The phytoavailability of potassium to small grains as influenced by edaphic and environmental factors
by Robert Olson Miller

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Crop and Soil Science
Montana State University

Abstract:
Soil characteristics and rhizosphere conditions greatly influence plant available potassium (K). Research in Montana has shown crop response to K fertilizers on soils testing high in ammonium acetate extractable K (Kex). The objective of this research was to use an in-vitro technique to determine: (1) plant available K on Montana soils and its relation to soil properties; (2) the influence of temperature and water potential on K uptake; and (3) the influence of K additions on plant available K.

Soil characteristics which were found to be strongly related to plant available K (R2 0.93) are: clay content, Kex diffusion gradient coefficient, and cation exchange capacity. Spring wheat in these studies utilized a portion of Kex, but quantities differed across soils. This data suggests that spring wheat utilizes significant quantities of soil K from nonexchangeable and K-mineral sources.

Spring wheat K uptake increased exponentially with temperature with little or no K absorbed at 8° C. Water potentials alone had little influence on K uptake. The interaction with temperature suggests that K uptake was not limited by water potential (water content) until temperature exceeded 16° C. Thus until spring wheat K demand reached a critical K demand K uptake was not limited by water potential. Potassium additions increased spring wheat K uptake nonuniformly across soils. Greatest K uptake occurred on the Kevin soil and the least on the Beaverton. Data on soil rhizosphere Kex indicated K additions enhanced the availability of Kex supplies in the near rhizosphere (0 - 0.5 mm). Soil Kex flux data indicated that K additions did not necessarily increase Kex utilization.

These results indicate that phytoavailable K is governed primarily by three soil factors and that environmental water potential play important roles as regulators. Spring wheat utilizes soil K forms other than that explained by Kex in the rhizosphere, and that the quantity utilized is highly soil dependent.

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APPROVAL

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Robert Olson Miller

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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VITA

The author, Robert Olson Miller, was born on August 12, 1955, in Lincoln, Nebraska, to Russell H. Miller and Beatrice Miller. He received his primary and secondary education in Springfield, Nebraska. He attended the University of Nebraska 1973-1981, where he completed his Bachelor of Science in 1978 and Master of Science in 1981 in agronomy. He married Annette J. May on June 20th 1981. From January 1982 until July 1984 he worked as a Research Associate in the Horticulture sciences Department of Texas A&M University. Bob and Annette have one son, Jason D. Miller.

He began study and research toward the Ph.D. in the fall quarter of 1984 at Montana State University.

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ABSTRACT

Soil characteristics and rhizosphere conditions greatly influence plant available potassium (K). Research in Montana has shown crop response to K fertilizers on soils testing high in ammonium acetate extractable K (K_{ex}). The objective of this research was to use an in-vitro technique to determine: (1) plant available K on Montana soils and its relation to soil properties; (2) the influence of temperature and water potential on K uptake; and (3) the influence of K additions on plant available K.

Soil characteristics which were found to be strongly related to plant available K (R^2 0.93) are: clay content, K_{ex} diffusion gradient coefficient, and cation exchange capacity. Spring wheat in these studies utilized a portion of K_{ex}, but quantities differed across soils. This data suggests that spring wheat utilizes significant quantities of soil K from nonexchangeable and K-mineral sources. Spring wheat K uptake increased exponentially with temperature with little or no K absorbed at 8 C. Water potentials alone had little influence on K uptake. The interaction with temperature suggests that K uptake was not limited by water potential (water content) until temperature exceeded 16 C. Thus until spring wheat K demand reached a critical K demand K uptake was not limited by water potential. Potassium additions increased spring wheat K uptake nonuniformly across soils. Greatest K uptake occurred on the Kevin soil and the least on the Beaverton. Data on soil rhizosphere K_{ex} indicated K additions enhanced the availability of K_{ex} supplies in the near rhizosphere (0 - 0.5 mm). Soil K_{ex} flux data indicated that K additions did not necessarily increase K_{ex} utilization.

These results indicate that phytoavailable K is governed primarily by three soil factors and that environmental water potential play important roles as regulators. Spring wheat utilizes soil K forms other than that explained by K_{ex} in the rhizosphere, and that the quantity utilized is highly soil dependent.

