Frontiers in Potassium Science: Developing a Roadmap to Advance the Science of Potassium Soil Fertility Evaluation

Summary Report

This report provides a summary of the structure and outcomes of the Frontiers in Potassium Science Workshop held 26-30 January, 2015 in Kailua Kona, Hawaii in conjunction with the International Symposium on Soil and Plant Analysis (http://www.isspa2015.com/).

Rationale

During the past few decades, the move toward site-specific nutrient management has created a demand for greater accuracy and precision in soil potassium (K) evaluation. In many areas, the desired accuracy and precision are not attainable with current soil testing approaches. Practitioners have often not been able to explain why soil-test K varies across the landscape or over time in response to management practices. Additionally, definitive calibrations of K soil tests to crop responses have not been achievable in some areas.

The International Plant Nutrition Institute (IPNI) hosted a workshop to convene a small group of highly creative and accomplished scientists from around the world to discuss these issues and create a roadmap that outlines what scientific work must be done in the future to improve our ability to evaluate soil K fertility and predict the impact of K amendments on crop productivity. This roadmap is of critical importance to IPNI Member Companies whose objective is to manufacture and distribute K fertilizers in quantities needed to provide K in the right form, rate, time, and place for proper plant nutrition. Only then can we meet the needs for food, feed, fiber, and fuel production and provide other ecosystem services of interest to society now and into the future.

Scope

The scope of the workshop was confined to creating a list of strategies for explaining and managing significant spatial and temporal variability in the contributions of fertilizer K and soil K to plant nutrition. The group was asked to identify critical concepts that were missing or were inadequately characterized in existing soil K assessments or K recommendations.

Objectives

The objectives of the workshop were:

1. to create a network of innovative scientists who effectively communicate across disciplines to advance the science of soil K evaluation;
2. to describe the key issues in evaluating soil K fertility and to communicate those issues to applied scientists; and
3. to develop a roadmap that guides future efforts to advance the science of soil K evaluation.

Significant progress was made on all objectives before or during the meeting, as discussed below.

Objective 1: creating a network of innovative scientists

Over the course of several months, IPNI used the following methods to identify scientists to invite to the K Frontiers Workshop:

- IPNI surveyed its own staff. IPNI staff currently work in most countries around the world, with the exception of most of the Middle East and western Europe. IPNI staff is engaged with university, industry, and agency personnel.
- IPNI conducted several searches of the peer-reviewed literature using the Web of Science citation database. Scientists were identified as potential candidates if they 1) authored or co-authored several publications on topics IPNI deemed important to advancing the science of soil K evaluation; 2) were actively working; 3) were not on sabbatical or a comparable activity.
- IPNI limited the initial invitees to a small group to foster discussion and brainstorming activities. Many more scientists were identified as conducting work that is important to advancing the science of K nutrition of crops; these scientists will be contacted at a later date and invited to participate in the network and in future meetings.

The scientists who comprise the nucleus of the network are listed in Appendix A. Bringing these scientists together as a group for the first time to discuss previous research and to brainstorm about a roadmap was an important step toward creating a scientific network that IPNI envisions will grow and increase in activity for years to come.

Objective 2: describe key issues and communicate them to applied scientists

During 2013, IPNI gathered together scientists and practitioners in two separate meetings (Istanbul, Turkey, and Tampa, Florida, USA) to identify major issues with K. A summary of those issues is below. Although many specific issues were identified, IPNI grouped them into the following general categories where improved knowledge was needed:

- temporal synchrony between soil nutrient supply and crop demand;
- alternative methods for evaluating plant-available K in soil as well as plant K status during the season;
- past approaches to soil testing;
- models that have been used to simulate soil K nutrient supply and crop uptake;
- factors that significantly impact the probability and extent to which crops respond to K additions;
- infrastructure for sharing and archiving past and future data and methodologies.

These categories, coupled with the scientific input of IPNI staff and topics identified during Web of Science citation database searches, served as guidance for developing topics for the K Frontiers Workshop.

During 2014, invited scientists and industry representatives were asked to provide brief, written descriptions of the issues identified as important for improving K soil assessments and K recommendations. These descriptions served as background information that informed the brainstorming session on Wednesday, 28 Jan., when the roadmap was developed. Written responses were in the form of abstracts. The issues, often framed as questions, and the written responses comprise Appendix B. This information was presented orally on Monday, 26 Jan. as part of the ISSPA workshop titled “Unraveling Potassium Requirements.” This session provided a forum to discuss each of the issues not only among invited scientists and industry representatives, but also among ISSPA conference attendees, many of whom represented commercial and private soil testing and plant analysis laboratories or scientific disciplines impacting soil testing and plant analysis methodology.

Objective 3: develop a roadmap

On Wednesday, 28 Jan., only the invited scientists met, and through facilitated discussions, a roadmap was developed. The roadmap consisted of a list of educational and research strategies. The next day, this roadmap was presented at the ISSPA. Conference attendees represented private and public analytical laboratories, research institutions, fertilizer manufacturers and other agricultural input providers, as well as agricultural service providers. This group of stakeholders vetted the roadmap and provided feedback during a discussion period following the presentation.

Strategies in the roadmap are listed below. The first five strategies are general. The remaining strategies are specific to components of the K cycle as it is defined below.

Strategy 1:
Define scientific terms.

Discussions during the workshop revealed a lack of consensus on the meanings of scientific terms used in K plant nutrition research. The lack of agreement within the group reflected the lack of consensus within the greater scientific community. Terminology that is accurate, clearly understood, universally accepted, and used consistently by the scientific community is key to communicating effectively to make advancements. Examples of terms that require the building of scientific consensus to create clear definitions are:

- fixed K
- K holding capacity
- K-fixing soil
- K recovery efficiency
- leached K
- particulate K
- plant-available K
- soluble K
- throughfall K

These examples serve as the start of future discussions. More terms will be added to this effort as it proceeds.

Strategy 2:
Develop a revised K cycle that is comprehensive and reflects the most current knowledge.

There was agreement that existing K cycle diagrams were not appropriate for the objectives of this effort. The purpose of the updated diagram is to show how various pools of K, soil physical and chemical processes, and plant processes are related. This diagram provides a conceptual framework for scientific investigations, modeling, and education. The group created a rough draft with the understanding that it would be revised several times before being finalized (Figure 1). The purpose of the initial draft was simply to get major components of the K cycle diagrammed. The simplified K cycle provided by de Barros et al. (2004) was used as a starting point.

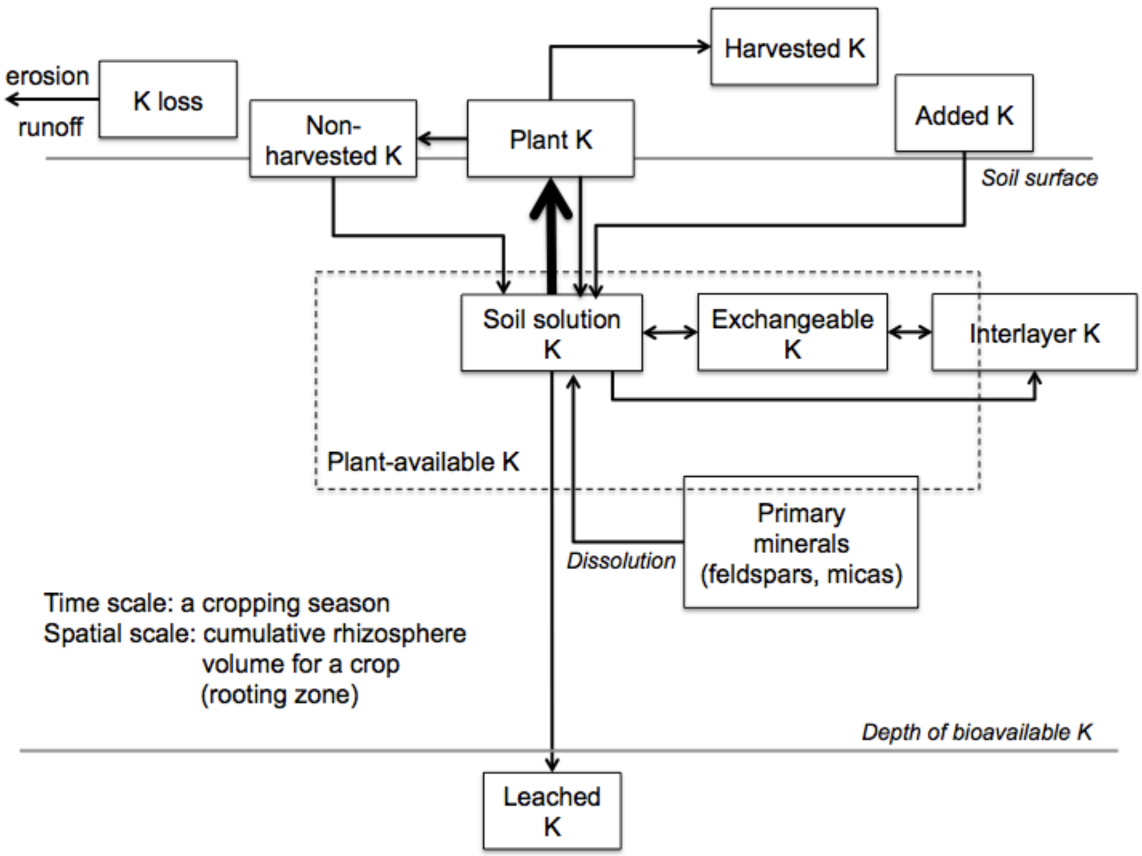

Figure 1. Initial draft of an updated K cycle.

Strategy 3:
Use K flux as the defining metric of K nutrition of plants.

Potassium flux, as we use the term here, is the rate of K supply to the plant root per unit of root surface area. The ultimate goal of research and modeling efforts is to provide information about how various factors impact K flux during the growing season or the periods most critical to plant uptake. The group felt that an overall research strategy should:

- devise methods for estimating contributions of various pools to K flux;
- investigate factors that regulate both K pools and K flux (i.e. temperature, moisture, soil mineralogy, plant uptake, etc.);
- summarize, through systematic reviews and meta-analyses, existing knowledge on contributions to K flux by various pools.

The group drafted a decision tree to guide future K research and K recommendation development (Figure 2). The decision tree uses flux as the defining metric. In devising this figure, it was acknowledged that categorizing soils according to their K holding capacity was a needed component for improving K assessments and K recommendations. Additionally, the sizes of K pools and their respective, daily, weekly, and season-long fluxes needed to be adequately characterized and evaluated for their ability to meet the demand of specific crops.

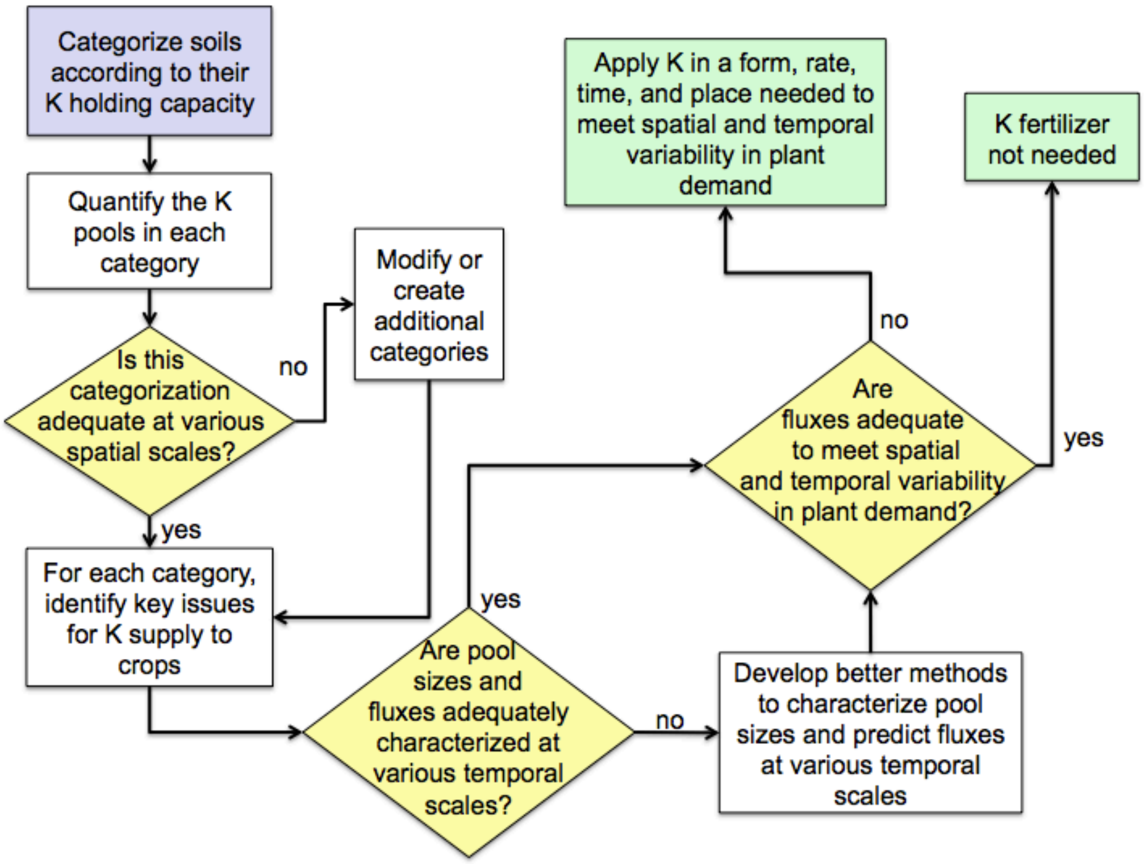

Figure 2. Diagram of a decision tree for an overall strategy for improving soil K assessments and K recommendations.

Stretegy 4:
Categorize soils according to their K holding capacity

Categorization of soils according to their K holding capacity requires soil-specific and site-specific knowledge of the quantity of K in various pools as well as the quantity of K lost through leaching, erosion, and runoff. Characterization of K holding capacity would be prioritized on benchmark soils at sites with the largest inference space within the domain of arable land with cropping systems that are most economically significant to developing and developed countries.

Strategy 5:
Improve approaches for making K recommendations.

Current approaches have a long history of utility but lack both spatial and temporal resolution. The following concepts were believed to be worthy of further investigations:

A. the utility of incorporating binary decision trees into the K recommendation process to complement soil test K information. Examples of binary decisions are:
    a. does K leach from the rooting zone sufficiently to limit plant uptake?: yes/no;
    b. quantify cation exchange capacity (CEC)?: high/low;
    c. are there other dominant, competitive cations?: yes/no;
    d. is the plant able to use sodium (Na) as a substitute for K for various essential functions? yes/no;
    e. is this a "K-fixing" soil? yes/no;
B. the time between soil sampling and crop planting
C. the usefulness of conducting detailed characterizations of K pools and fluxes of benchmark soils
D. developing new ways to quantitatively assess the spatial variability of soil K and to incorporate that variability into field-scale crop growth models to make K recommendations
E. the flexible use of different soil test interpretation philosophies (sufficiency vs. build and maintenance) to address risk management, including economic risk, by farmers and land owners.

The remaining strategies below are for investigating specific components of the K cycle drafted in Figure 1.

Strategy 6:
Quantify leached K.

Quantifying leached K is important for soils with low K holding capacity. Specific areas that require investigation are:

A. the impact of rainfall quantity and intensity on the quantity and timing of K leaching;
B. the impact of crop management strategies, e.g. cover crops and crop residues;
C. the impacts of fertilizer K management (form, rate, time, and place);
D. the impact of soil organic matter on K leaching

Strategy 7:
Quantify other K losses.

Losses of K in runoff and from erosion have not been studied as extensively as those of nitrogen (N) and phosphorus (P) losses because K, as far as is known, is environmentally benign. In the future, the following topics require investigation:

A. The magnitude of runoff and erosion losses, measuring soluble K and particulate K as we have done for P;
B. How form, rate, time, and place impact K losses.

Educational materials need to be produced to make the current knowledge useable by crop producers and their advisers, fertilizer manufacturers, and policymakers.

Strategy 8:
Quantify the contribution of dissolution of K-bearing minerals to K flux.

Dissolution of K-bearing minerals contributes to soil solution and exchangeable K. In some soils, contributions are significant and may account for a large portion of the K taken up by plants.

Strategy 9:
Quantify the pool of non-harvested plant K.

The potential for recycling of K from plants and plant residues to the soil is not currently embedded in K recommendations. In particular, the following issues need to be examined:

A. the factors affecting the rate of K leaching from the plant and from plant residue (rainfall quantity and intensity, quantity of K in throughfall, residue composition, rate of residue decomposition, etc.);
B. the timing of soil sampling relative to the release of non-harvested K back into the soil system.

Strategy 10:
Improve the quantification of plant-available K.

