91	3.49	.65	.57	.70	.70	.44
Chama	0-6	13.47	2.67	371	368	357	357	391	17.9	16.1	16.4	18.4	16.2	4.55	3.72	4.14	4.51	4.49	.71	.54	.67	.61	.40
clay loam	6-12	14.39	2.70	204	265	279	282	280	27.8	24.1	26.8	26.8	25.9	8.02	6.39	7.17	7.50	8.10	.71	.50	.65	.67	.33
Evanston	0-6	10.78	2.88	375	347	366	362	384	7.8	8.8	7.2	7.2	6.9	2.98	3.63	3.03	2.91	3.28	.60	.29	.72	.70	.34
clay loam	6-12	12.20	2.70	126	200	225	210	214	27.5	24.4	28.6	31.6	27.5	6.65	5.27	6.39	6.39	6.85	.61	.38	.72	.74	.50
Williams	0-6	10.89	2.76	385	387	440	390	427	11.1	9.2	10.4	9.6	9.9	4.17	3.56	4.00	3.85	4.49	.62	.47	.78	.74	.35
clay loam	6-12	15.81	2.77	203	250	275	263	267	15.9	21.1	24.4	25.6	23.4	7.29	5.59	6.23	6.39	6.85	.61	.65	.78	.74	.44
Bainville	0-6	11.45	2.72	387	397	390	375	414	13.4	12.4	13.6	14.4	12.7	4.77	4.07	4.67	4.67	5.07	.68	.50	.72	.70	.47
clay loam	6-12	15.53	2.81	178	256	267	263	265	28.4	27.7	32.4	28.8	30.3	8.52	6.86	8.00	8.00	8.76	.65	.54	.70	.70	.34
Cherry	0-6	15.26	2.72	395	407	450	450	444	14.9	13.3	14.0	12.8	13.3	5.67	4.82	5.16	5.10	5.61	.71	.44	.74	.78	.40
silty clay loam	6-12	17.37	2.76	142	211	229	214	222	45.6	35.8		40.8		7.61	6.08	6.89	6.72	7.60	.63	.47	.78	.65	.40
Arnegard	0-6	15.67	2.70	431	415	430	440	452	14.3	13.5	13.4	14.4	12.9	5.73	4.82	5.29	5.29	5.82	.82	.50	.70	.70	.44
clay loam	6-12	18.26	2.72	303	358	371	366	374	16.3	14.1	15.6	16.0	14.9	7.28	5.83	6.76	6.72	7.31	.64	.47	.74	.74	.40
Cherry	0-6	12.66	2.83	443	426	470		465	33.4	27.0	31.6		29.9	6.37	5.29	5.98		6.31	.71	.69	.91		.47
silty clay loam	6-12	16.09	2.71	133	183	202	183	197	46.0	35.4		40.4		9.30	7.60	8.36	8.36	8.97	.87	.47	.96	.87	.50
Gerber	0-6	15.76	2.81	490	472	500	530	525	14.9	11.6	11.4	12.8	10.9	4.87	3.78	4.14	4.00	4.61	.65	.44	.83	.70	.50
clay loam	6-12	18.67	2.74	263	347	348	320	354	33.9	25.6	29.6	31.2	28.7	6.90	5.26	6.23	6.07	6.81	.64	.68	.70	.70	.51
Gilt Edge	0-6	11.57	2.66	512	493	510	490	520		40.2				6.64	5.29	6.23	6.07	6.65	.85	.47	.70	.74	.44
sandy clay loam	6-12	14.97	2.72	220	283	304	282	285		39.0				7.78	6.46	7.50	7.50	8.31	.84	.46	.76	.67	.51
Absarokee	0-6	14.55	2.82	586	552	570	600	606	16.3	15.7	14.0	15.0	13.5	7.57	6.40	7.09	7.17	7.93	.73	.33	.74	.78	.50
clay loam	6-12	21.83	2.79	383	462	510	490	505	24.5	24.5	22.8	21.6	22.2	10.51	9.04	10.00	9.67	11.09	.81	.38	.78	.74	.50
$\bar{X}$	0-6			366	372	388	373	399	15.1	14.6	13.9	12.6	13.5	4.83	4.05	4.50	4.34	4.91	.73	.50	.77	.74	.43
	6-12			177	248	264	246	254	23.7	22.9	21.1	23.2	20.3	6.83	5.55	6.32	6.21	6.95	.68	.53	.77	.74	.43

* 1. Field moist. 2. Air dried, 25 C. 3. Oven dried, 60 C, less than 20-mesh. 4. Oven dried, 60 C, less than 10-mesh. 5. Oven dried, less than 20-mesh, rehydrated to 40% water.