INTRODUCTION

Soil potassium (K) can be characterized by four major indices: (1) Soil solution K (K_{sol}); (2) exchangeable K (K_{ex}); (4) nonexchangeable K (K_{nex}); and (4) mineral K (K_{min}). Soils are relatively high in total K but only a small relative proportion is found in solution form, which is available to plants. Replenishment of solution K at the soil-root interface is dependent on rates of release from other forms and ion transport in the rhizosphere.

Research in Montana over the past twenty years has shown crop response to K fertilizers on soils testing "high" in NH_4OAC-extractable K (Skogley, 1976). Similar results have been noted for many crops around the world (Talibudeen et al. 1978). This is due to the fact that the NH_4OAC procedure does not measure factors relating to crop K demand, soil K release equilibria, and K transport in the rhizosphere. A method using intact plants to study soil K release and transport at the soil-root interface using in-vitro techniques would aid the development of a reliable K soil test that is sensitive to these factors which control K availability.

Nutrient phytoavailability can be separated into two components, absorption characteristics of plant roots and the capacity of the soil to supply nutrients. Factors influencing soil nutrient capacity are (1) quantity and form of nutrient present, and (2) the chemical equilibria of the soil system affecting the replenishment (intensity) of a given nutrient in the soil solution. Such relationships have been used extensively in describing solution cation activity in inorganic systems.

Nutrient absorption and uptake is dependent on the nutrient status in the plant, morphological characteristics of the root system, root age and influx characteristics, and rhizosphere environment. Nutrient acquisition occurs via three mechanisms, interception, mass flow, and diffusion. Interception results from direct contact between a root and a soil nutrient. Mass flow is the movement of a nutrient to the root via the convective flow of soil water, the result of transpiration. Diffusion, is the movement of a nutrient down the chemical potential gradient established by the plant at the soil-root interface. Work of Barber (1962) and Barber (1972) has established that diffusion, and mass flow to a lesser extent, are the major mechanisms by which nutrients are acquired by plant roots.

In many instances the constraints of the rhizosphere environment limit soil nutrient transport and plant uptake. Temperature affects both plant biochemistry and soil chemistry. Soil water potential in the rhizosphere affects soil nutrient availability and transport, plant physiology, and soil-root contact.

Several methods have been proposed to study the soil-root interface in an attempt to describe nutrient availability. However, physical limitations and the complexity of the processes involved have impeded research.

Recently Kuchenbuch and Jungk (1982) described a procedure for studying soil K concentration gradients in the rhizosphere of rape.

Plant roots are separated from the soil by a flat nylon screen which prohibits root penetration but permits root hairs to make contact with the soil surface. Such a system allows the rhizosphere to be treated as a plane and, with microsampling techniques, be analyzed according to traditional soil testing procedures. Accurate information can thus be obtained depicting plant nutrient availability and absorption in addition to the status of soil rhizosphere K.

The objectives of this study were to: (1) determine those soil physical and chemical properties related to phytoavailable K; (2) research the effects of temperature and soil water potential on plant K uptake; and (3) evaluate the influence of K additions on K phytoavailability and K dynamics in the rhizosphere. The in vitro method of studying the soil-root interface provides detailed information on both phytoavailable K and K dynamics within the soil rhizosphere.

Definitions

A list of abbreviated terms used in describing phytoavailable K are as follows:

K_{ex} - Soil extractable K, by 1 N Ammonium acetate, pH 7;

K_{sol} - Soil solution K concentration determined by immiscible liquid displacement (ILD);

K_{nex} - Soil nonexchangeable K concentration, determined by sodium tetraphenyl boron;

K_{min} - Soil mineral K, associated with micas and feldspars;

D - Rhizosphere distance perpendicular to the soil-root interface;

$d[K_{ex}]/dD$ - Rhizosphere K_{ex} diffusion gradient coefficient;

D_c - Effective diffusion coefficient for K_{ex} in rhizosphere;

D_l - Distance of estimated K depletion in the rhizosphere;

SK_{ex} - Calculated soil flux of K_{ex} removed by plants.

LITERATURE REVIEW

Soil K Phytoavailability

Soil K can be divided into four major forms: K solution, that portion of K dissolved in the soil solution; K exchangeable, that portion which is readily exchangeable for other cations; K nonexchangeable, which is not readily exchangeable and is released slowly to the solution; and K bearing minerals (Mclean and Watson, 1985). Each of the solid phases tends to be in equilibrium with K in solution.