Assessments of plant-available K may be improved by investigating the following:

A. the interaction of plant-available K, soil water content, and root distribution;
B. the contribution of K at various depths in the soil profile to uptake by different crop species under different management regimes;
C. variations in crop demand for K throughout the growing season;
D. the contribution of soil taxonomic information to predictions of K pools and K holding capacity;
E. evaluating various soil K tests (ammonium acetate, Mehlich I, Mehlich III, ion exchange resins, etc.) and their correlation to plant uptake and/or crop yield.

Education of farmers and crop advisers is needed to create an accurate understanding of what information a soil test does and does not provide.

Strategy 11:
Clarify interpretations of mass balance calculations.

Mass balance compares the quantity of K removed with harvested crop portions to the amount of K added. The following needs were identified:

A. investigate how the terms “maintenance application” and “mass balance” have been used;
B. create standard definitions that address two common objectives with mass balance calculations:
    1. maintain soil test levels, or
    2. replace the mass of K that was removed through crop harvest.

Strategy12:
Quantify recovery efficiencies of added K.

Recovery efficiency is defined as the change in total K uptake by the plant that results from a given rate of K applied. Conceptually, it is interpreted as the proportion of applied K that is taken up by the plant. Recovery efficiency is a key factor in creating nutrient recommendations; however, little work has been published that quantifies K recovery efficiencies. Therefore, the following needs exist:

A. conduct a systematic review and meta-analysis on K recovery efficiencies of various crops;
B. research how form, rate, time, and place of K additions impact K recovery efficiency;
C. compare and contrast the root-soil interactions of various plant species, examining how root exudates, root architecture, root hair formation, etc. impact K recovery efficiency;
D. educate farmers and advisers on the concept of K recovery efficiency.

Strategy 13:
Incorporate interlayer K into recommendations and soil test interpretations.

"Fixed K" is a term that has been used widely to categorize K that exists in or migrates to interlayer positions in 2:1 layer silicates; however, "interlayer K" is probably a more appropriate term, since research has demonstrated repeatedly that K in these positions is not permanently fixed. Under certain conditions, it can migrate out of the interlayers to edge and planar sites where it can enter the soil solution and be available for plant uptake. Potassium flux from interlayer positions has not been often measured, and its regulation is poorly understood. Interlayer K has not been widely considered in K recommendations. It is therefore necessary to investigate:

A. the impacts of three types of interlayer K in 2:1 layer silicates on K flux:
    1. K located at frayed edges of high-charge layer silicates;
    2. interlayer K that is blocked by hydroxy aluminum polymers in 2:1 layer silicates of acid soils;
    3. K retained in the interlayer space of Fe-bearing 2:1 layer silicates when redox potential is low;
B. the impacts of soil organic matter, pH, and seasonal variation in drainage on fluxes of interlayer K to the soil solution;
C. the utility of using Soil Taxonomy to identify "K-fixing" soils, i.e. soils where a significant portion of K may be temporarily retained in interlayer positions.

Summary
These thirteen strategies represent the roadmap developed by the K Frontiers Workshop; however, it is expected that additional strategies and sub-strategies will be developed over time as work in this area continues. Due to time constraints, several important topics were not discussed during the workshop but will be addressed in the future. Examples are listed below:

- Interactions of K with other nutrients;
- Interactions of soil microbes with soil minerals, particularly in the rhizosphere;
- The extent to which resins can be used to quantify K flux

This list is far from complete and will be expanded in the future as work continues.

The K Frontiers Workshop has generated renewed interest in the issues that have kept soil K assessments and recommendations from having the temporal and spatial resolution that is being demanded by precision agriculture and data-intensive management approaches. It is critical to build upon the work achieved during this workshop and maintain momentum toward making needed improvements now and into the future.

Reference

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Appendix A: Invited Scientists and Industry Representatives

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Appendix B

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Challenges in evaluating potassium soil fertility: An introduction

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In the past few decades, the adoption of site-specific nutrient management has increased the demand for accuracy and precision in soil potassium (K) evaluation. Soil K evaluation has increased in importance in regions of the world where long-term negative K balances have increased the frequency of K deficiency in crops. The importance of effective soil K evaluation has been intensified by the need for improved cropping system productivity and for the efficient use of all inputs, including K and other inputs with which K interacts. In many areas, the desired accuracy and precision are not attainable with current soil testing approaches.

Therefore, the visibility and importance of the following soil K assessment problems have increased.

- Lack of definitive calibration of soil test K (STK) to crop response in some areas.
- Within a given STK range, great variability in response to applied K among growing seasons at a single site, or among sites within a single growing season.
- Unexpected spatial variability patterns of STK within fields.
- Large temporal variability in STK that appears unrelated to K additions or K removal by crops and contributes to substantial “noise” in long-term STK records.
- Directionally inconsistent effects of weather-related factors such as soil moisture content on STK levels across sites for both research plots and grower fields.
- Alterations in measured K levels and their interpretation due to sampling or sample handling procedures.
- Genetic changes in crops that impact progressive K demand through the growing season and root development that may in-turn influence requirements for soil K and its release to the soil solution.
- Unknown impacts of changes in subsoil K levels as a result of long-term crop removal on surface STK interpretation, crop susceptibility to moisture stress, and general K management.
- Abandonment of K soil testing approaches in some parts of the world due to poor access to soil testing or limited supporting calibration and interpretation.

In an attempt to gather input from scientists on major issues with K plant nutrition, IPNI held two workshops in 2013 as side events at major scientific conferences in the U.S. and Turkey. Key issues identified in these workshops were: 1) lack of understanding in the temporal synchrony between soil nutrient supply and crop demand; 2) the need for a review of alternative methods for evaluating plant available K in soil as well as for evaluating plant K status during the season; 3) the need for a comprehensive review of the theories driving past approaches to soil testing; 4) the need for a review and subsequent improvement of models that simulate soil K nutrient supply and crop uptake;

5) lack of sufficient data to accurately quantify the relative magnitudes of effects of factors that significantly impact the probability and extent to which crops respond to K additions; and 6) lack of an effective infrastructure for sharing and archiving past and future data and methodologies.

We believe that resolution of many if not all of these issues and problems with soil K assessment reside in the answers to appropriate mechanistic questions about the behavior of K in soil-plant systems. The following questions have been posed to a group of the world's leading K scientists in an attempt to assemble and synthesize our current knowledge surrounding these critical questions and identify knowledge gaps that deserve future research attention.

1. What theoretical approaches have already been tried for measuring plant-available K?
2. What factors significantly affect variation in soil test calibration relationships?
3. How site-specific are soil test calibration relationships?
4. How accurately can we measure K fixation potential and to what extent can it be part of K fertilizer recommendations?
5. What is the potential role of soil classification in soil K assessment and fertilizer recommendations??
6. How does redox potential impact K fixation and release?
7. How does the application of other nutrients affect K reactions in soils?
8. What root-mineral interactions are occurring in the rhizosphere?
9. To what extent can K efficiency describe differences in crop responsiveness to K additions?
10. How does the distribution of water and roots in the soil profile impact K uptake, crop growth, and water productivity?
11. How does K leaching from crop residues impact the spatial and temporal variability in soil fertility?
12. What are the unique attributes of K that require specific features in nutrient uptake models and how do existing models factor in those features?
13. How can K nutrition be incorporated into decision support systems and production simulators like APSIM and DSSAT?

Much of each of the answers to these questions is already known but only a portion of what is known is currently utilized in soil testing and the associated interpretation tools. It is likely that improved synthesis of existing knowledge plus research to fill the identified knowledge gaps will greatly improve the accuracy and precision of soil K assessment and its appropriate use in making K management decisions.

What does an updated K fertilizer recommendation need?

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A good fertilizer recommendation has to give information for the farmer about the amount of nutrients, the time and place of application, and the right form of the fertilizer. The target is to feed the crops and to improve soil fertility. Since the soil is the major source of nutrient supply, we need an improved soil testing method for potassium (K) which takes into consideration both the recent status of plant available nutrients in the soil and the subsequent supply of K from mineral and/or organic sources. Furthermore the synergistic or antagonistic effects of other nutrients like Ca or Mg have to be taken into consideration. However, soil conditions are not the only important factors determining variability in nutrient availability. The plants also play an important role. They can modify the nutrient uptake to a significant extent. Therefore, the soil testing results have to be augmented with crop data. Demand for nutrients by the plant is just as important as the supply potential from the soil. Diffusion rates through soils provide a supply-side estimate, while modeled growth provides a demand-side estimate. Simulation models of plant growth and root growth in particular give a better understanding of crop demand. Furthermore, changing environmental conditions have to be taken into account. Factors like drought stress do not just affect nutrient uptake. The nutrients themselves have a significant effect on the mitigation of stress factors. In particular, potassium plays an important role, among others, by preventing unproductive water losses and by promoting root growth. An updated model of K fertilizer recommendation has to quantify these effects as well. New approaches like precision farming and remote sensing systems can help to update the K fertilizer recommendations. Besides these soil- and crop-based data, the knowledge transfer to the farmers is absolutely necessary to bridge the gap between science and practice. This is often the bottleneck in the improvement of nutrient management in modern agriculture.

Potassium Research Considerations

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Potassium (K) deficiency has been one of the most difficult for me to diagnose. Alternate causes for symptoms, differing soil mineralogy, and changing cultural practices are complicating factors.

When I started over fifty years ago, the conventional wisdom was that there was no K deficiency in California. The wisdom came from the University of California. Forrest Fulmer, a representative of IPNI, forerunner the Potash Institute, thought otherwise. So did Fresno County farm advisor Les Stromberg who established field trials proving occurrence of K deficiency in Fresno County cotton. The deficiency had been obscured by verticillium wilt which has similar symptoms. Interesting how K cured some verticillium.

Several years later using tissue analysis, K deficiency was diagnosed in an almond orchard. Before the fertilizer recommended was applied, one of the trees fell due to a trunk rot. Slow irrigation water infiltration resulted in the wet conditions fostering the disease. The low K concentration in tissue was a symptom of disease - not limited supply. No amount of K would have cured this disease.

K deficiency was diagnosed in grape with higher ammonium acetate extractable concentrations than in soils that supported vineyard without K deficiency. Soil structure restricted root exploration of the first soil.

Increased yields of crops like tomato have resulted in potential assimilation rates faster than soil could supply. K responses occurred in soils that were otherwise considered to have adequate supply. Use of buried drip irrigation increased yields further and depleted K from the small volume of soil wetted.

Potassium deficiency also in cotton occurred in soils having low K release rates. Release rates were shown to differ in soils having the same concentrations of ammonium acetate extractable K but with differing parent materials. The test did not mimic field conditions. Diagnostic tools were developed to evaluate release rates.

The following derive from experiences. Consider not only experience but anticipate what is to come.
1. Challenge conventional wisdom.
2. Consider alternate causes for symptoms.
3. Consider increasing yield potential
4. Consider changing practices that may impact uptake.
5. Consider assimilation demand vs soil release rates
6. Consider mineralogy

Fertility Challenges and Opportunities from an Industry/Manufacturer Perspective

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Research efforts devoted to understanding and predicting the response to potassium (K) fertilizers in agricultural crops have long been overshadowed by research committed to other nutrients and agronomic disciplines. There are many potential research topics that could improve K fertilizer management. Four subjects are of particular interest for The Mosaic Company and our customers:

1. a proper assessment of K availability in the soil and re-evaluation of current soil test calibrations that are used for making K recommendations;
2. evaluation of new methods and technologies that aid in understanding the role soil mineralogy plays in K nutrition;
3. investigating the proper rates, timing, and placement of K applications in tropical and sub-tropical cropping systems;
4. the role of proper K nutrition, including N:K ratios and quantifying the benefits on plant health, which relates back to ensuring a proper balance of nutrients and the adverse impacts of an unbalanced approach to crop nutrition.

In summary, the subjects discussed could lead to a better understanding of exchangeable and non-exchangeable potassium and how that correlates to plant availability and overall plant health.

Economic Decision Support Model for Potassium Recommendations

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Potassium response models exist at most Land Grant universities and are the basis for agronomic recommendations for various crops. Few of these agronomic models are presented to farmers in an economic fashion to help farmers make informed decisions with today's volatile commodity prices. PotashCorp has developed an economic decision tool based upon landgrant university response models. The model is available at http://potashcorp-ekonomics.com/. The hope is that this approach can be applied to a much broader suite of crops and geographic regions.

What theoretical approaches have already been tried for measuring plant-available K?

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Approaches for measuring plant-available potassium (K) can be grouped into the following categories:

(1) mild extractants, e.g. water, salt solutions such as ammonium acetate, calcium lactate, double lactate, Eigner-Rheim, sodium tetraphenyl boron;
(2) strong extractants such as acids;
(3) resins, including Diffusive Gradient Thin Film;
(4) ion selective electrodes;
(5) complex techniques such as electro ultra filtration;
(6) pot experiments;
(7) plant analysis;
(8) adsorption isotherms, e.g. quantity/Intensity relationships;
(9) statistical methods and models, e.g. path analysis.

Attempts to develop new methods continue, increasingly with the aim of avoiding soil sampling and analysis through remote sensing techniques. For example, Paz-Kagan et al. (2014) created a spectral soil quality index using reflectance spectroscopy. They used the Cornell Soil Health Test, which uses 14 physical, biological and chemical properties, to indicate soil health. They used a partial least-squares-regression (PLS-R) cross-validation procedure to correlate the selected spectral data against available K as extracted by Morgan's reagent, and found an r^2 of 0.76.

No method quantitatively extracts what a plant 'sees' as available K apart, perhaps, from plants grown in pots. However, even pot experiments do not directly correspond to field conditions because, unlike field soils, soils in pots are usually well mixed and extensively, if not completely, explored by plant roots. All methods must be calibrated against field experiments, preferably over a wide range of soil types, crops and climatic regions. Countries, local regions and individual laboratories tend to select one method and use it exclusively, learning through experiment and experience to interpret the results in the context of the K requirement of the crop and soils. This is perfectly acceptable in practice but often lacks scientific rigor. Is it possible to develop a scientifically rigorous method of analysis for the K in soils available to all, or at least the main, crop plants, and is there just one form of 'available K'?

Research done 30 years ago by Goulding (1984) identified various categories of soil K according to their amounts and rates of release to calcium-saturated ion exchange resin.

The amounts and rates of release of the different categories of soil K were measured on 21 soils from field experiments in England, Wales and West Germany using a calcium-saturated cation exchange resin. The soils contained various categories of K, identified by their rates of release (Figure 1) that are often described as 'available', 'fixed' and 'mineral matrix'. These were qualitatively related to the clay contents of the soils.

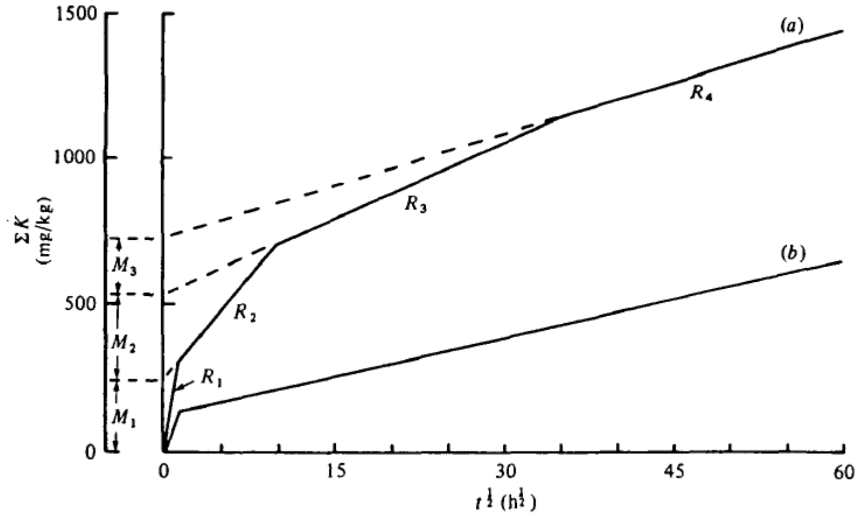

Figure 1. Potassium released to Ca-resin by (a) an English soil containing 49% clay and (b) a German soil containing 2% clay. Plotted as cumulative K released against the square root of the cumulative reaction time in hours, $t^{½}$. M_1, M_2, etc. are the amounts of K released and R_1, R_2, etc. are the rates of release associated with the first, second, etc. linear segments of the release curve.

