**FINAL REPORT to CALIFORNIA DEPARTMENT OF FOOD & AGRICULTURE**
**Period of Work: January 1, 2011-June 30, 2014**

**Project Title: Relationship of soil K fixation and other soil properties to fertilizer K rate requirement (project 10-0012-SA)**

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## OBJECTIVES

1. Determine the rate of K fertilizer required to achieve sufficiency levels (yield not K limited) in both K-fixing and non K-fixing soils.

2. Relate K fertilizer responsiveness of soil profiles for regional model categories (O'Geen et al., 2008). The model groups soils by K fixation potential, landscape location, and geology.

3. For the 1-hour K-fixation potential soil method, determine the effect of sample wetting and drying and sequential K-additions.

4. Provide research summaries and K fertilization recommendations for K-fixing soils to crop management professionals, analytical laboratories, and growers.

## ABSTRACT

Potassium fixation – conversion of soluble and exchangeable K (XK) to non-exchangeable forms – has been identified as a possible source of concern for managing fertility in granitic soils in the San Joaquin Valley of California. Previous work in our laboratory has demonstrated that vermiculite in the silt and fine sand fraction is predominantly responsible for observed K fixation in these soils. We have undertaken several projects to illuminate the properties of K-fixing soils and to relate laboratory measurements to fertilizer K rates required for crop production. Additions of K equal to the measured capacity of the soil to fix added K fertilizer (Kfix), followed by moist incubations of varying lengths demonstrated that added K is fixed quickly, and that some K fixation potential persists after additions, with drying after incubation increasing final Kfix values. Incremental additions of K at multiple rates up to an amount equivalent to the soil CEC provided estimates for maximum K fixation capacity of the soils, with

increasing efficiency of recovery by extraction of exchangeable K and by another more intensive method, tetraphenyl boron (TPB) as rates increased. Roughly half of fixed K was found to be plant-available by the TPB method. A single air drying event was found to increase measured Kfix values by about 50 mg $kg^{-1}$ for K-fixing soils, but effects of drying on XK was less consistent. Multiple cycles of wetting and drying did not further enhance the effect of a single drying event on XK, Kfix, or TPB-K values. Soil profile (to depths of 90-170 cm) weighted mean XK and Kfix levels differed greatly from values for surface samples, with profile mean XK lower than, and Kfix values were higher than for the surface 10 or 20 cm. A greenhouse pot experiment with annual ryegrass (*Lolium multiflorum*) fertilized with multiple K rates was used to determine critical K values for the XK and TPB-K methods. K fixation potential of the soils in the greenhouse study was in some cases significant in reducing the impact of added K, but in other cases did not appear to play a significant role.

## INTRODUCTION

Soils of the Central Valley and bordering uplands display a wide range in the properties that determine K fertilizer requirements. Soil K fixation, which is associated with persistent crop K deficiencies, is found in some soils on the east side of the Central Valley that are derived from granitic parent material and contain the silicate layer mineral vermiculite. During the past 40 years, UC researchers have demonstrated the significance of K fixation for cotton and processing tomato production in the Central Valley (Miller et al., 1997; Hartz et al., 2008). In a UC field experiment (Cassman et al., 1989), 86% of the 1540 lb K2O/acre applied in a 3-yr period was fixed beyond extraction by $NH_4^+$, and cotton plants remained marginally deficient.

We expanded on previous UC research by investigating the relationship between soil mineralogy and K-fixation behavior in San Joaquin Valley soils used primarily for cotton production. Important findings were the dominant role of silt and fine sand fractions in K-fixation in soils in our study that were derived from Sierran granites (Murashkina et al. 2007b) and the observation that some soils that contain little vermiculite fix K, probably due to the presence of tetrahedrally substituted smectite (Murashkina et al. 2008). More recently, we have identified soils with high K fixation potential in winegrape vineyards in the Lodi district. Research supported by the Lodi Winegrape Commission is in progress to determine whether higher rates of K fertilizer are needed on K-fixing vineyard soils in that district than on non K-fixing soils.

Although several UC researchers have examined K fertilizer responsiveness in K-fixing and non K-fixing soils (Cassman et al., 1990; Cassman et al., 1992; Gulick et al., 1989), additional work is needed to develop practical laboratory methods for determining the K fertilizer requirements of such soils. We have developed a 1-hr incubation method for measuring soil K fixation potential (Murashkina et al., 2007a). Other researchers have shown that a modified version of an older test -- sodium tetraphenyl boron, $NaBPh_4$ -- is useful for estimating the portion of fixed K that is plant-available (Cox et al., 1999). To be useful to growers in California, these tests must be correlated with K fertilizer response. In research funded by the California Department of Food & Agriculture

Fertilizer Research & Education Program, we are using soils previously collected from the Lodi winegrape district and San Joaquin Valley cotton fields to determine whether our regional model categories (O'Geen et al. 2008) are informative with respect to K fertilizer requirement and whether the two analytical procedures described above predict the rate of K required to achieve sufficiency levels.