Phytoavailable K is described as that K fraction in the soil which is accessible to plant roots for absorption, and involves aspects of both soil characteristics and plant nutrient absorption (Bertsch and Thomas 1985). Soil solution K is a reflection of the parent material and the degree of weathering that has occurred. Feldspars and Micas are the dominant K minerals which contribute to and control the dynamics of soil solution K (Sparks and Haung, 1985). Interfacial reactions are the most significant means by which K is weathered from feldspars. Micas, such as muscovite, undergo zonal weathering which results in the release of K from interlayer positions. Thus, the stage of weathering determines the equilibrium each mineral phase has with the soil solution and with each other.

The equilibrium between solution phase and solid phase K indices dictates the availability of soil potassium. Beckett (1964) described

K availability in terms of a quantity and intensity ratio (Q/I). He plotted the amounts of K adsorbed or desorbed against the activity ratio for K in solution, and was thus able to predict the capacity of a soil to maintain solution K. Such a method could be used to make K fertilizer recommendations. However, it was shown by Rasnake (1973) that Q/I curves change with fertilization, and thus have limited applications.

Both physical processes, such as freezing and thawing and wetting and drying, and biological activity affect the release or fixation of K from the soil solution. Cook and Hutcheson (1960), reported that the drying of soil samples increased exchangeable K concentrations. Song and Haung (1983), in a review of the physical chemistry of soil K, reported several instances where rhizosphere organic acids increased K release from micas. Thus, soil solution K is affected by physical processes and amount of biological activity as well as chemical processes.

Ultimately the phytoavailability of potassium is not only dependent on the amount of K in the soil and the capacity of the soil to replenish solution K. It is also dependent on the absorption characteristics of plant roots, which are determined by overall nutrient requirements, type of root system, physiology, and growing conditions (Olsen, 1968 and Barber 1985b). Nutrient acquisition occurs via three mechanisms, interception, mass flow, and diffusion. Interception results from direct contact between a root and a soil nutrient. Mass flow is the movement of a nutrient to the root via the convective flow of soil water, the result of transpiration. Diffusion, is the movement of a nutrient down the chemical potential gradient established by the plant at the soil-root interface. Work of Barber (1962), Nye et al. (1975), and Nye and Tinker (1977) has established that diffusion and, to a lesser degree, mass flow are the major mechanisms by which nutrients are transported to plant roots.

Temperature and Phytoavailable K

Temperature effects on nutrient availability can be divided into two components: (1) Plant aspects and (2) soil aspects. Plant aspects can be further separated into direct and indirect effects. Temperature indirectly influences ion absorption by affecting growth rate, translocation, and transpiration. It directly influences the kinetics of physical and biological processes. Nobel (1974) estimated a Q10 of 1 to 2 for physical reactions and 2 to 4 for biological reactions. With respect to water absorption, a physical process, Markart et al. (1979) found the Q10 for water absorption by soybeans increased from 1.3 to 13 between temperatures of 14 and 9 C. This was attributed to a phase change in plasmalemma membrane lipids. Ion absorption was found by Carey and Berry (1978) using solution culture to be strongly inhibited at 10 C, resulting in a change in Q10 from 15 to 8 below this temperature. Similar results were found for P by Barber (1985a), where P uptake by fescue ceased when temperature was lowered to 10 C.

The influence of temperature on cereal root system growth and morphology has been reported by Abbas Al-Ani-ani and Hay (1983). Root systems of wheat increased in length and in number of seminal axes as temperature rose from 5 to 25 C. Nye and Tinker (1977), have found that the mean angle of maize roots to the horizon was smallest at a temperature of 17 C. The angle increased with increases in temperature. Thus temperature determines the size and morphology of the root system, in addition to its three dimensional orientation in the soil.

Physical effects of temperature on soil aspects can easily be seen in terms of effects on ion diffusion and soil solution viscosity. As temperature decreases ion diffusion decreases according to the Stokes-Einstein equation. Viscosity also increases with decreasing temperature and the combined effect results in a 22 % decrease in diffusion of K for a temperature change from 25 to 15 C (Barber 1985a). Temperature also influences the vapor pressure and surface tension of water, therefore soil water movement is modified as temperature changes.