Regression analyses of K removed at harvest by spring barley, winter wheat, field beans and sugar beet, grown in the field experiments, were made on the quantities measured by the Ca-resin method and on 'available K' measured as K exchangeable to 1*M* ammonium acetate (EK). The Ca-resin method proved a better predictor of K availability than EK for all four crops. A multiple regression of the amount and rate of release of exchangeable K, and the rate of release of fixed K, as measured by Ca-resin, gave the best correlation with K removed. The contribution of fixed K to the regression increased with the demand of the crop for K and with the length of time the crops had been grown without K fertilizer. For the cereals, fixed K appeared to be either completely available or unavailable depending on whether its rate of release exceeded a critical value characteristic of each crop. This suggests that no single measure of 'available K' exists for a soil but rather K availability is determined by soil and crop characteristics.

Thus a single chemical extractant, or a remotely-sensed variable that approximates to it, is unlikely to definitively quantify the K available to crops grown in the field. Methods that extract K in the same way as a crop, such as ion exchange resins, can provide a better estimate than simple extractants, but is there sufficient benefit in using them? They are probably too laborious for routine soil analysis and still need to be calibrated against field experiments. They could be used to characterize the long-term K release properties of a soil or even map soil reserves, as suggested by Goulding and Loveland (1986). However, even a technique such as resin extraction does not accurately resemble the dynamic uptake process that occurs in the field. Uptake is not constant throughout the growing season but varies with crop physiology (i.e. its growth pattern), modified by the weather. Potassium uptake in the above-ground part of a wheat crop is shown in Figure 2. The amount in the crop at harvest was approximately two-thirds that at maximum uptake, and the K removed in grain represented only 15% of the maximum taken up by the crop.

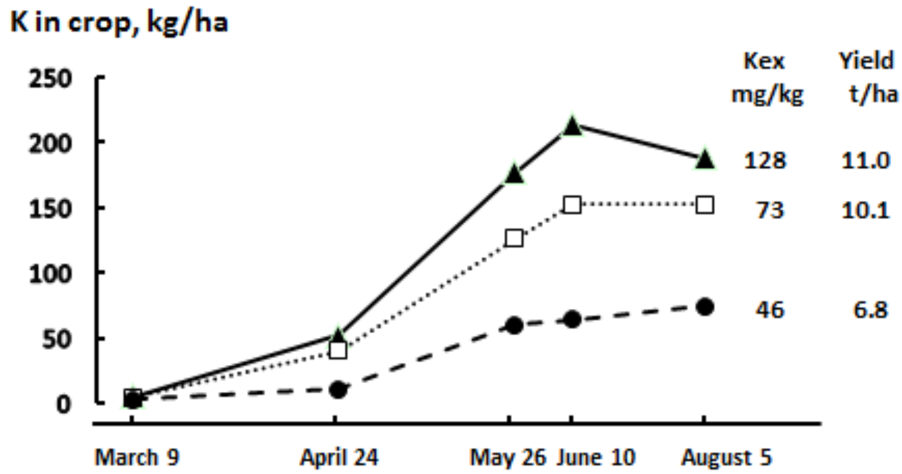

Figure 2. K uptake by a winter wheat crop from March to anthesis at three exchangeable K contents (Kex), and grain yield at harvest, Sawyers Field, Rothamsted, 2004 (George Milford, Personal communication).

Thus we have an additional problem in measuring available K: a crop may need much more K for good growth than is removed at harvest. Comparisons of analytical methods with K removal do not reflect the total crop requirement.

Conclusion

As yet there is no simple or even complex analytical method to quantitatively extract the K available to crops. All methods must be calibrated in field experiments.

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Measuring soil K availability: Theory and methods

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It has been generally accepted that potassium (K) concentration in the soil solution depends on four types of negative charges: (1) K-preferring bonds in the wedge-shaped void of micaceous clays closed by adsorbed K; (2) wedge voids not closed; (3) non-preferring permanent charges on the exposed internal surfaces of micas; and (4) charges on the exposed external surfaces of clays. In tropical, weathered soils with variable charge, organic matter, and to some extent soil aggregates may also play a role in K availability. There is not much argument on the availability of soil solution and exchangeable K to plants, and also on the non-availability of K fixed on primary minerals.

Ammonium acetate has been used as the reference extractor to assess exchangeable K, and dissolution with diluted strong acids and electrochemical ultra filtration have been investigated with several degrees of success, depending on the soil. But because these methods do not estimate the amount of K made available during plant growth, the correlations with plant response have not been always satisfactory. The problem has always been on how much and how fast less exchangeable K will be available and how to estimate it. It has been recognized that some K considered "non-exchangeable" is important to meet plant demand and soil equilibrium. Boiling molar HNO_3 has been used to estimate this K pool, but it has shown no correlation with plant response. Furthermore, it has been shown that when soybean depended on HNO_3-K, the yields were lower (Machado et al., 1988, Steiner, 2014).

In tropical weathered, acidic, low CEC soils, the mixture of cation and anion exchange resins has been shown to be practical and cheap, correlating very well with ammonium acetate-K (Raij et al., 1986). The correlation between resin extracted K and plant response has been very good in these soils because resin can extract some of the non-exchangeable K, which mimics K movement to plant roots. Soil exchangeable K is extracted by resin in less than 20 minutes, followed by a sharp change in the release curve inflection, showing that some "non-exchangeable" K is released for at least five hours (Meurer and Rosso, 1997). In Brazil, the recommendation is to shake soil samples with resin for 16 hours, as suggested by Hislop and Cooke (1968). Hence, besides the exchangeable K, some non-exchangeable K is extracted.

It has been shown that the extractants Mehlich-1, Mehlich-3 and ion exchange resin extracted similar K amounts from well-developed, weathered soils. However, in less-developed soils, Mehlich-1 and Mehlich-3 extracted similar and higher amounts of K as compared with resin, particularly with higher clay content and a larger proportion of 2:1 minerals. Unlike Mehlich-1 and Mehlich-3, ion exchange resin was not well-related with the exchangeable K content in the less developed soils (Medeiros et al., 2010).

There is no soil K extractant that does not require calibration. Resin has been shown to correlate well with plant K uptake and response to K fertilization, mainly in oxisols.

However, another desired feature of a chemical extractant is the ability to show changes in soil K due to the history of plant removal and fertilization. Steiner (2014) observed that in a sandy loam an application of at least 75-100 kg ha^{-1} of K was required to maintain the initial soil K concentrations (Figure 1A).

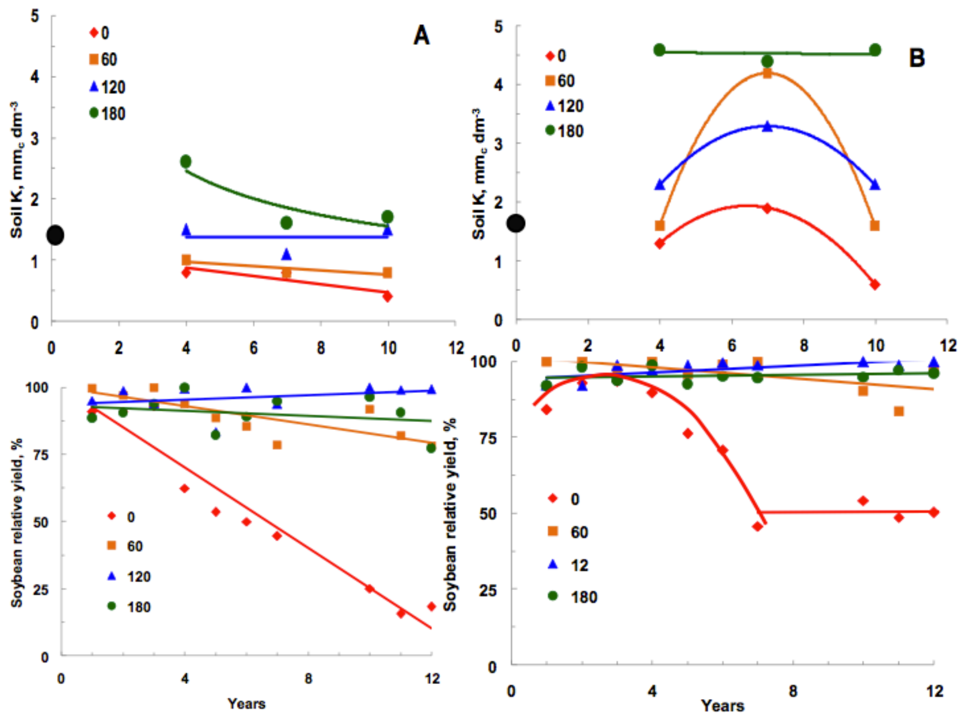

Figure 1: Soil K, as extracted by resin, and relative soybean yields in a 12-year experiment in Botucatu, Brazil, in two oxisols, as affected by K fertilization (0, 60,120 and 180 correspond to around 50, 75, 100 and 150 kg K ha^{-1}) on A) a sandy loam soil with 210 g kg^{-1} clay; and B) a clay soil with 580 g kg^{-1} clay. The black-filled dot indicates the initial K concentration (adapted from Steiner (2014)).

When K was applied at 100 to 150 kg ha-1, there was an initial increase in available soil K, and then a decrease, tending to a constant around 1.5 mm$_c$ dm^{-3}, what appears to be the maximum K holding capacity of this soil. Soybean yields decreased from the first year without K and decreased from the fourth year with 50 kg K ha^{-1} (Figure 1 A). However, in the clay soil the response was completely different (Figure 1B). Soybean yields started to decrease from the fifth year when K was not applied, and soil K was decreased below approximately 1.5 mm$_c$ dm^{-3}. Soil available K increased up to the seventh year, probably due to K cycling to the soil surface. This experiment was conducted under no till, so there was K being leached from the straw left on the soil surface. Soybean has been shown to take up non-exchangeable K (Machado et al., 1988), so part of the K recycled to the soil from the plant residue came from non-exchangeable forms. With time and K exports, soil available K finally started to decrease (Figure 1 B).

Conclusion

Cation-anion resin is a reliable method to assess soil available K as well as soil K changes due to agricultural use, mainly in well-developed soils. When soil K is very high, cation-anion resin usually extracts less K than the reference extractant ammonium acetate.

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Factors Affecting the Calibration of Potassium Soil Test Results with Crop Yield Response

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The calibration of soil-test methods with crop yield response to fertilization based on field trials is an essential part of the process of implementing soil testing in production agriculture. This process gives a meaning to soil-test results in terms of determining sufficiency for a specific crop and for quantifying the nutrient application rates needed when there are different degrees of deficiency. Often different calibrations are required for different methods used for a specific nutrient, because the amounts extracted from the soil and the measured concentration in extracted solutions can differ when different methods are used. The calibration process includes correlation and calibration with crop yield response. The correlation relates soil-test values to crop yield response compared to a non-fertilized control (yield increases or relative yield) across many sites and years, and determines critical concentrations or ranges and interpretation categories. Fertilizer treatments for the field correlation can be just a non-fertilized control and one non-limiting but not excessive nutrient rate. The calibration goes further and determines the nutrient rates needed to maximize yield or economic yield for a wide range of soil-test values. Calibration field trials need to include several nutrient application rates.

Decades-old research has demonstrated that soil-test potassium (STK) methods often need different calibrations for different soils with contrastingly different chemical and/or mineralogical properties, and also that the soil sample drying temperature in the laboratory can greatly affect the amount of potassium (K) extracted from a soil. These factors can affect in different ways the STK correlation and calibration processes. Soil properties and sample drying strongly influence the amount of K extracted and influence the determined critical concentrations. Soil properties and moisture sometimes interact with the K application method to affect the efficiency of the applied K fertilizer, the capacity of a certain rate to supply K to the plant, and the rate needed for adequate crop nutrition at different STK values. This presentation focuses on the correlation of STK methods with yield response to K fertilization in Iowa.

Iowa research conducted during the last decade was used for a recent, major update of STK interpretations. This research explained well the impact of some factors influencing the assessment of optimum soil K supply, and it suggested ongoing research was needed to evaluate others. Field response trials were conducted at more than 200 site-years for each crop. The trials encompassed several soil series (mostly Argiudolls, Calciaquolls, Endoaquolls, and Hapludolls), many of which also are found in neighboring states. Soil was analyzed for plant-available K with the ammonium acetate (NH4OAc) and Mehlich-3 extraction methods, using conventionally dried samples at 35 to 40 ºC (DK) and also field-moist (MK) samples. Ranges of organic matter, clay, CEC, and K saturation were 25-106 g kg^{-1}, 97-341 g kg^{-1}, 12-37 cmol kg^{-1}, and 1-5%, respectively. Figure 1 shows that MK correlated better than DK with crop yield response. Potassium extracted by DK was more than three times greater than for MK. The DK/MK ratio decreased following an exponential decay trend with increasing soil K level (R^2 = 0.77) and tended to be higher in soils with moderately poor to poor drainage but having alternating periods with excess or deficient moisture. The DK/MK ratio increased linearly with soil clay, organic matter, cation exchange capacity, (Ca+Mg)/K ratio, and decreased with sample moisture, but the relationships were poor (r^2 = 0.03 to 0.32), the highest being for CEC.

The extracted K difference between DK and MK was highly affected by the drying temperature and varied greatly across soil series (Figure 2). Soil clay mineralogy for several of the soil series that were included in those trials was not useful for explaining the very poor correlation of DK with crop yield response or differences between DK and MK. This result was not surprising, because there is a narrow range of mineralogy and texture in Iowa row-crop regions; however, as examples in Figure 3 show, measurements of non-exchangeable K in a few trials indicated that this K fraction sometimes is more available in the short term than previously thought, which partly explains poor correlation between STK and crop responses.

Ongoing field response trials and indoor incubations complemented by soil mineralogical and chemical analyses are studying these relationships further by sampling soil at different times, analyzing soil for non-exchangeable K at different times, measuring K recycling from residues, and considering soil moisture relations better.

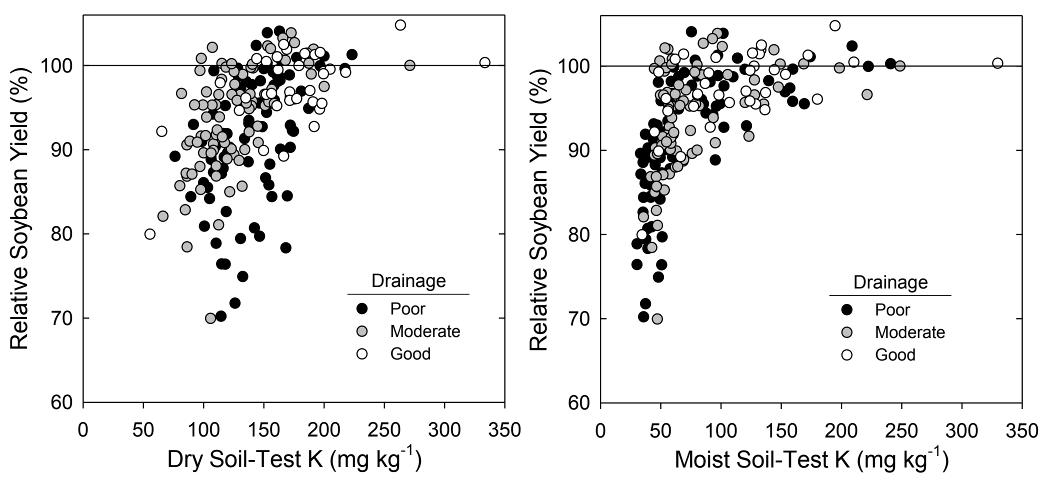

Figure 1. Relationship between K extracted from dried or moist soil samples and soybean relative yield response to K fertilization.

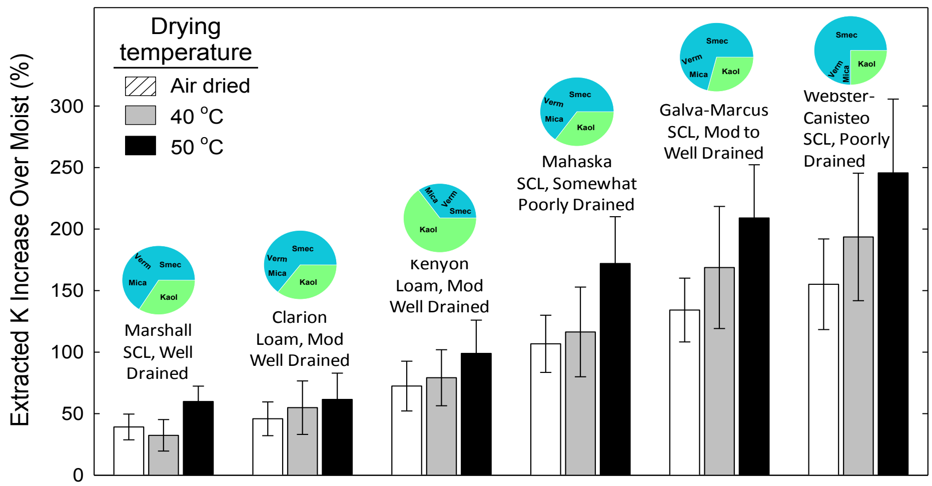

Figure 2. Effect of soil sample drying temperature on extracted K (ammonium acetate method) for several Iowa soil series.

