# RATE LIMITING PROCESSES OF PHYTOAVAILABILITY OF POTASSIUM ON MONTANA SOILS

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## ABSTRACT

Throughout Montana crops have frequently responded to K fertilizers on soils testing "high" in $NH_4OAc$-extractable $K^+$. It is hypothesized that this response is a true plant nutrient response, and that $K^+$ diffusion is the major rate-limiting process for $K^+$ availability in these soils. Analyses of soil solution extracts obtained by immiscible liquid displacement, in conjunction with previously reported crop and water use data, are used to estimate amounts of K which could be derived from alternative processes (primarily mass flow). Results further support the hypothesis that most $K^+$ must reach the plant root via diffusion. Fertilizing with K increases soil solution concentrations of $K^+$ so that increasing proportions of the crop requirement can be met through mass flow, thus decreasing the demands on diffusion.

## OBJECTIVES

A decade of field research with K fertilizers on major crops of Montana has shown a high frequency of crop yield response even though most of the soils are high in soil test extractable $K^+$ (Skogley, 1976; Skogley and Haby, 1981). We hypothesize that this response is primarily a true response to K as a yield-limiting nutrient, and that $K^+$ diffusion is the rate-limiting process under our cropping conditions. In this presentation I will review literature and reasoning which led us to this hypothesis, and present more data to support it.

## RESULTS AND DISCUSSION

Chloride Involvement - First, I want to dispel the suggestion that what we are measuring is primarily a response to Cl in the fertilizer. Many of our field experiments were conducted with both KCl and $K_2SO_4$ as comparative sources of K. Although this was done mainly to determine the need for supplemental S, the data can also serve to indicate whether or not crop responses to Cl may have occurred. Table 1 presents a summary of results from 17 experiments where a yield increase from K fertilizers was measured, and where both sources of K were included.

Table 1. Comparison of small grain yield response to KCl and $K_2SO_4$ fertilizers in Montana field experiments, 1972-1983.

| - Number of Experiments - | | | | | |
|---|---|---|---|---|---|
| Where KCl and $K_2SO_4$ were compared, and a grain yield response occurred* | | Where $K_2SO_4$ response was ≥KCl response | Where KCl response was >$K_2SO_4$ response | Where $K_2SO_4$ response was >KCl response | Where response to both occurred and additional response to one @ higher rate |
| Winter wheat | 12 | 10 | 2 | 1 | 2** |
| Spring wheat | 1 | 1 | 0 | 0 | 0 |
| Barley | 4 | 3 | 1 | 1 | 0 |
| Totals | 17 | 14 | 3 | 2 | 2 |

* All yield responses were significant above the 90% confidence limit.
** One additional response to KCl; one to $K_2SO_4$.

In a few instances there was apparently a yield response to KCl which did not occur with $K_2SO_4$, but in over 80% of the experiments, yield response occurred to both sources of K fertilizer.

Another reason we feel that Cl is not the primary factor is that its benefits have generally been implicated in various disease severity relationships (Christensen, et al., 1982). Levels of disease in most of our field plots have been insignificant. Most of these were on dryland sites. At a few irrigated sites where diseases (mainly "take-all" complexes) were present, disease severity ratings indicated a trend toward greater severity when $K_2SO_4$ was applied, as compared to KCl, but the lowest level of disease was always recorded when no fertilizers at all were applied. We also found no relationship between the severity of disease and crop yield.

Rate-Limiting Processes for $K^+$ - A number of processes have been identified which can influence the amount of $K^+$ which will reach the plant root surface where it is "available" for absorption. Plant "uptake" mechanisms or metabolic processes could also limit the quantity of K absorbed. However, studies by Barber (1985) suggest that ion uptake mechanisms probably do not normally become rate-limiting for plant K nutrition. Plant root factors of major importance are rate of growth and proliferation. As the root grows and proliferates, it presents an increasing demand for K, and an increasing ability to respond to this demand.

Root Proliferation - Careful measurements by a number of researchers indicate that the roots of annual crops occupy something less than 1% of the total soil volume in which they are growing (see for example Barber, et al., 1962). The amount of $K^+$ coming in contact with the plant root via this process is consequently a small proportion of the plant's demand.