Appendix Table 3. Saturated paste extraction of soluble Ca, Mg, and K from the 1967 through 1971 experimental site soils.

Cooperator	Site year	Calcium		Magnesium		Potassium	
		ppm					
		0-6	6-12	0-6	6-12	0-6	6-12
Bates	1971	49.6	44.5	16.8	18.5	14.5	14.0
Bramlette	1967	31.4	31.4	19.5	24.0	23.0	11.0
Carter	1969	24.0	40.5	17.3	27.0	25.4	13.6
Dahlman	1967	44.5	34.0	31.5	22.0	18.7	7.7
Dahlman	1969	18.0	18.0	15.0	20.5	11.3	6.0
Dyk	1971	76.0	55.5	24.0	34.5	23.0	18.7
Fadhl	1967	69.0	49.0	30.5	57.0	14.5	4.9
Gagnon	1967	60.0	31.4	42.5	28.3	10.5	5.5
Goodan	1967	44.5	46.0	48.5	47.9	77.0	77.0
Hanser	1967	72.5	48.0	28.8	16.6	21.5	6.1
Holland	1971	44.5	47.0	28.3	26.0	18.7	8.6
Iverson	1967	55.5	53.6	24.5	18.3	29.0	9.5
O'Conner	1969	92.6	37.0	44.8	17.3	30.5	15.0
Ross	1967	41.5	39.0	31.8	24.5	25.4	10.5
Schultz	1967	78.0	62.0	57.0	25.5	22.5	6.9
Torski	1971	59.0	37.6	44.8	29.3	23.5	10.9
Walker	1969	46.0	53.6	16.3	19.5	22.0	8.3

Appendix Table 4. Equilibrium reaction of Ca, Mg, and K with the 1967 through 1971 experimental site soils by the dilute cation method of Baker (1971).

Cooperator	Site year	Calcium		Magnesium		Potassium	
		ppm in solution					
		0-6	6-12	0-6	6-12	0-6	6-12
Bates	1971	209	205	28.6	33.6	25.1	16.7
Bramlette	1967	179	203	37.5	38.0	25.3	15.4
Carter	1969	193	211	34.6	34.6	21.9	13.2
Dahlman	1967	191	191	34.6	37.0	15.9	11.0
Dahlman	1969	177	168	40.9	49.0	16.2	11.2
Dyk	1971	218	197	27.6	38.4	19.8	16.7
Fadhl	1967	216	207	32.2	37.0	13.7	8.8
Gagnon	1967	185	170	47.0	52.3	11.7	9.3
Goodan	1967	166	166	48.6	48.1	43.6	46.8
Hanser	1967	205	214	29.5	29.5	17.7	9.8
Holland	1971	193	201	36.0	37.0	17.5	11.2
Iverson	1967	195	213	30.4	29.5	24.3	13.2
O'Conner	1969	216	216	29.5	30.4	15.9	15.2
Ross	1967	189	187	37.0	38.9	19.3	12.7
Schultz	1967	211	216	28.1	31.8	17.5	9.5
Torski	1971	187	185	46.0	48.1	21.9	14.7
Walker	1969	214	214	28.1	31.8	21.6	12.2
Equilibrating solution		107		11.2		4.64	

Appendix Table 5. Equilibrium reaction of K with the 1967 through 1971 experimental site soils by the dilute K method.