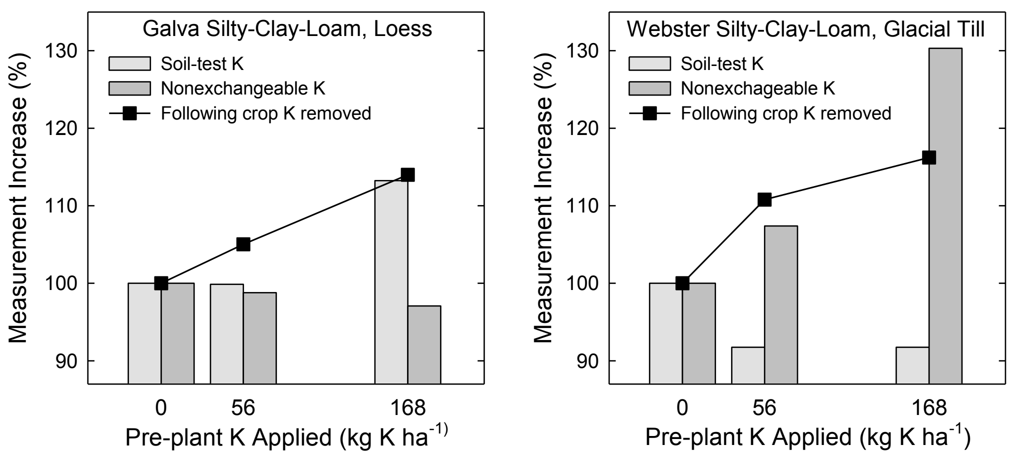

Figure 3. Residual effect of K fertilizer applied for one crop on post-harvest soil-test K and non-exchangeable K, and K removed by a following crop.

How site-specific are soil test calibration relationships for potassium?

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The challenge in developing calibration relationships for potassium (K) is the multitude of factors that influence its availability in soil. These factors fall into four categories – (i) the size and nature of available K pools in a soil; (ii) the rates at which each pool replenishes a depleted soil solution; (iii) the rates of diffusive supply to depleted zones around active roots; and (iv) the root system structure and its interaction with soil moisture which determines where in the profile the crop will access nutrients.

Examples of the variation in size and nature of the available pools in a subset of moderate CEC (25-30 cmol(+) kg^{-1}) Vertisol soils of the northern Australian grain belt are shown in Figure 1a. Soils have similar soil solution K (29-31 mg kg^{-1} equivalent), a 2-3 fold variation in exchangeable K (100-300 mg kg^{-1}) and a 10-fold variation in (exchangeable + slow release) K measured using the tetraphenyl borate (TB-K) extractant (Moody and Bell 2006). However, being able to quantify the release rates from those pools, especially the slow release pools measured using the TB-K extract, is proving challenging. As illustrated in Figure 1b, while the quantum of K released during a 1h TB-K extraction is commonly 80-90% of that extracted over 24h or 7d extraction times, there are soils with both moderate and substantial K reserves where the release from those pools is quite slow.

Relating the differential release rates of slowly available K reserves in a laboratory test to plant availability and the rate of release relative to the rates required by crops during periods of peak uptake is an ongoing challenge. In a glasshouse study in which a variety of soils (predominantly Vertisols) were cropped to K exhaustion (i.e. plant death) using repeated above-ground biomass harvests, the cumulative K removal represented 80-140% of initial exchangeable K but 35-100% of initial TB-K. This suggests that in at least some soils either the release rates at which the slow release K can replenish the soil solution K concentration are much less than that required to sustain plant growth or that the soil solution concentration at which these K forms dissolve is too low to be achieved by plant uptake. Identifying which soils have these slow release pools and their plant-availability will be the key to developing widely applicable soil test-crop response relationships.

Even where soils have a fairly well-defined source of plant-available K (e.g.,predominantly exchangeable K), differences in the selectivity of exchange surfaces for K (driven by soil mineralogy) or the efficiency of the diffusive supply process (affected by soil structure) will impact the critical soil test-crop response relationship. Recent Australian examples have been provided for wheat by Brennan and Bell (2013), with the critical Colwell K (0.5M $NaHCO_3$-extractable K) (0-10cm) ranging from 40-41 mg K kg^{-1} in Inceptisols to 49-50 mg K kg^{-1} in Alfisols and 65 mg K kg^{-1} in an Oxisol.

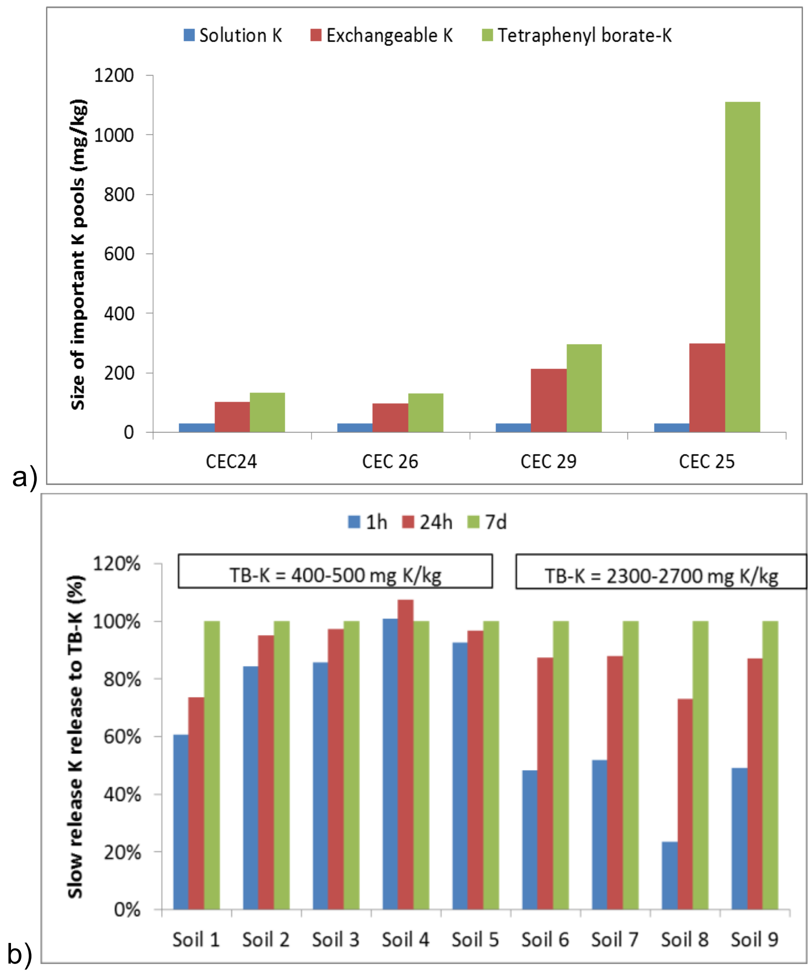

Figure 1. Variation in a) sizes of different K pools in a subset of moderate CEC Vertisols in northern Australia; and b) rate of release of slow-release K pools in Vertisols measured by different tetraphenyl borate extraction times.

Further complications are introduced when considering the interactions between root system distribution and moisture availability in different soil types and cropping systems. In rainfed systems in Australia, crops that are primarily dependent on in-season rainfall for growth and yield (i.e., fallow rainfall is low or soil water holding capacity is limited) typically respond to available K status in the 0-10 cm layer (e.g., the wheat examples from Brennan and Bell 2013). However, in northern Australia, cropping is predominantly on Vertisol soils that have a much greater ability to store soil water during a fallow period for subsequent crop extraction and use. In-season rainfall is typically low and/or variable and crop performance is more related to available K in the upper layers of the subsoil (10-30 cm depth) than in the top 10 cm in most seasons. Current research is attempting to identify the critical soil test values in those subsoil layers. In soils without substantial reserves of slow release K, these values are suggested to be as high as 80-120 mg exchangeable K kg^{-1}, dependent on crop species. Tap-rooted species like cotton and chickpeas seem to have a noticeably higher critical soil K concentration than cereal crops like wheat or sorghum.

The soil- and crop-specific nature of routine soil assessments of exchangeable K is further illustrated by results from a 5-location, 17-yr experiment conducted in Indiana, USA (Table 1). The non-traditional boundary analysis approach applied to crop yield plotted as a function of soil exchangeable K identified critical levels of 44 to 112 mg kg^{-1} across locations with markedly differing soils (coarse to fine texture, illitic or mixed mineralogy). Further, the more sparsely rooted soybean with its higher K demand tended to require higher critical levels for a given soil. These analyses are preliminary and critical level derivation is on-going using both traditional (relative, annual yields, linear and plateau modeling) and non-traditional (boundary analysis, cubic spline modeling). However, the analyses conducted to date found no apparent value for using cation exchange capacity to explain soil-specific differences in critical levels thereby negating the foundation of the current recommendation that relies exclusively on this attribute (Vitosh et al., 1995). An effective soil covariate to permit accurate, soil-specific test interpretation has yet to be identified, although attributes including fixed K reserves and seasonal rainfall are being explored. Likewise, our analyses show the lack of crop specificity in soil test interpretation to be inaccurate.

Table 1. Soil K critical levels (Coeff.) and their 95% confidence intervals (CI) for corn and soybean grown at 4 experimental locations in Indiana, USA. The relationship between yield and NH_4OAc-exctractable K at a 0-10 cm depth (K_{exch}) was derived from a “boundary analysis” using a linear-plateau model (modified from Navarrete, 2014).

	K_{exch}							
	Corn			Soybean			R^2	
Site	Coeff*	CI**		Coeff	CI		Corn	Soybean
	(mg kg^{-1})							
TPAC	77	72	81	117	104	130	0.80	0.79
SEPAC	44	41	47	57	40	74	0.95	0.49
DPAC	--	--	--	102	84	120	--	0.57
NEPAC	112	97	127	--	--	--	0.84	--

* Mean K_{exch} concentration where yield plateaus
** 95% confidence interval for the K_{exch} coefficient

Conclusions

Current commercially available soil K tests are not adequate to enable a unifying prediction of the plant-available K status across the diverse range of soils supporting various cropping systems, although there is work underway to commercialize soil tests that better characterize slowly available, as well as exchangeable, K pools. Additional soil- and crop-specific complications of differences in the efficiency of diffusive supply and root system characteristics, combined with climatic or seasonal rainfall patterns and root system activity, will ensure that soil test calibration relationships and soil testing methodology remain site-specific.

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What is the potential role of soil classification in soil K assessment and fertilizer recommendations?

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Soil test potassium (K) levels often fluctuate throughout the year and from year to year without apparent cause. In addition, K fluctuations observed in the field often do not correlate with crop response to K fertilization. To explain these fluctuations in soil K, many agronomic studies have focused on relationships between extractable K, moisture conditions, drying conditions, temperature, and soil mineralogy. The inability to understand and predict these fluctuations remains a critical issue in nutrient management. In the mineralogical literature, there is strong evidence that the ability to fix and release K is related to the mineralogy of 2:1 layer silicates and to the oxidation state of iron (Tran, 2012).

The Soil Taxonomy System of Soil Classification groups soils into classes that have similar behavior, use and management, and productivity. The lowest level of classification is the family level, which emphasizes the potential use and management of soils. Differentiating criteria at the family level include particle size classes, mineralogy classes, and cation activity classes. In the US, Soil Taxonomy is the basis for soil surveys, which are made by the National Cooperative Soil Survey. Maps and interpretations are available in various electronic formats with virtual coverage of the entire US. These surveys are typically intended for general agriculture and land use planning and are made at scales ranging from 1:12,000 to 1:31,680. Although soil surveys are not intended to be used for making fertilizer recommendations, they can be used to group and identify soils with potential for K fixation. This would help researchers identify sites for future K fertility trials or help producers and consultants identify soils that need K fertility recommendations designed to compensate for fixation or release.

We propose to use soil surveys to extrapolate mineralogical and K-fixation data for horizons at a specific site to other land areas by developing a procedure that does not make major changes to Soil Taxonomy or require development of new laboratory procedures. This procedure requires recognition of particle size, mineralogy, and cation exchange capacity (CEC) classes and subclasses that exhibit K fixation using data obtained from the USDA-NRCS Soil Characterization Query Interface:
(http://ncsslabdatamart.sc.egov.usda.gov/querypage.aspx).
Particle size classes will need no additional modification and will include all classes and subclasses with clay ≥ 18 %. This will include loamy and clayey particle size classes consisting of fine-loamy, fine-silty, fine, and very fine particle size subclasses.

The existing CEC classes (superactive, active, semiactive, and subactive) will need more work. The procedure will require the measurement of CEC using K as an index cation followed by heating to 110°C in addition to the regular measurement that uses calcium, ammonium, or sodium as the index cation and no heating. Then, a fractional reduction in CEC induced by K saturation and heating is calculated using the method described by Ransom et al. (1988). The % reduction in CEC needs to be added to the USDA-NRCS soil characterization database. Soils with a reduction in CEC greater than about 10% would be classified into a reductive subclass.

Hartley (2010) and Tran (2012) have shown that K fixation occurs with 2:1 layer silicates that commonly weather from mica and that have layer charge occurring in both tetrahedral and octahedral sheets. In general, tetrahedral layer charge favors fixation more than octahedral layer charge, and layer charge is also a function of the oxidation state of Fe in the octahedral sheet (Tran, 2012). The layer silicates known to exhibit K fixation include vermiculite, transitional vermiculte-smectite (TVS) minerals with a layer charge near the threshold of 0.6, and regularly interstratified mica-smectite or mica-vermiculte (RIMS/RIMV). The RIMS/RIMV mineral (Hartley et al., 2014) has also been sometimes referred to as hydrobiotite. The diagnostic basal spacings as determined X-ray diffraction for these K-fixing minerals (shown in bold) are given in Table 1.

Table 1. Diagnostic basal spacings (Å) of Mg-saturated clays following solvation with ethylene glycol (Mg-EG) or glycerol (Mg-GLY) or at room temperature (Mg-25).

Layer Silicate	Mg-EG	Mg-GLY	Mg-25
	------------------------------(Å) --------------------------------		
Mica	10	10	
Smectite (low charge)	17	18	
Vermiculite	**14**	**14**	
TVS	**17**	**14 - 15**	
RIMS/RIMV (Hydrobiotite)			**~ 24**

In order to identify TVS, both Mg-EG and Mg-GLY procedures are needed (Ransom et al., 1988). Most soil characterization laboratories currently use only the Mg-EG procedure.

The mineralogy classes as currently used in Soil Taxonomy need modification for recognition of the K-fixing minerals. Current classes, such as smectitic, are too broad indicating that the mineralogy of the clay fraction is dominated by smectite minerals. In addition, the mineralogy of fine-loamy and fine-silty classes are based on the mineralogy of the sand and silt fractions. Another problem is that the depth used to determine the mineralogy classes usually includes part of the B but not the A horizon. We propose to expand the control section depth to include the A horizon and to add a new k-fixic mineralogy subclass where K fixing minerals exceed approximately 5 – 10 % in the clay fraction, regardless of the particle-size class. Figure 1 shows the depth distribution of minerals in the clay fraction for an Eram soil that meets these criteria for the k-fixic mineralogy subclass.

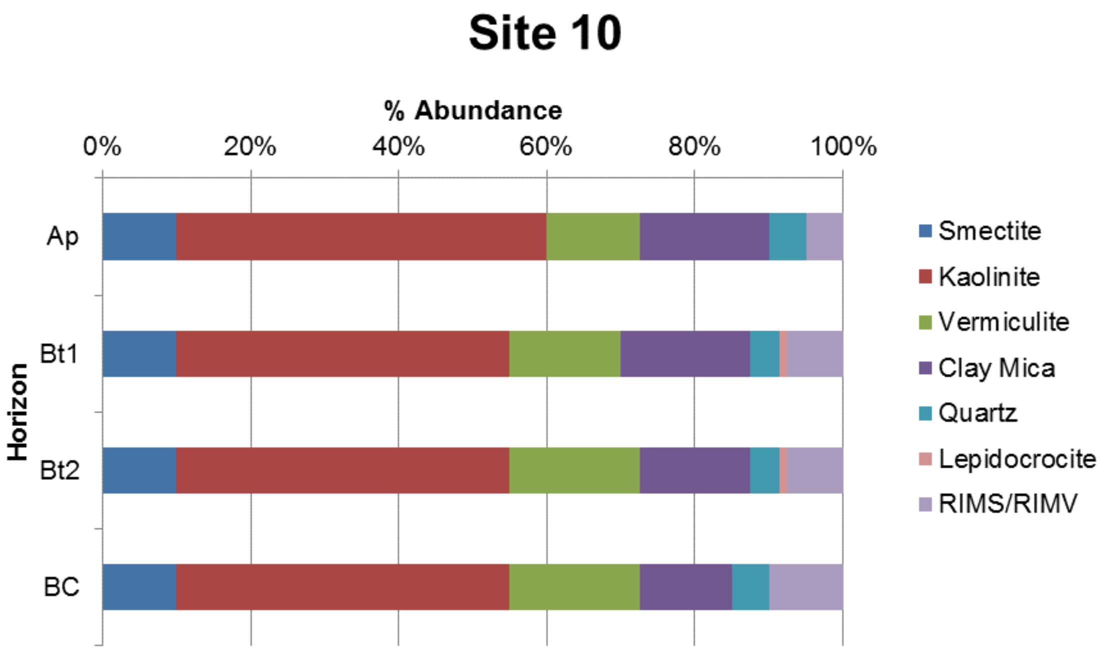

Figure 1. Mineralogy of total clay fraction of an Eram soil sampled in Neosho County, Kansas, USA.