Mass Flow - When plant roots absorb water and lose it through transpiration, they set up a convective flow of soil solution toward the root. Any dissolved $K^+$ in the soil solution will be carried to the plant root in this manner. If the concentration of $K^+$ in the soil solution is high enough, this process can account for moving the plant's K requirement to the root.

Barber (1985) presents results from saturation extracts of numerous soils and calculates the contribution from mass flow. Over a range of 200 to 600 kg of water per kg of dry plant tissue, and assuming a K requirement of 4%, his results suggest that as little as 2 to 5% of the total plant K demand may be met in this fashion. On a few soils with unusually high soluble $K^+$, most of the demand could be met.

To develop an estimate of the contribution of mass flow in soils of our region, I will compare results of field measurements of water use by winter wheat grown near Bozeman, and soil solution concentrations on extracts obtained through immiscible liquid displacement (ILD) (Mubarek and Olsen, 1976). The ILD data should more accurately represent the soil solution concentrations than do saturation extracts because the ILD extracts are taken at soil moisture conditions of 1/3 and 1 bar tension.

Results of the experiment conducted near Bozeman indicate a crop yield of 3300 kg $ha^{-1}$ (50 bu $A^{-1}$) on an Amsterdam silt loam soil which was adequately fertilized with N and P (Brown, 1971). The soil had a nearly full profile of stored soil water at seeding, and the growing season was described as "good." Total water use (evapotranspiration) was 28 cm (11 inches), and some water was removed from the profile to a depth of 183 cm (6 ft). This converts to $2.8 \times 10^6$ kg of water $ha^{-1}$. The total dry weight of the crop would be 3300 kg $ha^{-1}$ (grain), plus the straw, plus the root mass. McNeal, et al. (1971) report a harvest index (grain/grain + straw) of about 40% for small grains in this area, so the total weight of grain plus straw in Brown's experiment would be approximately 8250 kg $ha^{-1}$. Measurements of root mass of small grains have not been made in these studies, but reports summarized by Troughton (1962) provide a mean weight for winter wheat roots of 2600 kg $ha^{-1}$. Using this value, the total plant dry weight for this experiment would be approximately 10,850 kg $ha^{-1}$.

Determining the K demand for a crop is not readily accomplished, because the actual K requirement may greatly exceed the values obtained for K removal. Peak demands for K occur before crop heading (Gasser and Thorburn, 1972), and only 50 to 60% of the plants' maximum K accumulation may remain at maturity (Gregory, et al., 1979). Considering these facts, it may be reasonable to assume that a certain $K^+$ concentration of plant tissue must be maintained, at least during some stage of development, for all final plant dry matter produced. Based on data summarized by Beaton and Sekhon (1985), an estimate of 4% $K^+$ for healthy, vigorous, non-stressed plants may be reasonable. Based on this estimate, the total K "demand" for the crop in Brown's experiment would be approximately 430 kg $ha^{-1}$.

Results of soil solution analysis of $K^+$ in ILD extracts for samples of soil which had received 0, 100, or 400 kg K $ha^{-1}$ are presented in Table 2. Data for $NH_4OAc$-extractable $K^+$ are included. The soil was the same as that on which Brown conducted his experiment (Amsterdam silt loam), but only the surface 15 cm sample was used. Samples were incubated at the indicated moisture and temperature conditions for periods up to 14 days, and results are averaged over 36 observations each.

Table 2. Soil solution concentration of $K^+$ in ILD extracts and $NH_4OAc$-extractable K as influenced by K additions, temperature, and soil moisture on 0-15 cm layer of Amsterdam silt loam. Bozeman, MT. 1985.

| Added K kg $ha^{-1}$ | $K^+$, m mole $L^{-1}$ (ppm) | | | |
|---|---|---|---|---|
| | 5°C | | 20°C | |
| | 1 Bar | 1/3 Bar | 1 Bar | 1/3 Bar |
| 0 | 1.25 (48.7) | 1.01 (39.4) | 1.54 (60.2) | 1.24 (48.3) |
| 100 | 1.85 (72.2) | 1.57 (61.5) | 2.15 (83.9) | 1.83 (71.7) |
| 400 | 4.87 (190.1) | 4.16 (162.7) | 5.62 (219.6) | 4.51 (176.6) |
| | $NH_4OAc$-Extractable $K^+$, c mol $kg^{-1}$ | | | |
| 0 | 1.22 | 1.23 | 1.31 | 1.34 |
| 100 | 1.50 | 1.51 | 1.51 | 1.55 |
| 400 | 2.01 | 2.08 | 2.08 | 2.04 |