Cooperator	Site year	Calcium		Magnesium		Potassium		Sodium	
		ppm in solution							
		0-6	6-12	0-6	6-12	0-6	6-12	0-6	6-12
Bates	1971	13.26	16.75	1.85	2.82	10.10	8.28	3.65	4.09
Bramlette	1967	4.13	15.76	1.28	3.72	8.30	7.38	4.15	4.02
Carter	1969	4.86	9.88	1.73	1.91	10.60	8.26	4.26	6.05
Dahlman	1967	5.38	6.07	1.39	1.66	7.60	5.70	4.88	4.66
Dahlman	1969	4.51	4.80	1.57	2.00	6.88	5.40	4.00	4.65
Dyk	1971	17.81	15.72	2.37	3.46	8.98	8.08	3.45	3.66
Fadhl	1967	16.20	15.71	2.90	3.51	8.66	6.52	3.62	4.23
Gagnon	1967	14.89	12.86	4.32	4.59	5.80	5.22	7.02	11.68
Goodan	1967	5.60	5.37	2.46	2.18	16.36	16.72	5.20	5.58
Hanser	1967	8.90	11.76	1.67	1.84	8.50	5.50	3.27	5.42
Holland	1971	6.61	13.63	1.58	3.22	7.62	6.74	4.35	5.16
Iverson	1967	5.32	15.09	1.18	2.51	9.26	7.12	4.12	4.22
O'Conner	1969	13.80	13.59	2.45	2.29	9.48	9.46	4.98	5.74
Ross	1967	4.86	6.05	1.39	1.75	8.64	6.20	4.37	4.22
Schultz	1967	10.10	18.70	1.75	2.87	8.56	6.52	3.16	3.46
Torski	1971	13.03	15.15	4.13	4.73	9.74	7.24	7.27	5.01
Walker	1969	12.75	13.48	2.16	2.08	10.82	10.80	3.85	3.32
Equilibrating Solution		0.0		0.0		9.40		2.12	

Appendix Table 6. Magnesium and potassium extracted from the 1967 through 1971 experimental site soils by the DTPA method.

Cooperator	Site year	Fert. K lbs/Ac	Magnesium ppm in soil		Potassium ppm in soil		% Yield Response
			0-6	6-12	0-6	6-12	
Bates	1971	25	365	442	277	158	5.69
Bramlette	1967	25	387	525	240	149	-4.39
Carter	1969	25	262	288	189	96	-2.86
Dahlman	1967	25	272	384	123	77	3.61
Dahlman	1969	25	410	595	82	82	8.01
Dyk	1971	25	339	486	206	147	6.17
Fadhl	1967	25	307	387	109	50	5.31
Gagnon	1967	25	787	915	123	96	3.21
Goodan	1967	25	547	547	515	525	13.21
Hanser	1967	25	234	282	168	86	1.94
Holland	1971	100	387	442	157	91	-3.09
Iverson	1967	25	243	317	222	106	3.19
O'Conner	1969	25	224	224	118	114	8.90
Ross	1967	25	320	410	178	99	12.86
Schultz	1967	25	251	282	157	64	-0.05
Torski	1971	25	666	762	234	152	5.52
Walker	1969	25	269	320	189	86	-0.85

Appendix Table 7. Soil potassium extracted from the 1967 through 1971 experimental site soils by HEDTA, resin plus NH_4OAc, and [(resin + NH_4OAc) - NH_4OAc].

Cooperator	Site year	HEDTA		Resin + NH_4OAc		[(Resin + NH_4OAc)-NH_4OAc]	
		ppm in soil					
		0-6	6-12	0-6	6-12	0-6	6-12
Bates	1971	420	180	835	458	235	156
Bramlette	1967	336	326	688	569	156	147
Carter	1969	272	140	482	308	186	135
Dahlman	1967	172	128	332	284	129	105
Dahlman	1969	188	140	386	314	131	100
Dyk	1971	244	180	600	374	202	107
Fadhl	1967	128	60	326	179	117	52
Gagnon	1967	164	120	600	513	160	145
Goodan	1967	680	700	1173	1186	325	299
Hanser	1967	184	36	619	452	245	150
Holland	1971	248	132	440	290	150	93
Iverson	1967	300	120	600	362	202	124
O'Conner	1969	168	152	308	314	117	129
Ross	1967	232	132	458	332	179	129
Schultz	1967	260	72	495	231	181	86
Torski	1971	400	208	874	619	236	197
Walker	1969	240	104	575	302	213	117

Appendix Table 8. Soil potassium extracted from the 1967 through 1971 experimental site soils by the resin - thimble method.

Cooperator	Site year	Resin - Thimble extractable K, ppm 0-6	6-12
Bates	1971	160	106
Bramlette	1967	163	104
Carter	1969	125	62.5
Dahlman	1967	101	55
Dahlman	1969	84	58
Dyk	1971	136	103
Fadhl	1967	78	35
Gagnon	1967	76	68
Goodan	1967	360	366
Hanser	1967	125	69
Holland	1971	90	55
Iverson	1967	144	85
O'Conner	1969	94	87.5
Ross	1967	106	68
Schultz	1967	105	48
Torski	1971	146	88
Walker	1969	149	58

Appendix Table 9. Sugarbeet and spring wheat yields and N NH_4OAc extractable moist soil K, C.E.C., organic matter, and percentage sand, silt, and clay from the 1973 selected experimental sites.