The current family classification is: fine, mixed, active, thermic Aquic Argiudolls. The family classification using our proposal is: fine, k-fixic-mixed, reductive-active, thermic Aquic Argiudolls. Hence, the K-fixing characteristics of this soil are recognized in the mineralogy and the cation exchange activity classes.

Summary

Currently, Soil Taxonomy and soil survey data cannot be used to predict soils with a capability of fixing K. However, the existing system can be modified to recognize K-fixing soils by using particle size, mineralogy, and CEC classes and subclasses that exhibit K fixation using data obtained with USDA-NRCS soil characterization database:

1. Particle size class and subclass
    a. No change is needed
2. Cation exchange activity class and subclass
    a. Include fractional reduction in CEC to standard CEC measurements and report in the USDA-NRCS soil characterization database
    b. Add a reductive CEC subclass for soils with CEC reduction greater than about 10%

3. Mineralogy class and subclass
    a. Use both Mg-EG and Mg-GLY procedures to determine the mineralogy of the clay fraction
    b. Expand the control section depth to include the A horizon
    c. Add a k-fixic mineralogy subclass where the K-fixing minerals (vermiculite, TVS, and RIMS/RIMV) exceed about 5 – 10 % regardless of the particle-size class

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How does redox potential impact potassium fixation and release?

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Potassium (K) in soils occurs in three forms: (1) at low-energy, electrostatic sites where K^+ is readily exchangeable with other cations, (2) at sites of temporary fixation by association with minerals, and (3) in structural positions in primary minerals such as micas and feldspars. In soils where iron (Fe)-bearing, 2:1 layer silicates dominate the clay fraction, potassium availability to plants may be regulated in complex ways by seasonal variability in the redox status of the soil. The potential for significant K fixation by Fe-bearing layer silicates (including high-charge smectite and vermiculite) has been demonstrated in a number of elegant laboratory studies. Thus, it is reasonable to hypothesize that the reduction of mineral-bound Fe could limit K solubility in agricultural soils under saturated conditions. In this scenario, the fixation process could be reversed later in the growing season as the soil drains and oxidizing conditions return. Interestingly, demonstrations that this process contributes significantly to temporary K fixation in soil clays (as opposed to reference clay minerals) are not abundant in the literature.

There are several reasons why redox fixation of K may be difficult to assess. First, redox fixation depends on the abundance of Fe-bearing layer silicates, and these minerals do not occur in all soils, of course. Second, tile-drained agricultural soils may rarely be saturated for periods long enough for redox potentials to drop sufficiently for structural Fe to be reduced and create K^+ fixation sites. Third, where secondary Fe oxides occur in a saturated soil, the redox potential is likely to be poised at a level higher than that required to reduce Fe in silicate structures. Fourth, as redox potentials drop in saturated, acid soils, the pH of the system tends to rise as protons are consumed by concomitant chemical reactions. The rise in pH also increases the abundance of pH-dependent, negatively charged sites that occur in organic matter and at the edges of layer silicate particles. Such low-energy sites may compete with redox sites for K^+ ions. Finally, other mechanisms of temporary K fixation, including fixation at sites of tetrahedral charge near the edges of clay mica particles and entrapment in hydroxy-interlayered vermiculite in acidic soils, may swamp out the impact of redox fixation.

How does the application of other nutrients affect K reactions in soils?

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Application of other nutrients could alter release, fixation, movement and reactions of potassium (K) in soils, but the effects were greatly related to the nutrient types and soil properties. Ammonium could alter K equilibrium in soils more significantly than other cations. Presence of ammonium (NH_4^+) generally increases water soluble potassium, decreases exchangeable potassium in soils, and retards the formation of fixed K in K-added soils or suppresses the release of fixed K from 2:1 type clay minerals in soils. Combined application of NH_4^+ and K^+ could also significantly increase movement of K in soils. Thus the high input of nitrogen fertilizer may enhance the inherent deficiency of K in the soils not only by increasing the K demand of the plant but also by reducing the release of fixed K. While presence of other cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+) and hydronium (H^+) will always facilitate release of fixed K. Application of phosphate such as mono-ammonium phosphate ($NH_4H_2PO_4$) could increase K release from K-bearing minerals in soil which could be explained by the dissolving effect of phosphate on soil minerals. However, when phosphate and K were applied together, the transformation of K in a red soil close to the fertilizer placement site was significantly affected by the addition of monocalcium phosphate (MCP), probably due to the reactions of MCP with aluminum and iron in soil. Analysis of the K amounts in different forms in soil implied that the addition of MCP may reduce the bioavailability of K at the beginning of fertilizer application.

What root-mineral interactions are occurring in the rhizosphere and play a key role in potassium biogeochemistry and plant nutrition?

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The prime function of roots is to take up water and nutrients. Doing so, roots can considerably alter the concentration of nutrients in the soil volume that is influenced by their activity, the so-called rhizosphere (Hinsinger 2004; Hinsinger et al. 2009). For those nutrients exhibiting restricted diffusion capacity such as potassium (K) as well as other major cations, the uptake activity of roots can thereby result in rather steep concentration gradients, with values dropping to the micromolar (µM) range in the immediate vicinity of roots, i.e. two- to three-orders of magnitude less than in the bulk soil. Claassen and Jungk (1982) estimated that soil solution K concentrations were about 2-3 µM close to root surface in the rhizosphere of maize. Such a sharp depletion of K-ions results not only in the diffusion of K-ions over several millimeters from the root surface, but also in a shift of adsorption/desorption equilibria between soil solution K and K-bearing minerals in the rhizosphere. Exchangeable K is thus desorbed in order to replenish soil solution K, ultimately resulting in a depletion of exchangeable K that can extend over several millimeters from root surface (Figure 1).

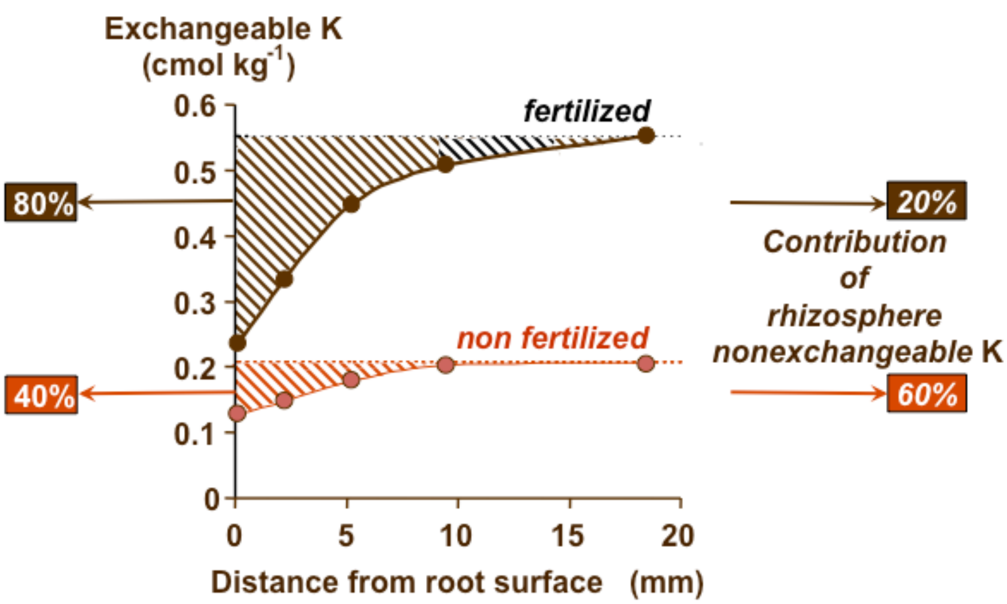

Figure 1. Depletion of exchangeable K in the rhizosphere extends to several millimeters from the root surface within 4 days of plant growth and contributes 40-80% of K uptake by oilseed rape grown in soils of the long-term K fertilizer trial of Gembloux, Belgium (modified from Hinsinger 2004).

Besides a rapid desorption of exchangeable K-ions from the surface adsorption sites of clay minerals, the root-induced depletion of soil solution K can be responsible for a significant release of nonexchangeable K-ions from the interlayers of micaceous clay minerals (illite-like) and primary minerals (micas). Even in the rather short term, this process can contribute a major proportion of K uptake, unless the soil has been heavily fertilized (Figure 1). However, even in such a case, it can contribute a significant percentage of K uptake by plants. Given the high affinity of the interlayer sites of micaceous minerals for K-ions, the release of non-exchangeable K is prevented beyond a critical K concentration of several µM. For instance, Springob and Richter (1998) showed that the rate of release of nonexchangeable K was steeply increasing with decreasing soil solution K concentration below a threshold value of about 3 µM, i.e. about the level of soil solution K concentration that typically occurs close to root surface as a consequence of root-induced depletion of K-ions in the rhizosphere (Claassen and Jungk 1982; Hinsinger 2002). Hinsinger and Jaillard (1993) showed that such root-induced depletion of soil solution K was the driving force for the rapid release of interlayer K in a phlogopite mica and its concomitant transformation into a clay mineral called vermiculite. They showed that as soon as K concentration in the rhizosphere decreased below a threshold value of about 70-80 µM (Figure 2), the weathering of the phlogopite mica became detectable by X-ray diffraction through the appearance of a typical vermiculite peak forming at the expanse of the mica-characteristic peak. This process took only about 2 to 3 days (Hinsinger 2012). In the absence of plants, no significant vermiculite formation was detected. In addition, root-induced acidification and organic ligands (e.g. citrate, oxalate, siderophores) produced by roots or rhizosphere microorganisms can result in proton-promoted or ligand-promoted dissolution of K-bearing minerals such as micas and feldspars (Hinsinger 2012). The contribution of this alternative root-mineral interaction mechanism to plant nutrition is less documented and more difficult to quantitatively assess in the rhizosphere (Hinsinger 2002).

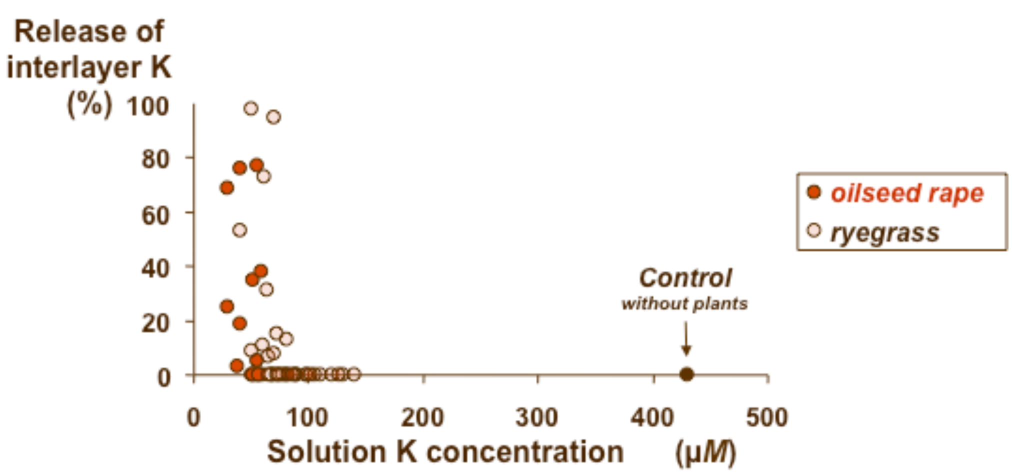

Figure 2. The percentage of release of interlayer K of a phlogopite mica and concurrent weathering to vermiculite in the rhizosphere of oilseed rape and ryegrass sharply increased below a threshold value of about 80 µM (modified from Hinsinger and Jaillard 1993 and Hinsinger 2012).

In agroecosystems, accounting for rhizosphere processes has proven essential to understanding the observed K budgets in long-term fertilizer trials (Hinsinger 2002). In most field trials conducted in Europe, the cumulative K offtake by successive crops in the rotation was much greater than the decrease of exchangeable K in the absence of fertilization (Hinsinger 2002). The rates of release of nonexchangeable K amounted to 11-94 kg K ha-1 yr-1 as an average value computed over the whole duration of these long-term fertilizer trials (Hinsinger 2002 and 2012). The release of nonexchangeable K contributed a major proportion (up to 90%) of K uptake by crops (Hinsinger, 2002), in line with results obtained in short-term pot experiments (Figure 1). Barré et al. (2007) indeed showed that K uptake by ryegrass in a pot experiment was matching the formation of interstratified illite-smectite minerals in the rhizosphere, at the expense of the illite-like clay minerals. Barré et al. (2008) confirmed that K uptake by plants in a long-term K fertilizer trial quantitatively matched the release of nonexchangeable K that was evidenced by the increased amount of interstratified illite-smectite minerals occurring at the expense of illite-like clay minerals. The sink effect of roots and subsequent depletion of soil solution K in the rhizosphere is thus the driving process for the release of interlayer K and concomitant weathering of micaceous minerals in soils (Hinsinger 2002). Plants thereby have a major role in the biogeochemical cycle of K and in the formation and fate of expandable clay minerals (vermiculites or smectites) in topsoils, with illite-like clay minerals playing the role of a large K reservoir in soils. Depending on soil mineralogy, root-induced weathering and release of nonexchangeable K in micaceous minerals can contribute a significant or even prominent proportion of K nutritional requirements of plants, including high-yielding crops.

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To what extent can K efficiency describe differences in crop responsiveness to K additions?

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Potassium (K) is required for plant growth, development and fecundity (Hawkesford et al., 2012). It is the most abundant cation in plants and can contribute up to 10% of a plant's dry weight (Broadley et al., 2004). Many agricultural soils lack sufficient K for the rapid growth of crop plants, and K-fertilizers are, therefore, applied in agriculture (White and Brown, 2010). However, in the interests of agricultural sustainability, it is necessary to optimize the use of K-fertilizers. One strategy to effect this is to develop crop genotypes that achieve maximal yields with less K-fertilizer and also facilitate less K-offtake from the field. The development of such genotypes requires screening for appropriate phenotypic traits. This is often an expensive and time-consuming task, especially if genotypes must be screened at many rates of K-fertilizer application. Thus, there is a need to minimize the number of K-fertilizer treatments required to identify better genotypes. This might be achieved by exploiting the mathematical relationships between crop yield, crop K content and K-fertilizer application.

A crop's agronomic K use efficiency (KUE) can be defined as its yield per unit K available to it (g Y [g K_a]$^{-1}$; White, 2013). This is numerically equal to the product of crop K content (K_{crop}) per unit K available (g K_{crop} [g K_a]$^{-1}$), which is referred to as its K uptake efficiency (KUpE), and yield per unit crop K content (g Y [g K_{crop}]$^{-1}$), which is referred to as its K utilization efficiency (KUtE). Although the values of KUE, KUpE and KUtE vary with K_a, in theory, the dependence of KUE, KUpE and KUtE on K_a can be modeled from measurements of Y and K_{crop} at two (or more) K_a assuming that the relationships between (a) Y and K_a and (b) Y and K_{crop} are both approximated by Michaelis-Menten equations with two parameters: Y_{max}, the maximum yield that can be obtained, and $Km_{(Ka)}$ or $Km_{(Kcrop)}$, the K_a or K_{crop} at which Y equals $Y_{max}/2$ (White and Karley, 2010; White, 2013).