Temperature affects soil chemical reactions by influencing cation ion solution activity, cation bonding energies and extent of the double layer (Barber, 1985a). These reactions ultimately determine solubility, solution speciation and the stability of the soil system to chemical change (Yang, 1987). Sparks and Leibhardt (1982) found K selectivity coefficients decreased with temperature, indicating decreased K sorption with higher temperatures. In many instances temperature changes affect physical and chemical processes as a unit. A decrease in temperature results in decreased solubility, but precipitation is inhibited by decreased diffusion. Thus the system can be considered a physiochemical process which is very sensitive to temperature change and which influences nutrient availability (Sutton, 1969).

Soil Water Potential and K Availability

Water potential is defined as the chemical potential of water with respect to pure water at the same temperature, expressed in terms of energy. Equivalent water potential in different soils implies equal free energy levels, but different volumetric and /or gravimetric water contents (Nye and Tinker, 1977). As water potential decreases (more negative), resistance to water withdrawal increases. As with temperature, the influence of water potential (ie. water content) can be divided into plant and soil aspects. Danielson (1967) reviewed the effects of soil water content and found that root to shoot ratios increased with decreases in water content. This was attributed to an increased root system and decreased shoot growth associated with drier soils. Hsieh et al. (1972) found similar results for maize. Mackay and Barber (1987), evaluated the effects of water potential on root hair growth on corn and found that increasing water potential, from - 175 to - 7.5 Kpa, resulted in cessation of root hair growth behind the root cap. Reversing water potential (decreasing it) resulted in new root hair formation. In another experiment, Mackay and Barber (1983) found the total root length with root hairs and root hair density increased as soil moisture content decreased from 32 to 22 percent. With soil drying, root hair growth increased, with respect to length and density, to maintain liquid continuity with the soil.

Water potential (water content) has great significance with respect to physical and chemical processes. Decreases in water potential result in the physical draining of soil pores of ever decreasing diameter, and a decrease in water film thickness over the surface of particles. This reduction in the continuity of water films decreases the mobility of ions subjected to chemical gradients (Nye and Tinker, 1977). Thus nutrient diffusion is impeded by increased tortousity as soil becomes drier (Warncke and Barber, 1972).

Bertsch and Thomas (1985), reviewed the influence of soil water content on soil chemical processes. As water content decreased, ion speciation in the solution changed because the activity ratio (AR) must be maintained, as demonstrated by results of Mengel and von Braunschweig (1972). With increased water potential solution ion concentration decreases, the result of dilution accompanied by a net adsorption divalent cations and desorption of monovalent cations (Moss, 1963). With decreased water potential the opposite reaction occurs, resulting in a decrease in solution monovalent ions such as K. Thus K availability decreases with reduced water potential due to slowed diffusion, a physical process and the AR mechanism, a chemical process.

Study of Phytoavailable K

Soil tests of plant available K traditionally have relied on correlation between a K extractable index based on cation displacement and K response to K additions (Feigenbaum and Hagin, 1967). This 'Index' value of soil then implies a level of phytoavailable soil K.

Reitemeier et al. (1947) studied K availability based on greenhouse, Neubauer, and laboratory methods using fourteen soils.

Their results indicated a relatively high correlation between K uptake by clover and electrodialysis of K, as well as Neubauer extractable K. The Neubauer technique was developed by Thornton (1935) to study nutrient accumulation and involves growing plant seedlings in soil for one to to three weeks followed by nutrient uptake assessment. The technique has been modified numerous times for specific experiment purposes (Massee, 1973).

Research in methods of evaluating soil changes in nutrient concentration were first described by Brown et al. (1964), using ion exchange resins. This method involved mating a resin against a soil column and thin slicing the soil at micrometer distances from the resin at the end of the experiment. Several papers have since used this methodology to study K, P and N availability (Vaidyanathan and Nye, 1966).

Kuchenbuch and Jungk (1982) described a method combining the Neubauer technique with that of Brown et al. (1964). In it, plant seedlings are grown on nylon screen. Root hairs grow through the screen and make contact with the soil but roots do not. Potassium depletion gradients are then studied to determine K diffusion in the rhizosphere. This technique has many advantages for the purpose of studying spring wheat phytoavailable K, and was adapted for use in the studies reported here.