Cooperator	Fert.K lbs/Ac	Yield, lbs/Ac Tmt.	Control	Soil K, ppm 0-6	6-12	CEC, meq/100g 0-6	6-12	O.M.% 0-6	6-12	Sand 0-6	6-12	Silt 0-6	6-12	Clay 0-6	6-12
Sugarbeets															
Foos Reps 1&2	80	7992	7305	230	226	15.1	14.3	1.23	1.16	54.0	54.4	28.7	28.7	17.3	16.9
Foos Reps 3&4	80	7580	7873	223	189	15.3	15.3	1.23	1.25	52.7	54.7	30.4	28.4	16.9	16.9
Kolb Reps 1&2	80	11516	12381	247	241	16.2	16.9	1.35	1.35	34.7	36.7	44.4	42.7	20.9	20.6
Juhl Reps 1&2	80	11395	12274	102	105	19.8	20.8	1.39	1.49	10.7	10.7	48.0	48.0	41.3	41.3
Bruski Reps 1&2	80	6817	7593	532	396	19.5	17.4	1.69	1.35	31.4	23.4	40.0	46.0	28.6	30.6
E.Agric.Res.Center	80	8932	8959	565	279	30.6	26.9	3.69	2.62	12.9	9.4	36.6	38.0	50.5	52.6
Spring Wheat															
Breigenzer	40	1606	1458	390	114	21.9	22.5	1.46	1.09	37.6	27.6	32.0	30.0	30.4	42.4
Johnson	40	1260	992	591	265	25.9	22.9	2.53	1.39	35.6	27.3	23.2	24.0	41.2	48.7
Redekopp	20	1924	1838	239	100	18.2	21.2	1.75	.84	53.8	51.8	22.9	20.9	23.3	27.3
Pedwerbecki	40	1879	1679	344	142	15.2	14.1	1.09	.78	57.6	67.6	19.1	13.1	23.3	19.3
Hanson	25	1190	1092	255	229	11.7	12.0	1.68	1.23	75.0	75.1	12.7	10.4	12.2	14.6

Appendix Table 10. Winter wheat and barley yields, climatic variables and N NH_4OAc extractable moist soil K, C.E.C., organic matter, and percentage sand, silt, and clay from the selected 1973 experimental sites.

Variables	Cooperators* Winter Wheat							Barley		
	1	2	3	4	5	6	7	8	9	10
Fert. K, lb/acre	40	20	20	40	20	20	80	80	40	40
Yield, lb/acre										
Treatment	2645	2674	2218	2945	2462	3296	3500	2341	2142	2046
Control	2284	2497	1944	2914	2702	2899	2827	2086	1786	2194
Climatic Variables										
Aver. Soil T., °C	16.8	17.1	17.5	13.5	17.0	16.0	20.7			
Avail H_2O, Inches	9.16	6.95	3.66	6.46	3.11	3.69	4.36			
Rainfall, Inches	1.84	5.11	4.09	3.35	5.86	4.35	4.95			
Evap. cm/day	.435	.522	.531	.439	.278	.319	.563			
Soil K, ppm										
0-6	441	412	444	496	232	260	266	281	390	314
6-12	309	201	142	285	120	96	110	115	114	97
CEC, meq/100g										
0-6	20.4	18.0	18.7	21.9	12.9	15.5	13.0	16.8	21.9	19.4
6-12	24.3	22.1	17.1	25.1	14.5	16.3	14.1	20.9	22.5	21.9
Org. Matter, %										
0-6	1.93	1.94	2.43	2.43	1.25	1.16	.95	.98	1.46	1.72
6-12	1.69	1.52	1.89	1.43	.68	.93	.74	.95	1.09	1.62
Sand, %										
0-6	36.9	38.7	19.1	35.6	50.2	46.0	60.0	19.4	37.6	35.8
6-12	30.9	32.7	15.0	34.2	50.2	45.6	59.6	35.8	27.6	29.8
Silt, %										
0-6	35.3	32.7	48.7	30.2	34.0	36.2	24.2	54.8	32.0	34.9
6-12	34.9	32.7	42.4	28.0	34.0	34.5	24.4	38.4	30.0	28.9
Clay, %										
0-6	27.8	28.6	32.2	34.2	15.8	17.8	15.8	25.8	30.4	29.3
6-12	34.2	34.6	42.6	37.8	15.8	19.9	16.0	25.8	42.4	41.3

* 1 = Miklovich, 2 = Jergenson, 3 = Helm, 4 = Perry, 5 = Pehl, 6 = Holland
7 = Erpelding, 8 = Erpelding, 9 = Breigenzer, 10 = Rocky Boy.