These relationships can be exemplified by measurements of shoot dry biomass (DM) and plant K content of seedlings of barley varieties ('Volla' and 'Prisma') with contrasting responses to K availability grown hydroponically in solutions containing insufficient (10 μM), sufficient (0.75 mM) and excessive (10 mM) K concentrations for plant growth (Figures 1, 2). From the relationship between Y and K_a, the Y_{max} values for shoot biomass of 'Volla' and 'Prisma' were estimated to be 1.578 g DM and 1.534 g DM, respectively, and the $Km_{(Ka)}$ values for shoot biomass of 'Volla' and 'Prisma' were estimated to be 0.238 and 0.032 mM K, respectively (Figure 1a). The values for Y_{max} for shoot biomass and $Km_{(Kcrop)}$ for 'Volla' were estimated to be 1.453 g DW and 5.97 mg K, respectively, and those for 'Prisma' were estimated to be 1.665 g DW and 13.908 mg K (Figure 1b). It is likely that the Y_{max} values for shoot biomass were estimated most accurately from the relationship between Y and K_a. The relationship between K_{crop} and K_a for 'Prisma' could be predicted from the two preceding relationships, but the relationship between K_{crop} and K_a for 'Volla' could not (Figure 1c). The reason for this was the accurate fit of the Michaelis-Menten equation to the relationship between Y and K_{crop} for 'Prisma', but not for 'Volla' (Figure 1b). This illustrates the need to choose K_a wisely when estimating the relationships between Y and K_a and Y and K_{crop} from so few data. The relationships between Y and K_a, K_{crop} and K_a, and Y and K_{crop} can be used to calculate the dependencies of KUE, KUpE and KUtE on K_a, respectively (Figure 2).

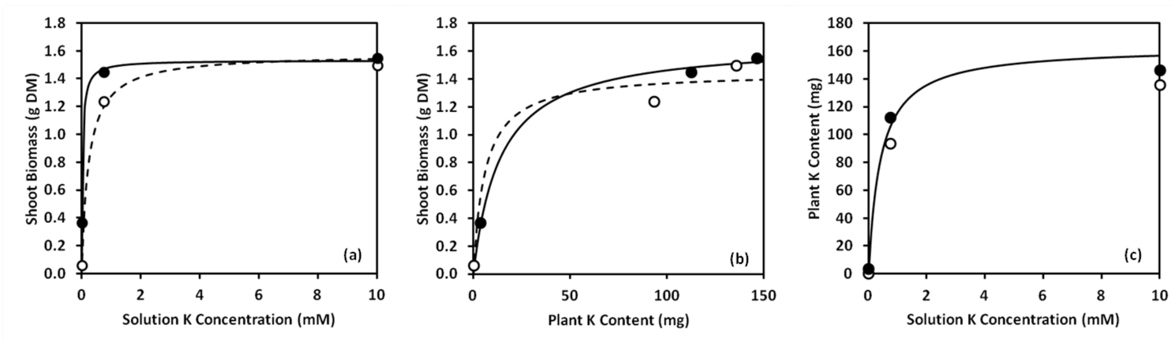

Figure 1. Relationships between (a) shoot dry biomass (Y) and the K available to the plant (K_a), (b) Y and the K content of the plant (K_{crop}), and (c) K_{crop} and K_a. Data are for seedlings of spring barley 'Volla' (open symbols, dashed lines) and 'Prisma' (closed symbols, solid lines) grown hydroponically for 21 days in complete nutrient solutions containing 10 µM, 0.75 mM or 10 mM K^+. Lines show regressions to the data assuming Michaelis-Menten relationships (a, b) or the relationship between K_{crop} and K_a predicted using these regressions (c).

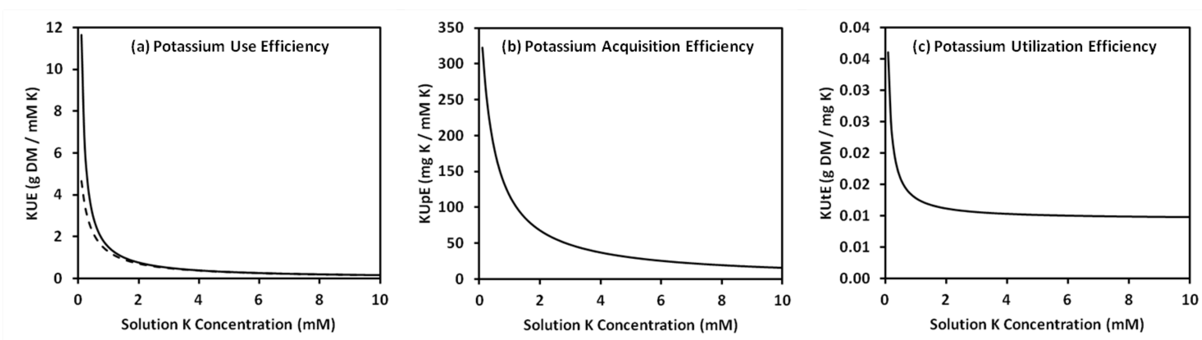

Figure 2. Relationships between (a) agronomic K use efficiency (KUE) and the K available to the plant (K_a), (b) K uptake efficiency (KUpE) and K_a, and (c) K utilization efficiency (KUtE) and K_a calculated from the data shown in Figure 1. Relationships are shown for seedlings of spring barley 'Volla' (dashed lines) and 'Prisma' (solid lines) grown hydroponically for 21 days in complete nutrient solutions containing various K concentrations.

The response to K-fertilizer is defined by the relationship between Y and K_a (Figure 1a), and is commonly expressed as the difference, or quotient, of yield of a K-fertilized crop compared to that of an unfertilized crop. Predictions of the responsiveness to K-fertilizer applications in the field can, therefore, be obtained from the relationship between agronomic K use efficiency (KUE) and K_a (Figure 2a), provided that K_a can be estimated reliably from knowledge of soil properties and their interactions with K-fertilizers and the environment. Physiological insight to the mechanisms underpinning differences between genotypes in their responsiveness to K-fertilizers can be obtained from the relationships between KUpE and KUtE and K_a (Figures 2b, 2c). It can be observed that, provided the relationships between (a) Y and K_a and (b) Y and K_{crop} can be approximated by Michaelis-Menten equations, then the relationships between KUE, KUpE and KUtE and K_a can be estimated from measurements of Y and K_{crop} at a minimum of two K_a. However, the K_a at which these measurements are taken must be chosen wisely (c.f. Greenwood et al., 2006).

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Potassium uptake, crop growth and water productivity: does the distribution of roots and water in the soil profile matter?

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Despite the central role water and roots are thought to play in potassium (K) uptake, the body of scientific evidence supporting this understanding is scant at best. In addition, most experiments measure one or two apparent "drivers" of K uptake, but systematic studies that assess all key factors are few. Because of the inherent challenges in acquiring the data and in their interpretation, there are very few reports of root-K interactions from field trials. However, even relatively easy to measure factors like distribution of water with soil depth are rarely reported; instead, many authors presume that soil water increases with depth. While space does not permit a comprehensive discussion of the interactions among water, roots, growth, etc. in the context of K uptake, we highlight several key findings that can serve starting points for discussion of this important topic.

Where is the water?
There is general agreement that movement of K to roots occurs primarily via diffusion: a process where soil water plays a central role. Though extremely easy and inexpensive to measure, water distribution in the soil profile is rarely reported. Instead it is generally assumed that soil moisture increases with depth in the soil profile. This presumption has spawned numerous, and often unsuccessful, studies aimed at increasing K uptake and yield using deep placement of K. Where positive effects of deep K placement have been reported, some of these experiments have cofounded the effect of deep K placement with the tillage effect of the placement equipment *per se* (Mullins et al., 1994). Surprisingly, when actually measured, soil moisture levels, following canopy closure that reduces evaporation, are often as high or higher in the uppermost depths of the soil profile as compared to deeper soil depths. Fernández et al. (2008) measured soil K and moisture over two years in a soybean field and found that both were high in the uppermost 5 cm of the profile, especially in 2003 (Figure 1). Increases and maintenance of soil moisture in this region of the profile were associated with precipitation events, and this coincided with known periods of rapid K uptake in maize and soybean.

Placing K deep in the profile may impair K uptake if soil water is so low as to limit diffusion. However, sensitivity analysis by Barber (1985) revealed that K uptake was influenced by root traits far more than the diffusion coefficient (D_e) of the system. A clear opportunity exists to explore the interaction of soil water distribution, root distribution, and K uptake given the scant data currently available.

Where are the roots?
Because of the challenges associated with quantification of roots in the field, few studies have been reported the effects of K on root distribution with soil depth. For alfalfa, the uppermost 5 cm of soil has at least twice the root length density (RLD) of any other soil profile segment, and RLD of alfalfa in this study was very low (<2 cm cm^{-3}) below 20 cm (Figure 2). Contrasting rates of P and K resulted in large differences in soil test K in the

0-5, 5-10 and 10-15 cm soil profile increments, but these differences did not impact RLD. Unlike N and P that stimulate localized proliferation of fine roots, localized high levels of K do not appear to enhance root growth (Rengel and Damon, 2008). Important species differences in vertical root distribution in the soil profile also have been reported (Gulick et al., 1989). In this greenhouse study, barley exhibited a RLD distribution similar to alfalfa with very high root densities in the uppermost 12 cm of the soil columns used for pots. Cotton appears unusual in that it has low RLD consistently throughout the soil profile.

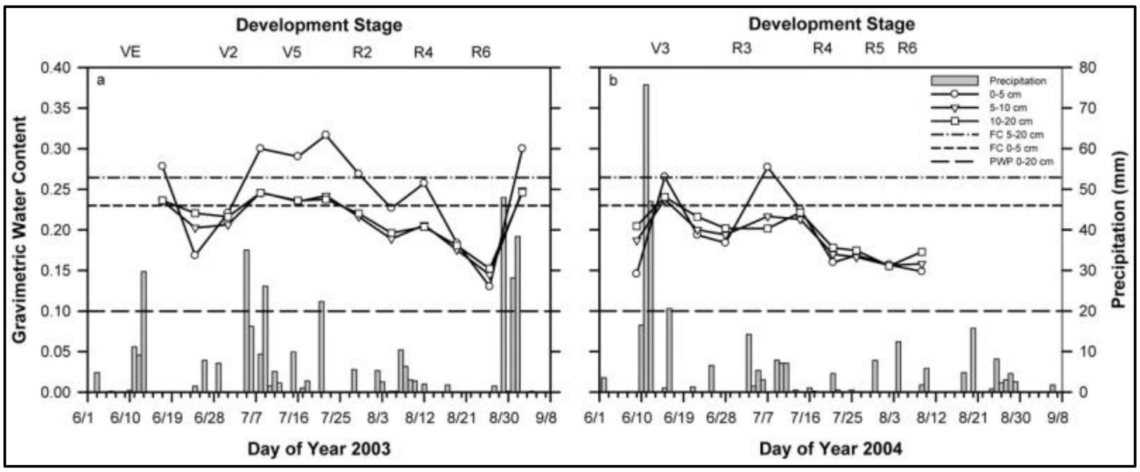

Figure 1. Gravimetric soil water content by soil depth increment in a soybean canopy. Precipitation is shown as vertical bars (Fernandez et al., 2008).

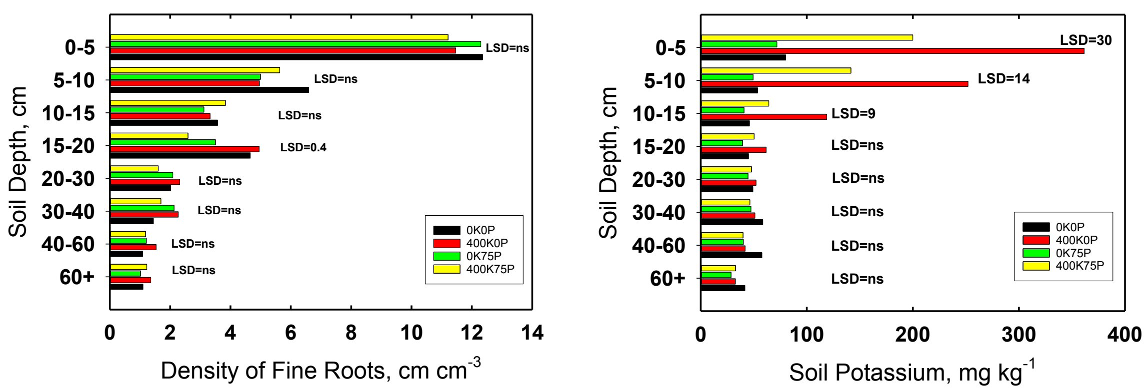

Figure 2. Distribution of alfalfa roots and soil K by soil depth in plots fertilized for 9 years with varied rates of P (0 or 75 kg P ha^{-1}) or K (0 or 400 kg K ha^{-1}). Alfalfa was harvested 4 times per year. The least significant difference (LSD) is provided where F-tests were significant (Evans, Brouder, Volenec, unpublished).

Water, roots and potassium uptake

Given the previous discussion regarding distribution of water and roots in the soil profile, broadcast application of K on the soil surface would potentially place this nutrient in a water-rich environment near roots and result in superior K uptake. Peterson and Smith (1973) tested this concept in a two year-old established alfalfa stand by injecting a K-sulfate solution (224 kg K ha^{-1}) in April at varied soil depths and comparing responses of

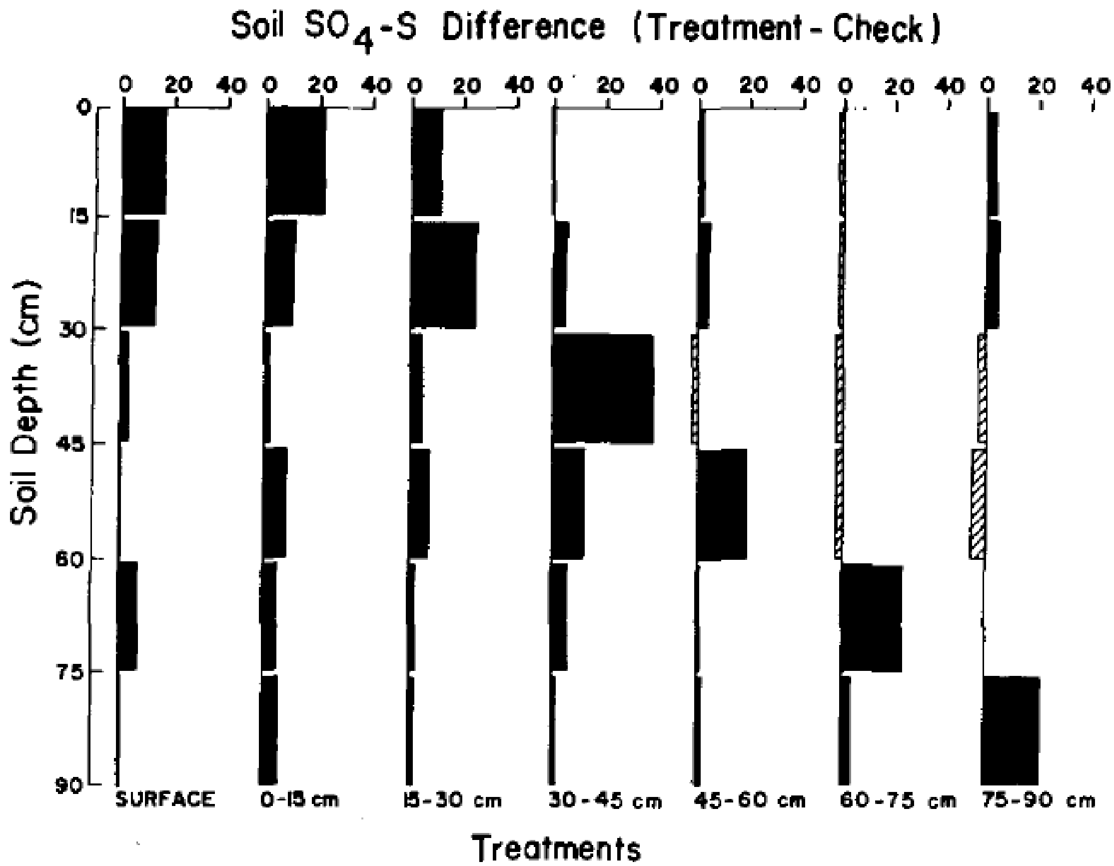

Figure 3. Soil sulfate concentrations at depth increments for various K-sulfate treatments showing the precision of K placement. From Peterson and Smith, 1973.

injected K at depth to surface broadcast K at the same rate. Soil sulfate analysis by depth increment in July verified that the K-sulfate solutions were accurately placed (Figure 3). First-harvest (June) yield and tissue K concentrations were highest for plots receiving broadcast K and declined with placement depth (Table 1). Recovery of applied K ranged from 28% for the surface broadcast treatment to about 4-5% for depths greater than 30 cm. Yield was greatest for the broadcast-treated plots and plots where K was injected at the 0-15 cm depth. Placing the K on the soil surface near the roots and the water (important note-not measured here!) provided the greatest K uptake and yield in this study. Fernández et al. (2011) used a split-pot study to vary spatial K and water distribution for soybean. They concluded that as long as a portion of the root system has access to adequate K, there is no need to have optimum fertility in the entire soil volume. In addition, the full advantage of increasing K was only realized with adequate soil moist-ure in the K-rich part of the profile. Even for cotton with its uniform vertical distribution of RLD described above, it appears that broadcast application of K is superior to deep placement for high K uptake and high yield (Mullins et al., 1994), suggesting that water, more than RLD, may be the key factor influencing K uptake. While these trends look promising, additional field studies are desperately needed where simultaneous collection of soil K and water data are integrated with RLD profiles in the soil in order to understand management and genetic effects on K uptake and K-yield responses of agronomic crops. Also important is separating the positive effect of water on K uptake; is this a diffusion effect for K movement in soil or an effect on root and shoot (the ultimate K sink) growth (see below)?