MATERIALS AND METHODS

To evaluate the influence of soil properties and environmental factors on K phytoavailability four experiments were initiated. These were: Methods Development (MD); Phytoavailability of K on Montana agricultural soils (KRTS); Temperature and moisture influences on plant and soil K (TMS); and Effects of K rate on soil and plant K (KRS). In the MD study, techniques were developed using spring wheat seedlings to evaluate plant available soil K. In the PKTS study plant available soil K dynamics were assessed on twenty Montana soils to identify soil characteristics important to K availability. The influence of temperature and water potential on plant K availability were investigated in the TMS study, and in the PRS study the affect of K additions on plant K uptake and K_{ex} concentration gradients were evaluated.

Methods Development

A modification of the method of Kuchenbuch and Jungk (1982), was employed to determine plant K uptake. Nylon cloth, 325 mesh, 38 percent porosity, and 40 um thickness (Nitex Co. Zurich, Switzerland) was cemented to one end of a plexiglass cylinder, 4.5 cm ID and 1.5 cm in height. The cylinders were washed with a 5 percent solution of sodium hypochlorite to reduce the possibility of contaminating molds (Rhizopus Sp.) The nylon covered end of the cylinder was then placed on a agar media consisting of 0.065 % agar purified (nutrient free) and 2 uM $CaSO_4$. Various numbers of spring wheat seeds (Triticum aestivum L. cv. Pondera,) were placed in the cylinder, on the screen and allowed to germinate/grow for 5 days at 22 C under etiolated conditions. An identical cylinder, but with no screen was filled with soil wetted to a water potential of approximately - 33 Kpa to a bulk density of 1.25 gm cm^{-3}. This cylinder containing soil was then placed on a high flow moisture plate maintained at a potential of - 33 Kpa. The cylinder containing the germinated seeds (referred to as a pot) was then placed on the soil column so that the nylon screen separated the seed from the soil (Figure 1). Root hairs but not roots penetrate the

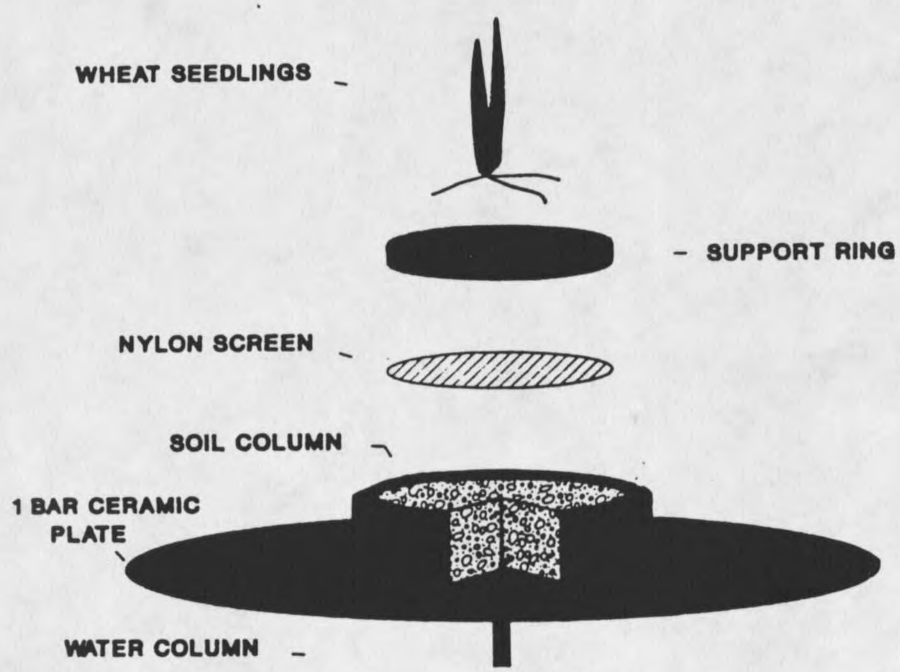

Figure 1. Schematic of method for growing wheat seedlings on soil columns separated by a nylon screen.

nylon screen into the upper layer of the soil. The system including the high flow plate was covered with a plexiglass chamber. Relative humidity in the chamber was regulated to near 100 percent to minimize mass flow of water from the soil to the plants. The photoperiod was 14 hr and light intensity was 12 Wm^{-2}.