Using these soil solution concentrations for $K^+$, the total amount of $K^+$ which would be present in (and presumably moved to the plant root by) the water used during the growing season would be 135 to 169 kg $K^+$ $ha^{-1}$ at 0 added K fertilizer. This is approximately 30 to 40% of the total plant demand as derived earlier. When K was added at a rate of 100 kg $ha^{-1}$, the concentration of $K^+$ in the soil solution increased to where maximum $K^+$ derived from mass flow would be 172 to 235 kg $ha^{-1}$, or 40 to 55% of the total crop demand. At the highest rate of K addition (400 kg $ha^{-1}$), more than enough K was present in the soil solution so that the entire plant K demand could be accounted for by mass flow. Colder soil temperatures would reduce mass flow contributions and drier soil conditions might increase it, based on ILD extract concentrations. However, mass flow is undoubtedly reduced as soil moisture tensions exceed 1 bar and as water viscosity effects at near 0°C are considered.

Several errors may be inherent in this approach, but they are probably at least partially counter-balancing. Perhaps the total plant K demand is inflated, but then so is the amount of mass flow. Total water use includes that water lost from the soil surface through evaporation, and this water would not deliver $K^+$ to the plant root. Also, surface soils in this region normally have at least twice as much extractable $K^+$ as do samples from the 15 to 30 cm soil depth. Lower soil depths are even less well supplied. The water use data indicated that plant roots were extracting water from as deep as 183 cm (6 ft) soil depth. Considering these facts, the estimates of the contribution of mass flow to the crop K demand are probably at least good "ball-park" estimates.

Data for $NH_4OA$-extractable $K^+$ (Table 2) indicate the fact that we are dealing with a soil which would normally be considered very high (about 475 ppm $K^+$) by soil test standards. In other field experiments on the same soil type, and very near the one reported by Brown, we have recorded crop responses to applied K fertilizers during some years, and on soils testing at least this high in extractable $K^+$.

Diffusion - These results further support the suggestion by Barber and others that much of the K requirement of crops must reach the plant root through diffusion. We have previously reported on rates of $K^+$ diffusion in many soils of our region, and on soil, weather, and site characteristics which influence diffusion (Schaff and Skogley, 1982; Skogley and Schaff, 1985). Results help explain why responses to K fertilizer in the field are highly season-dependent, because the rate of K diffusion in a given soil is highly influenced by temperature and moisture conditions. It is obvious also that the contribution of mass flow toward meeting plant demands for K are influenced by these same factors (and in the same direction).

The rate of $K^+$ desorption from non-K fixing clays (such as those predominating in Montana soils) is quite rapid (measured in minutes), and is not likely to be a rate-limiting process (Sparks and Huang, 1985). Current studies also indicate that these soils are highly buffered, and that as $K^+$ is depleted from the soil solution by plant uptake, replacement from exchangeable $K^+$ is quite rapid and efficient.

## SUMMARY

Theoretical and experimental evidence abounds to explain why the contemporary soil tests for K do not perform well for the purpose of predicting crop response to K fertilizers under many soil and climatic conditions. It is not necessary to invoke indirect effects (such as those of $Cl^-$) to understand and/or explain this apparent anomoly.

Underestimation of the true magnitude of crop demands for K, which differs greatly from that amount of K actually removed by a mature crop, is perhaps part of the problem. Relative contributions of mass flow and diffusion of $K^+$ to the roots of crops can vary tremendously, both when dealing with widely different soils, but also as conditions change within one soil. In a typical, normally high-K soil of our area, calculations indicate that more $K^+$ must be moved through diffusion than that which will move to the plant root by mass flow.