Table 1. Influence of K placement depth on tissue K concentrations, K recovery, and yield of alfalfa (Peterson and Smith, 1973).

Depth of K Placement	Tissue K	K recovery	Yield
(cm)	(g kg^{-1})	(%)	(MT ha^{-1})
Check, No K	10.7	-	4.46
Broadcast	21.7	28	5.06
0-15	16.5	15	4.93
15-30	14.5	9	4.66
30-45	12.2	4	4.59
45-60	11.6	4	4.73
60-75	12.0	5	4.82
75-90	11.4	-	4.12
LSD	2.6		0.51

Potassium and water use efficiency

It is generally accepted that K has a central role in increasing guard cell turgor that results in stomata opening thereby permitting both CO_2 uptake by leaves via photosynthesis (Ps) and transpiration; the latter plays a key role in mass flow and plant temperature regulation. In addition, Brag (1972) reported that for wheat and pea, adequate K nutrition also was essential for tight closure of stomata and reducing water loss. Thus, because of its impact on both Ps and water relations, K nutrition might be expected to influence water use efficiency (WUE)-the ratio of water transpired:unit of CO_2 fixed into plant dry matter. This ratio ranges from 400:1 in C_4 grasses like maize and sorghum to >1500:1 in alfalfa. Numerous studies have shown that adequate plant nutrition results in better WUE because Ps and yield are increased more than water use (e.g., Chander et al. 2012). Studies probing the specific impact of K on WUE have shown the most benefit of K under drought conditions (Pier and Berkowitz, 1987; Tsialtas and Maslaris, 2006; Grzebisz et al. 2013), but reports showing no impact of K on WUE also populate the literature (e.g., Gulick et al., 1989; Ashraf et al., 2001; Egilla et al., 2005). Varied results likely reflect genetics by environment by management interactions that limit generalized conclusions based on the limited number of studies reported. Nevertheless, water use in agriculture will continue to be very high, and a public concern. It is incumbent on the agricultural community to understand how plant nutrition, including K, can be used to improve WUE.

Potassium uptake and root versus shoot growth

Sensitivity analysis of the Barber-Cushman nutrient uptake model suggested that increases in root length (Figure 4, the “L” parameter) had the greatest impact on maize K uptake (Barber, 1985). However, root growth is not independent of shoot growth, and plants often maintain root:shoot ratios within certain set points. Thus, increases in L are confounded by what are very likely simultaneous increases in shoot growth that were not evaluated in the sensitivity analysis of the Barber-Cushman model. Rapid shoot growth creates a strong sink for K, and this could be as or even more important than L as a driver of K uptake. Peng et al. (2010) concluded that although a large root system and high RLD in the soil profile were beneficial for efficient N acquisition, the amount of N taken up by maize was determined by the shoot growth potential, and not by the root size. This conclusion that sink strength regulates N uptake likely extends to other macronutrients. Al-Khafaf et al. (1989) measured plant growth rates and macronutrient uptake rates during wheat growth in soils columns with varied amounts of top- and sub-soil. They reported that rates of dry matter accumulation of wheat mirrored uptake rates of N, P, and K. For K specifically, 60% of the variation in K uptake rate was accounted for by differences in plant growth rate (Figure 5; adapted from their Figure 7). While analysis of soils and roots are important to understanding regulation of K uptake, placing this knowledge in the context of shoot K use and sink strength may inform K uptake in ways not explored previously.

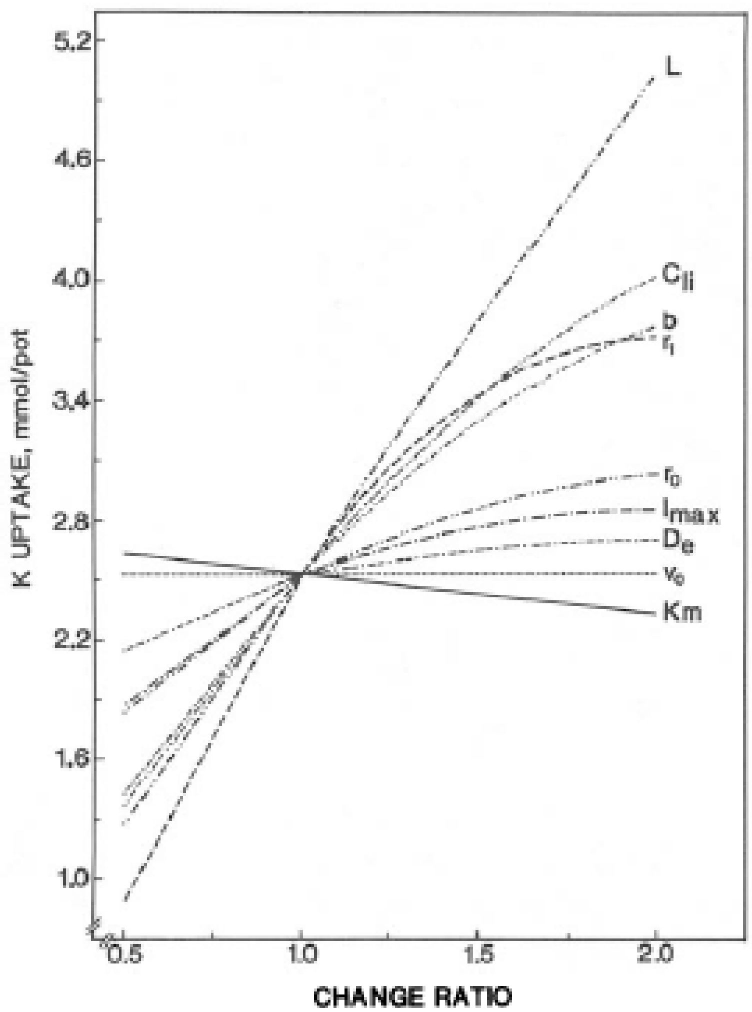

Figure 4. Sensitivity analysis of parameters influencing K uptake as predicted by the Barber-Cushman model (Barber, 1985).

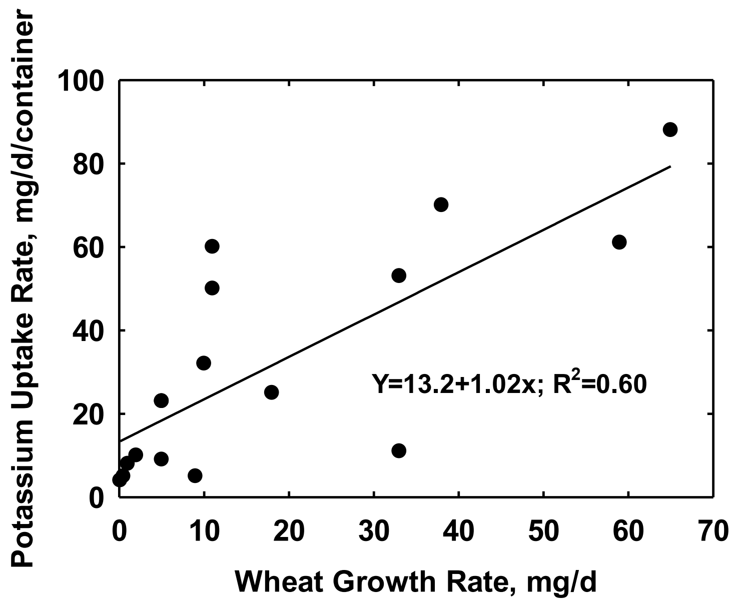

Figure 5. Relationship between wheat growth rate and K uptake rate. Plants were grown to maturity in pots that contained varied depths of high-fertility topsoil over low fertility subsoil (adapted from Al-Khafaf et al., 1989).

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Short-Term Potassium Recycling from Crop Tissue and Soil-Test Temporal Variability

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Research has shown high temporal soil-test K (STK) variation following the harvest of a grain crop, which could be explained by several factors. Since plants contain potassium (K) mainly in its ionic form or soluble inorganic salts, it could be easily released to soil by rainfall and during residue decomposition. Scarce previous research, mostly with other crops, suggested that the short-term K recycling from crop residue can be significant and could influence STK values. We recently investigated the K uptake by corn and soybean, K loss from plant tissues, and impacts of K loss from crop residue on short-term temporal variation (Oltmans and Mallarino, Soil Sci. Soc. Am. J., in press). Here we summarize results for K loss from plant tissue and impacts on STK.

Aboveground plant samples were collected from 19 Iowa K field-response trials that encompassed 12 soils series. The trials were evaluated from one to four years (33 site-years total for corn and 14 for soybean). Dry matter yield and K accumulation were measured in vegetative tissues at physiological maturity (PM) and in crop residue four additional times until the following spring (a five- to six-month period). Soil-test K was measured in the fall of each year, one to ten days after grain harvest (late September to the middle of October), and also in the following spring before planting the next crop (in early April) but only in the last two years of the study.

On average across K fertilizer treatments and sites, soybean accumulated 68 and 34 kg K ha^{-1} in grain and residue, respectively, whereas corn accumulated 29 and 52 kg K ha^{-1}, respectively. The K accumulation increase from K fertilization was much greater in residue than in grain, both at sites with or without a grain yield response to K (on average 60 and 9% for soybean and 57 and 7% for corn, respectively). Therefore, the amount of K in crop residue that can be recycled to the soil was greater in corn than in soybean.

The amount of K in corn and soybean vegetative plant tissue (excluding K in grain) decreased from PM until spring of the following year, and the rate of decrease was influenced by precipitation. Figure 1 shows mean results for each crop across all site-years for two fertilization rates. The greatest K loss from crop tissue occurred: 1) between PM and grain harvest, which can be can be attributed to K leaching from the plant and also leaf drop; and 2) from harvest to late fall (when soils froze and snowfall began). There were smaller additional K losses from soybean residue during winter to early spring, but significant additional losses from corn residue. In soybean, 43% of the K accumulated in vegetative tissues at PM remained in residue by early December, and only 12% remained by early April. In corn, however, 67% of the K accumulated in vegetative tissues at PM remained in residue by early December, and 31% remained by early April. Figure 2 shows that increasing precipitation decreased K remaining in tissues

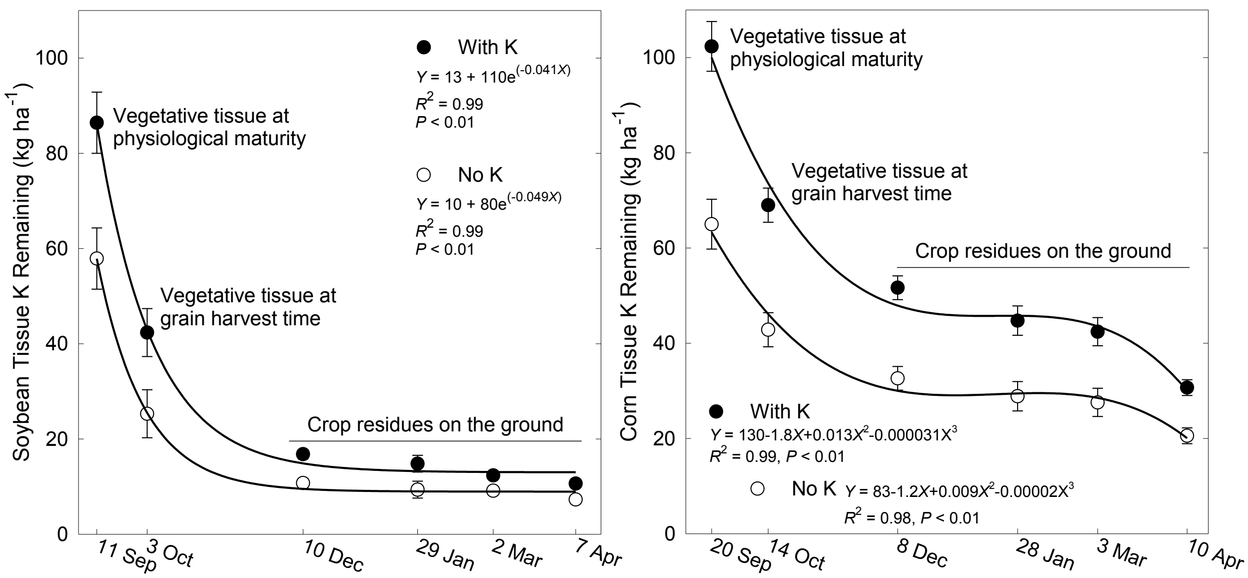

Figure 1. Potassium accumulation in soybean and corn vegetative tissues or residues over time for two K treatments (means across 14 site-years for soybean and 33 site-years for corn). Vertical lines indicate confidence intervals (P = 0.10).

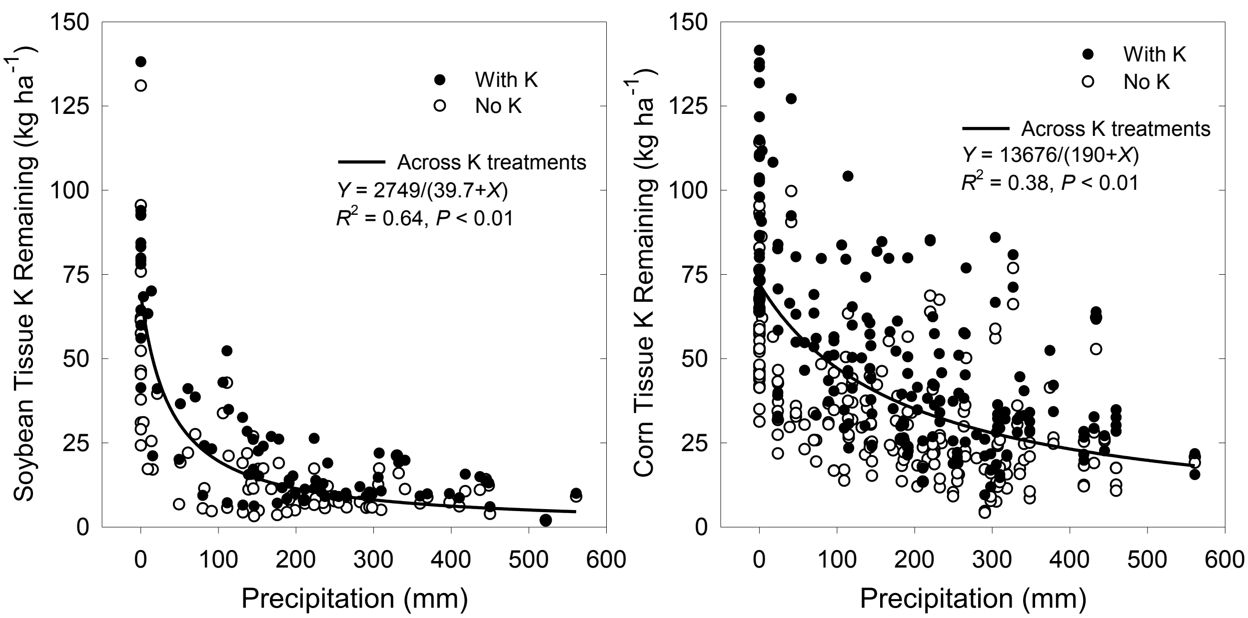

Figure 2. Relationship between the K remaining in soybean and corn vegetative tissue or residue and precipitation across all site-years and sampling periods.

exponentially to a minimum across all site years, although the unexplained variation was high mainly for corn. With a similar amount of precipitation, more K was lost from soybean tissue than from corn tissue. The difference between crops might be explained

by the type of plant material (stalks in corn, where the majority of K accumulates), the amount of residue (about double in corn), and the particle size (coarser for corn).
Soil-test K often (but not always) increased from fall to spring. The STK difference was linearly correlated with the amount of K lost from residue from harvest to spring across all site-years sampled and both crops (0.44 mg K $(kg\ soil)^{-1}$ per kg of K lost). There was large unexplained variability ($r^2 = 0.27$), however, mainly in plots with corn residue. The crop should not make much difference once the K is lost to the soil, so a lower variability in soybean might be explained by earlier K loss and lower sampling error due to the type and distribution of residue.