The plants were left on the soil column from one to eight days. At the end of each uptake period soil columns were thin sectioned, using a modified micrometer and thin slicing knife, at five planar distances representing mean distances of 0.25, 0.75, 1.5, 2.5, and 4.0 mm away from the nylon screen. Moisture content and exchangeable cations (as extracted by 1.0 N NH_4OAC) were determined on each soil thin section sample. Whole spring wheat plants were removed from the upper cylinder/pot and placed in digestion tubes for total K analysis by the method of Havlin and Soltanpour (1980). Control pots containing spring wheat plants were grown parallel without soil and used to calculate net K uptake.

Calculations

The quantity of a substance diffusing from a source across a plane to a sink of constant concentration is given by Crank (1956) and Vaidyanathan and Nye (1966):

$$M_t = 2\ (C_1 - C_2)\ ((D_c)t/\pi)^{0.5} \qquad [1]$$

where M_t = amount diffusing across the soil surface from zero to time t.

C_1 = initial concentration of ions in the soil.

C_2 = constant concentration at the soil-sink interface.

(D_C) = the effective diffusion coefficient for the system within the limits of C_1 and C_2.

If the ion sink maintains C_2 at or near zero concentration, then the effective diffusion coefficient can by calculated :

$$D_C = (M_t)^2 \pi / 4 \ (C_1)^2 \ t \qquad [2]$$

Physical and Chemical Methods

Physical and chemical analyses were performed as follows:

(1) particle size analysis by hydrometer method (Gee and Bauder, 1986);

(2) particle size distribution by pipette (Gee and Bauder, 1986);

(3) moisture retention curve by pressure plate (Peters, 1965);

(4) percent $CaCO_3$ by gravimetric loss (U.S. Salinity Lab, 1954);

(5) percent organic matter (Sims and Haby, 1970);

(6) soil pH and conductivity by 2:1 dilution (U.S. Salinity Lab, 1954);

(7) extractable K, Na, Ca, and Mg, by 1.0 N NH_4OAc extraction and atomic absorption analysis (Bower et al., 1952);

(8) extractable K by 0.5 N MgCl and 0.5 N NH_4OAc (Rich, 1964);

(9) soil extractable K by sodium tetraphenyl boron (Scott and Reed, 1960);

(10) soil extractable K by 1.0 N HNO_3 (Mclean and Simon, 1958);

(11) saturated paste pH, K, Ca, and Mg extraction and analysis by atomic absorption (U.S. Salinity Lab, 1954);

(12) soil solution K, Ca, Mg, NO_3, and Cl by extraction by immiscible liquid displacement (Mubarak and Olson, 1979) and determination of K , Ca, and Mg by atomic absorption, NO_3 by Cd reduction (Willis, 1980) and Cl by ferric cyanide reduction;

(13) soil sulfate by acetate soluble SO_4 (Bardsley and Lancaster, 1960);

(14) available phosphorus by $NaHCO_3$ (Olsen et al., 1954) and modified Bray #1 (Smith et al., 1957);

(15) extraction of NO_3-N in soils (Sims and Jackson, 1971) and analysis by Cd reduction (Willis, 1980);

(16) plant tissue K, Ca, and Mg by 15:1 nitric-perchloric digest (Havlin and Soltanpour, 1980), analysis performed by atomic absorption;

(17) clay mineralology, illite, vermiculite, and montmorillinite (Jackson, 1958).

RESULTS AND DISCUSSION

Methods Development Study

Phytoavailable K can be best described by a plant model which simulates K uptake and transport in the rhizosphere. Techniques for studying the soil-root interface have, in the past, proved quite difficult. Kuchenbuch and Jungk (1982) have described a method for studying rhizospheric soil. Using modifications of this technique a simple, accurate, and reproducible method is described for studying both soil K_{ex} concentration gradients and plant K uptake. Spring wheat was chosen for this study, due to its seedling growth characteristics and importance as a major crop on the Northern Great Plains.

To study phytoavailable K, plant seedlings must exhibit high demand for K, and growth conditions must be optimal with respect to root/soil contact. The objectives of the method development study (MD) were: (1) determine the plant density required to cover the soil-root interface (ie. nylon cloth) with roots; (2) determine seedling age (hours after germination) for maximum K uptake; and (3) assess the rate of plant K accumulation by spring wheat from soil columns to determine the time frame for subsequent studies.

Results of studies to determine the influence of plant density on net K accumulation are presented in Table 1. Accumulation of K increased with increasing plant density. Although high plant densities favored greater uptake, low populations are desirable to minimize plant root competition. Twenty-five seeds provide sufficient root mass to