Appendix Table 11. Results of duplicate soil sample analysis for K (ppm) by variations of the resin - thimble technique on the 0 to 6 and 6 to 12-inch depths of winter wheat experimental sites.

Technique* / Cooperator	1		2		3		4		5		6		7	
	0-6	6-12	0-6	6-12	0-6	6-12	0-6	6-12	0-6	6-12	0-6	6-12	0-6	6-12
Miklovich	150	81	126	71	145	80		80	145	100	265	150	170	190
	146	79	115	79	133	90	120	78	138	95	255	225	235	200
Jergenson	104	104	110	48	115	70	118	53	115	73	180	125	195	110
	116	116	116	53	128	70	118	58	135	70	180	125	180	120
Helm	109	50	130	43	148	50	145	48	155	60	220	90	205	90
	129	29	122	48	142	53	147	55	153	58	185	100	175	65
Perry	148	69	126	80	88	58	117	75	135	88	190	180	245	150
	157	64	114	58	98	55	115	75	130	88	210	180	180	165
Pehl	69	24	74	41	55	48	90	43	88	55	110	70	125	70
	69	26	68	26	60	43	82	45	90	53	125	65	120	50
Holland	79	27	57	30	68	38	70	48	83	58	100	75	125	105
	75	26	72	41	68	38	70	48	87	58	135	75	110	70
Erpelding	90	27	73	36	80	45	80	40	98	56	120	70	125	75
	84	29	48	34	75	38	80	45	98	58	110	75	120	75
Average	109	54	97	49	100	55	104	57	118	69	170	115	165	110
Std. Dev.**	8.43		11.86		7.29		1.72		5.72		17.86		45.36	

* 1. Moist 2 mm soil, unselected thimbles, measured resin. 2. Air dry 2 mm soil, unselected thimbles, measured resin. 3. Air dry 2 mm soil, selected thimbles, measured resin. 4. Air dry 0.5 mm soil selected thimbles, weighed resin. 5. Repeat of four. 6. Air dry 2 mm soil, machine made thimbles, weighed resin. 7. Repeat of six.

** Standard error determined only on the 0 to 6-inch depths.

Appendix Table 12. Results of extraction of the 0 to 6 and 6 to 12-inch depth soil samples from the 1973 winter wheat experimental sites for exchangeable plus moderately available K, moderately available K, percentage K saturation of the C.E.C., dilute cation solution K exchange and free energy calculated from this solution.

Extraction Method / Cooperator	1* K, ppm		2 K, ppm		3 K, ppm		4 % K sat'n.		5 K, ppm		6 G_K, cal		7 G_K, cal		8 G_K, cal	
	0-6	6-12	0-6	6-12	0-6	6-12	0-6	6-12	0-6	6-12	0-6	6-12	0-6	6-12	0-6	6-12
Miklovich	725	600	644	544	296	253	5.49	3.70	23.0	16.8	-2785	-2966	-2874	-3063	-2477	-2688
Jergensen	588	369	550	325	177	132	5.84	2.76	21.3	13.0	-2823	-3143	-2908	-3226	-2496	-2806
Helm	788	344	713	269	348	173	5.92	2.57	23.0	12.0	-2792	-3156	-2877	-3271	-2468	-2935
Perry	681	456	569	388	211	139	5.58	3.24	21.3	14.5	-2830	-3091	-2911	-3163	-2487	-2706
Pehl	394	275	313	225	154	118	4.72	2.87	16.8	16.8	-2973	-2973	-3056	-3056	-2939	-2639
Holland	475	306	419	244	188	149	4.56	2.51	16.8	11.3	-2973	-3222	-3058	-3306	-2648	-2891
Erpelding	413	275	400	250	130	112	5.57	2.98	19.3	12.0	-2883	-3191	-2968	-3267	-2556	-2827

* 1. N NH_4OAc extractable plus moderately available K by cation resin extraction. Air dry soil.

2. " " " " " " Moist soil.