Results strongly suggest that K recycling from residues as affected by precipitation can partly explain short-term temporal STK variability and its consideration would improve the value of soil testing for K. Unmeasured changes among soil K pools also could partly explain observed differences between fall and spring, so ongoing research is studying all these processes in the same field plots.

What are the unique attributes of potassium that challenge existing nutrient uptake models?

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Soil potassium (K) availability and acquisition by plant root systems are controlled by complex, interacting processes that make it difficult to assess their individual impacts on crop growth. Mechanistic, mathematical models provide an important tool to enhance our understanding of these processes and can enable better management of crop K nutrition (Barber, 1995). Current mechanistic models describe soil K supply by mass flow and diffusion to root surfaces. Root absorption of K follows Michaelis-Menten kinetics. Root growth rate is considered; however, model calculations have generally been based on a single, cylindrical root, rather than a three dimensional root system. Recent advances have allowed for consideration of water and nutrient uptake by root hairs and mycorrhizal hyphae (Roose and Schnepf, 2008). Advances have also been made in coupling root architectural models with models of soil processes (Dunbabin et al., 2013). These approaches move toward the goal of simulating root growth and function in response to heterogeneous soil water and nutrient availability.

Under optimal conditions, existing models can adequately calculate K uptake by growing roots. Problems generally arise when a biotic or abiotic process affects root system function, thus violating the assumptions built into the models (Barber, 1995). For example, research suggests that root exudates can mobilize soil K or influence release of non-exchangeable K (Hinsinger, 2012). Working with the NST 3.0 model (Claassen, 1994), Samal et al. (2010) found that calculated and measured K uptake by maize (Zea mays L.), wheat (Triticum aestivum L.), and sugar beet (Beta vulgaris L.) grown in a silty clay loam soil (Typic Argiaquoll) generally agreed when soil K supply was high (Table 1). Under low K supply, however, K uptake was under-predicted for all three crops, with prediction being the poorest for sugar beet at only 31% of measured uptake. Using sensitivity analyses to explain the results, Samal et al. (2010) speculated that chemical mobilization of K by root exudates may have increased rhizosphere solution K concentrations. The authors concluded that better measurements of K in rhizosphere solution around the root and root hair surfaces, as well as better estimates of K uptake kinetics for root hairs, are needed.

Because K is an important macronutrient, plants must be able to adjust their uptake systems rapidly to a varying supply, so that growth and development are maintained. Potassium uptake by roots has been described in classical experiments as a biphasic process (Epstein et al., 1963) with both a high-affinity system operating at external K concentrations less than 1 mM, and low affinity system operating at higher external K concentrations. However, internal, i.e., tissue, K concentrations also regulate K influx (Siddiqi and Glass, 1982). Hence, the parameters (Imax and Km) within the models that describe the relationship between external K concentration and K influx (Barber, 1995) will change with varying internal K concentrations. This makes it very difficult to accurately determine K influx parameters for roots growing in soils with heterogeneous solution K concentrations.

Table 1. Measured and calculated root K influx of maize, wheat, and sugar beet grown on a low K soil with (+K) and without (0 K) K fertilization (250 mg kg^{-1}). Modified from Samal et al., 2010.

		K influx		
Crop Species	K level	Calculated	Measured	Calc. / Measured
		------- (10^{-7} µmol cm^{-1} s^{-1}) ------		
Maize	0 K	1.27	1.99	0.64
	+K	4.33	3.87	1.12
Wheat	0 K	1.77	2.59	0.68
	+K	3.90	3.22	1.21
Sugar beet	0 K	2.64	8.45	0.31
	+K	15.10	19.00	0.80

Further, many functions of K within plant tissues and organs are at least partially substitutable. Potassium has a predominant role in osmoregulation and in maintaining cation-anion balance within cytoplasm, and these functions can be partially replaced by other cations and/or organic compounds. It is understood that a wide range of solution K concentrations affects the uptake kinetics of K, but the effects of substituting ions on the uptake process are not well understood. Such substitutions pose significant challenges to mechanistic representation of plant demand, especially K uptake kinetics.

Upscaling from a single root to whole-plant or field scales also presents challenges. Roots do not grow uniformly in soil. Moreover, resources, such as water and K, are not evenly distributed in the soil profile. However, the spatial and temporal scales of the rhizosphere and the root system are sufficiently different that they can be treated separately, which simplifies the modeling effort (Darrah et al., 2006). ‘Upscaling’ to predict uptake at the whole-plant level by integrating individual fluxes requires a measure of the growth and senescence of the root system. Root architecture models are increasingly successful in providing this (Dunbabin et al., 2013).

The modeling approach of Schnepf et al. (2011) illustrates the capabilities of a current structural-functional root architecture model (Figure 1). The model of Leitner et al. (2010) was used to investigate phosphorus (P) uptake and soil P depletion as affected by maize root system development and architecture. Results demonstrated that chemotropism, i.e., stimulation of root growth by soil P, enhanced P uptake by the root system, as well as P depletion from the soil. In this example, soil water movement and upscaling of single-root traits, such as exudates, were not considered.

Soil water movement would be important for K uptake, because as roots absorb water, rhizosphere soil dries, so that K diffusion to root surfaces decreases. Although depletion of water around roots has been modeled (Javaux et al., 2008), at this point, the effect on K supply has not has been investigated (Zed Rengel, 2014, personal communication).

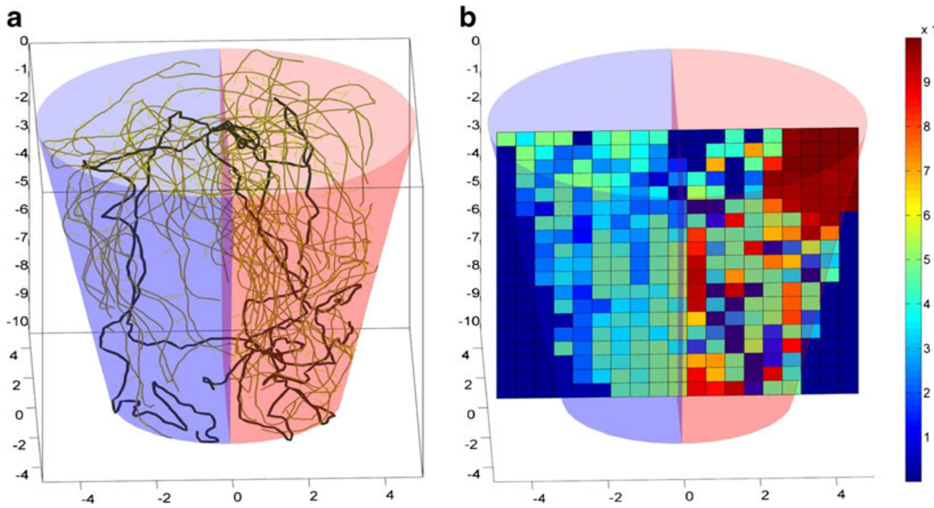

Figure 1. Maize root system development (a) and soil inorganic phosphorus (P) depletion (b) after 20 days as simulated by the Rootbox model. Initial P concentration in the right half of the pot was 1 x 10^{-4} µmol cm^{-3} versus 0.5 x 10^{-4} µmol cm^{-3} on the left, resulting in a denser root system in the right half. Phosphate uptake was computed by averaging the P influxes into the root segments. Modified from Schnepf et al. (2011).

As demand for food, feed, and fiber increases, and climate change affects productivity, improved understanding of crop K nutrition becomes more important. Quantitative mechanistic models can help us advance, but upscaling from a single root to full-season crop growth requires thoughtful adaptation of existing crop growth and nutrient uptake models.

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How can K nutrition be incorporated into decision support systems and production simulators like APSIM and DSSAT?

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Background

The difficulty in modeling the behavior of potassium (K) and phosphorus (P) in soils is that there are often multiple pools of different availability. Release rates from these pools to the soil solution are initiated by depletion of the soil solution nutrient concentration, but release processes from the various pools are different (e.g. sorption/desorption or precipitation/dissolution for P, and rapid or slow exchange or dissolution of minerals, for K). The rates of release will vary for each pool in each soil type, and are influenced by soil characteristics like buffer capacity.

Additional complexity is introduced when dealing with nutrients like P and K that are (effectively) immobile in most soils. Crop uptake is therefore dependent on nutrient distribution within the soil profile and crop root distribution and activity in response to environmental (soil moisture) and management (tillage, fertilizer application methods) factors.

Examples of complexity

We present two examples of the types of complexity encountered with (a) the response to applied K by different crops in a rotation sequence in the field and (b) the effect of soil type and associated soil K pools on the quantum and rate of K release to plants in a pot trial.

In the first example, a field trial was established on an alkaline Vertisol with low available P and marginal available K in the subsoil layers (10-30 cm) at a site where zero tillage was practiced. Bands of fertilizer supplying 40 kg P ha^{-1}, 100 kg K ha^{-1} or a combination of both nutrients (supplied as mono-ammonium phosphate (MAP) and muriate of potash (MOP), respectively) were applied in bands 50 cm apart and at a depth of 20 cm in May 2011. Differential nitrogen inputs were corrected with urea and the site was then sown to crops of sorghum (2011/12) and chickpea (2013). The grain yield and K uptake data are shown in Figure 1a below, and there are two key findings: (i) both crop species were able to increase K uptake in response to K application, but there was also evidence of increased K concentration and uptake with application of MAP, perhaps because of improved root activity; and (ii) despite the increased K acquisition, only grain yields of chickpeas responded positively to K application, with the latter crop not able to respond to P until K had been supplied. The reason for these apparent species differences may be related to root system characteristics or seasonal conditions, and these interactions need to be better understood if decision support tools are to be developed to aid producers and advisors make K fertilizer decisions.

The second example is from an exhaustive K depletion assay conducted on 24 soils with differing K contents and distributions of K between exchangeable and non-exchangeable K pools. This study was conducted in the glasshouse using repeated harvests of above-ground biomass of forage sorghum, with biomass production and K removal of each soil related to these parameters from equivalent soil with fertilizer K applied. Relative dry matter yield (nil applied K/+K) and shoot K uptake were calculated for each harvest. Severe K deficiency prevented plant regrowth in all but 7 K-unfertilized soils by the fifth harvest. Results from three soils (two Vertisols and an Oxisol) with low initial exchangeable K (0.13-0.21 cmol(+) kg^{-1}) but differing tetra-phenyl borate extractable K (TB-K - Moody and Bell 2006, indicating different sizes of the non-exchangeable K pool) are presented in Figure 1b. Key points illustrated from this study are: (i) the Vertisol with mineral K reserves was able to maintain plant growth, albeit at a low relative yield, for four harvests whereas plants had died from extreme K deficiency in the two soils with no mineral K reserves after H3; (ii) in the absence of mineral K, the more efficient diffusive supply process in the well-structured Oxisol resulted in more rapid and complete exhaustion of exchangeable K at the time of plant death (100% vs. 85% of initial exchangeable K) than in the shrink-swell Vertisol; and (iii) slowly available mineral K was able to make a significant contribution to plant available K in the Vertisol in which reserves were present, indicating substantial buffering of soil solution K by dissolution of soil K minerals. In this soil, cumulative plant removal represented >140% of initial exchangeable K but was approximately 100% of initial TB-K.

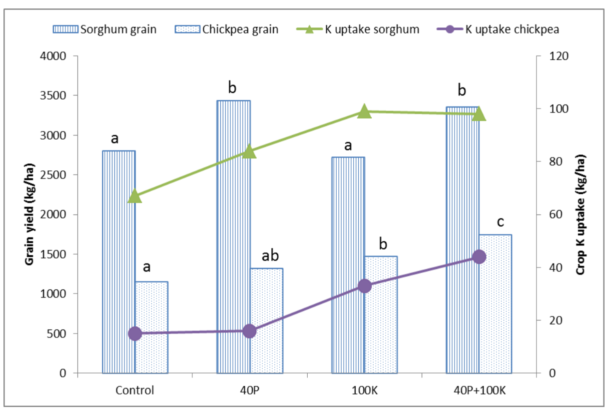

Fig. 1a. Yield (represented by columns) and crop K uptake (lines) in response to P and K fertilizer application for consecutive sorghum and chickpea crops on a Vertisol in Queensland, Australia.

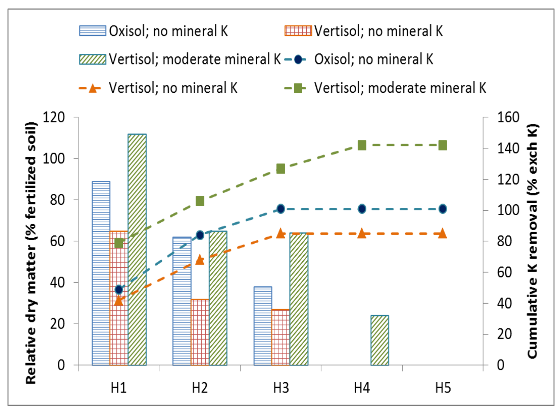

Fig. 1b. Relative dry matter production (% treatment with K fertilizer applied) (represented by columns) and cumulative K removal (lines) over five harvests of forage sorghum grown on three soil types

Conceptual framework on which to base DSS development for K

Current attempts to simulate dynamics of immobile nutrients like P and K typically (e.g., the P module in APSIM) consider only one pool of nutrient and a single supply process (e.g. sorbed P pool and sorption/desorption reactions). These simulators, and any developed for K, will need to have the capability of modeling several pools based on conceptual supply frameworks. Parameterization will require the quantity of nutrient in each pool and the rate coefficients describing the movement of nutrients between pools and the soil solution. An illustration of what we consider to be the key pools and dynamic processes affecting soil solution K and (potential) crop K acquisition are shown in Figure 2 below.

Models will also need a sophisticated capability to describe the distribution and uptake efficiency of crop root systems of different species grown in rotations, how those roots proliferate in amended soils (i.e., root response to banded applications) and the effects of fertilizer form on distribution of added nutrient into the various pools and on rhizosphere characteristics like pH that can alter rates of dissolution.

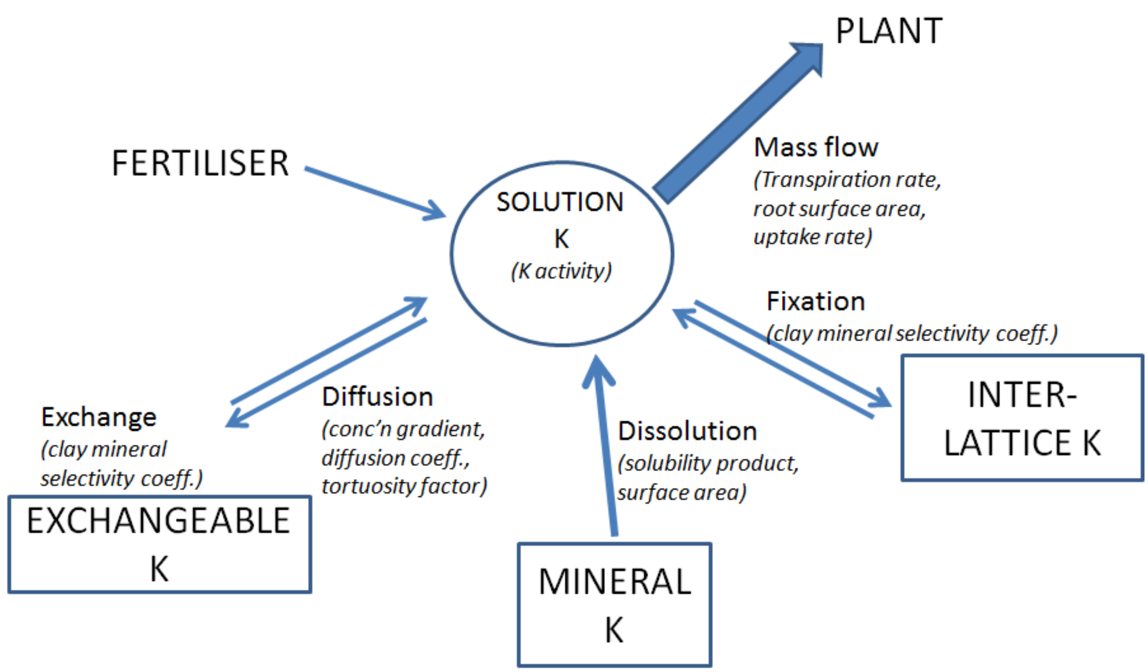

Figure 2. Conceptual framework for understanding K dynamics and availability in soils. The key pools, processes and rate factors that will need to be quantified are indicated.

Collectively, development of such tools that are effective across soil types (characterized by different K pools and supply processes), environmental conditions (e.g. rainfed vs. irrigated) and cropping systems (different species with contrasting root systems) are challenging because, particularly with regard to root system behavior, they highlight our limited understanding of the interacting processes affecting acquisition of immobile nutrients like K.

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