Fertilization with K helps overcome the (sometime) inability of these soils to supply adequate available K in two ways. First, soil solution concentrations of $K^+$ are increased by fertilization. Increased soil solution $K^+$ means that proportionately greater percentages of the $K^+$ demand can be accounted for through the mass flow mechanism, thus reducing the relative demand for $K^+$ diffusion. At the same time, $K^+$ diffusion is driven by the concentration gradients between the bulk soil solution and that adjacent to the plant root surface (which is presumably near zero). Thus, the rate of $K^+$ diffusion is simultaneously increased. Second, the amount of $K^+$ adsorbed on the soil exchange complex is increased. This increases the soil K buffer capacity and allows it to maintain higher levels of supply over more extended periods of the growing season.

## LITERATURE CITED

Barber, S. A. 1985. Potassium availability at the soil-root interface and factors influencing potassium uptake. In Potassium in Agriculture, R. D. Munson (ed.) Chap. 11:309-324. ASA-CSSA-SSSA, 677 S. Segoe Road, Madison, WI.

Barber, S. A., J. M. Walker, and E. H. Vasey. 1962. Principles of ion movement through the soil to the plant root. p. 121-124. *In* G. J. Neale (ed.) Trans. J. Meet. Comm. 4, J. Int. Soc. Soil Sci. Soil Bureau, P.B., Lower Hutt, New Zealand.

Beaton, J. D., and G. S. Sekhon. 1985. Potassium nutrition of wheat and other small grains. *In* Potassium in Agriculture, R. D. Munson (ed) Ch. 31:701-752. ASA, CSSA, SSSA J., 677 S. Segoe Rd., Madison, WI.

Brown, P. L. 1971. Water use and soil water depletion by dryland winter wheat as affected by nitrogen fertilization. Agron. J. 63:43-46.

Christensen, N. W., T. L. Jackson, and R. L. Powelson. 1982. Suppression of take-all root rot and stripe rust diseases of wheat with chloride fertilizers. Plant Nutrition 1982. *In* Proc. 9th Int. Plant Nutrition Colloquium, Warwick Univ., England. 22-27 Aug. 1982. 1:111-116. Commonwealth Agric. Bureau.

Gasser, J. K. R., and M. A. P. Thorburn. 1972. The growth, composition and nutrient uptake of spring wheat. Effects of fertilizer-N, irrigation and CCC on dry matter and N, P, K, Ca, Mg and Na. J. Agric. Sci. 78:393-404.

Gregory, P. J., D. V. Crawford, and M. McGowan. 1979. Nutrient relations of winter wheat: 1. Accumulation and distribution of Na, K, Ca, Mg, P, S, and N. J. Agric. Sci. 93:485-494.

McNeal, F. H., M. A. Berg, P. L. Brown, and C. F. McGuire. 1971. Productivity and quality response of five spring wheat genotypes, *Triticum aestivum* L., to nitrogen fertilizer. Agron. J. 63:908-910.

Mubarek, A., and R. A. Olsen. 1976. Immiscible displacement of soil solution by centrifugation. Soil Sci. Soc. Am. J. 40:329-331.

Schaff, B. E., and E. O. Skogley. 1982. Diffusion of potassium, calcium, and magnesium in Bozeman silt loam as influenced by temperature and moisture. Soil Sci. Soc. Am. J. 46:521-524.

Skogley, E. O. 1976. Potassium in Montana soils and crop requirements. Montana Agric. Exp. Stn. Res. Rpt. No. 88.

Skogley, E. O., and V. A. Haby. 1981. Predicting crop responses on high-potassium soils of frigid temperature and ustic moisture regimes. Soil Sci. Soc. Am. J. 45:533-536.

Skogley, E. O., and B. E. Schaff. 1985. Ion diffusion in soils as related to physical and chemical properties. Soil Sci. Soc. Am. J. 49:847-850.

Sparks, D. L., and P. M. Huang. 1985. Physical chemistry of soil potassium. *In* Potassium in Agriculture, R. D. Munson (ed.) Ch. 9:201-276. ASA, CSSA, SSSA J., 677 S. Segoe Rd., Madison, WI.

Troughton, A. 1962. The roots of temperate cereals (wheat, barley, oats and rye). Mimeographed Pub. No. 2/1962. Commonwealth Bureau of Pastures and Field Crops. Hurley, Berkshire. The Commonweatlh Agric. Bureau, Farnham Royal, Bucks, England.