3. Moderately available soil K by resin extraction, [(Resin K + N NH_4OAc K - N NH_4OAc K)].

4. Percentage K saturation of the soil CEC, (N NH_4OAc K/CEC) x 100.

5. Equilibrium solution K from the dilute cation procedure.

6. Free energy computed from the dilute cation solution ratio $[K]/[Ca]^{\frac{1}{2}}$

7. " " " " " " " " $[K]/[Ca+Mg]^{\frac{1}{2}}$

8. " " " " " " " " $[K]/[Mg]^{\frac{1}{2}}$

Appendix Table 13. Location of 1967 through 1971 experimental sites, and soil type, crop variety, available soil moisture* and growing season rainfall. Winter wheat.

Cooperator	Year	Town	County	Soil type	Crop variety	Rainfall	Available soil moisture
						inches	
Dahlman	1967	Forsyth	Rosebud	Edgar clay loam	Winalta	7.17	3.3
Dahlman	1969	Forsyth	Rosebud	Edgar clay loam	Cheyenne		4.4
Ross	1967	Terry	Prairie	Ft. Collins loam	Winalta	4.85	3.2
Hanser	1967	Broadview	Stillwater	Cushman sandy clay loam	Cheyenne		3.3
Gagnon	1967	Chester	Liberty	Marias silty clay	Cheyenne	1.17	4.0
Schultz	1967	Bloomfield	Dawson	Chama clay loam	Lancer	7.75	3.3
Goodan	1967	DeSmet	Missoula	silty clay loam	Westmont	4.48	3.8
Iverson	1967	Sunburst	Toole	Scobey clay loam	Winalta	2.35	3.9
Bramlette	1967	Ft. Benton	Chouteau	Haywarden clay loam	Cheyenne		2.8
Fadhl	1967	Angela	Rosebud	Thurlow clay loam	Karmont	6.79	2.3
Walker	1969	Bloomfield	Dawson	Cushman sandy clay loam	Worrior	9.57	
Carter	1969	Coalwood	Powder River	McRae loam	Winalta	5.61	5.2
O'Conner	1969	Plevna	Fallon		Lancer	8.45	
Torski	1971	Hardin	Big Horn	Gilt Edge sandy clay loam		2.89	
Dyk	1971	Amsterdam	Gallatin	Amsterdam silt loam		4.0	8.7
Holland	1971	Rosebud	Rosebud	Edgar loam	Cheyenne	3.6	5.5
Bates	1971	Amsterdam	Gallatin	Amsterdam silt loam	Winalta	5.1	7.7

*By 15 atmosphere determination.

Appendix Table 14. Location of 1973 experimental sites and soil type, crop variety, available soil moisture and rainfall.

Cooperator	Town	County	Soil type	Crop variety	Rainfall	Available soil moisture
				Winter Wheat		
Miklovich	Lodge Grass	Big Horn	Arnegard clay loam		1.84	9.16
Jergensen	Chinook	Blaine	Williams clay loam	Cheyenne	5.11	6.95
Helm	Rock Springs	Garfield	Cherry silty clay loam	Winalta	4.09	3.66
Perry	Fort Benton	Choteau	Gerber clay loam	Cheyenne	3.35	6.46
Pehl	Terry	Rosebud	Chanta loam	Worrior	5.86	3.11
Holland	Rosebud	Rosebud	Edgar loam	Cheyenne	4.35	3.69
Erpelding	Forsyth	Rosebud	Fort Collins sandy loam	Centurk	4.95	4.36
				Spring Wheat		
Pedwerbecki	Glasgow	Valley	Telstad sandy clay loam		4.24	5.54
Redekopp	Lustre	Valley	Martinsdale sandy clay loam		3.15	6.65
Breigenzer	Glasgow	Valley	Phillips clay loam	Fortuna		
Johnson	Cut Bank	Glacier	Pendroy attewan loam	Thatcher		
Hanson	Richland	Valley		Fortuna		
				Barley		
Breigenzer	Glasgow	Valley	Phillips clay loam	Compana		
Rocky Boy	Box Elder	Choteau	Phillips clay loam	Compana		
Erpelding	Forsyth	Rosebud	Fort Collins sandy loam		4.95	4.36
				Sugar Beets (Irrigated)		
Foos	Park City	Yellowstone	Wanetta loam	G.W. Mono HY,D2		
Kolb	Hysham	Treasure	Havre loam	"		
Juhl	Custer	Yellowstone	Lohmiller silty clay	"		
Bruski	Huntley	Yellowstone	Haverson loam	"		
E. Mont. Agric. Res. Center	Sidney	Richland	Savage silty clay	H.H. 21		

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