## WORK DESCRIPTION

### Soils

Soil samples from 18 pedons and a total of 52 depth increments were used. These combined freshly collected bulk and field moist samples along with materials previously collected, from twelve wine grape vineyard locations, two cotton fields, one alfalfa field, and three almond orchards in the Central Valley of California. Samples were screened to 2 mm and generally stored air-dried, with a subset of samples sealed in plastic bags and stored under refrigeration at field moist water content. Fields with a history of large K fertilizer applications were excluded from the study. Selected soil properties are shown in Table 1.

### Soil analytical procedures

<u>K fixation potential (Murashkina et al., 2007a) (Kfix)</u>
Soil K fixation potential procedure: Three g soil samples were shaken in 30 mL of 2 mM KCl for 1 h followed by extraction for 30 minutes with 10 mL 4M $NH_4Cl$. Following centrifuging, K in solution was measured by flame emission using an atomic absorption spectrophotometer. K fixation potential was calculated as the difference between a without-soil blank and the measured K solution concentrations in triplicate subsamples. Results are expressed as mg K fixed per kg soil, but can also be expressed as percent of initial solution K removed from the solution by fixation.

<u>Hartz K fixation potential (Hartz et al., 2002) (Kfp)</u>
3.00 mL of 10mM $KNO_3$ was added to 3.00-3.05 g of soil, followed by air drying. 30ml of 1M $NH_4Cl$ were added, and samples were shaken for 30 minutes, followed by immediate centrifugation. A second set samples was prepared following the same procedure, but with no added K. K was measured by AA flame emission, and added K not recovered was assumed to have been fixed (Kfp = no enrichment + added – enriched).

<u>Ammonium acetate-extractable K (Soil Survey Staff, 2004) (XK)</u>
2.5-3 g soil were saturated and extracted overnight with 1 M $NH_4OAc$ (pH 7) using a mechanical vacuum extractor, and K was determined by flame emission spectrometry.

<u>Sodium tetraphenylboron-extractable K (Cox et al. 1996, 1999) (TPB-K)</u>
1 g soil was extracted without shaking for 5 minutes with 3 mL of extracting solution (0.2 M NaTPB + 1.7 M NaCl + 0.01 M EDTA). 25 mL of quenching solution (0.5 M NH4Cl + 0.11 M CuCl2) was then added, and samples were heated, then boiled for 30-45

minutes to dissolve the resulting precipitate. Samples were shaken by hand and then filtered. Solutions were analyzed for K by flame emission using an atomic absorption spectrophotometer.

Aqua regia Total K (Rajashekhar Rao et al., 2011) (TotK)
0.500 g soil (ball milled to 80 mesh) was weighed into 100 – 250 mL glass beakers, to which 12 mL of aqua regia (3 parts concentrated HCl mixed with 1 part concentrated $HNO_3$) were added. Samples were covered with a watch glass, digested on a hot plate at 110° C for 3 hours, and allowed to evaporate to near dryness. 20 mL of 2% nitric acid were added followed by gently swirling to mix, and filtration through Whatman 42 filter paper into a 100 mL volumetric flask. Samples were brought to volume with DI and K K was determined by AA flame emission.

Tissue K (Miller, 1998)
200.0 ± 3.0 mg oven-dried plant tissue (ground to 40 mesh) was extracted with 50.0 ± 0.2 mL 2% Acetic Acid, placed on a reciprocating mechanical shaker for 30 min. Samples were filtered K was measured by AA flame emission.

**Work directed to Objective 1**
Task: Incremental K additions – completed 8/1/2012
Subtask: Application of K equal to 2x Kfix values in solution at 25% water content
Subtask: Moist incubation for 24 hours, followed by air drying
Subtask: Analysis of XK, TPB-K, and Kfix on subsamples
Subtask: Repetition of K addition, incubation, drying and analysis for 4x, 6x, 8x Kfix, and 1x CEC rates

Task: Greenhouse pot study – completed 6/15/2014
Subtask: Collection of bulk soil samples
Subtask: Soil preparation by mixture with quartz sand, addition of soluble and controlled-release N and P, and K at rates of 0, 50, 250, and 1000 mg $kg^{-1}$
Subtask: Greenhouse trial, growing annual ryegrass from seed with clippings at 1 cm above soil surface at 3, 6, and 9 weeks after germination
Subtask: Measurement of oven dry biomass (yield) and uptake (Tissue K)

**Work directed to Objective 2**
Task: Data analysis – mean weighted soil profile exchangeable K and K fixation capacity of soils representing regional model categories -- completed July 31, 2014

**Work directed to Objective 3**
Task: 16 day K incubation – completed 6/1/2011
Subtask: Application of K equal to Kfix in solution at 25% water content
Subtask: Incubation with K for 1, 2, 4, 8, and 16 days
Subtask: Air drying of subsamples
Subtask: Analysis of moist and air-dry samples for XK, TPB-K, and Kfix

Task: Multiple cycles of wetting and drying – completed 10/3/2011
Subtask: Application of K equal to Kfix in solution at 25% water content
Subtask: Incubation with K for 24 hours
Subtask: Air drying, and analysis of subsamples for XK, TPB-K, and Kfix
Subtask: Re-wetting with DI to 25% water content
Subtask: Repetition of drying, analysis, and re-wetting for a total of four cycles

Task: 4mM Kfix method trial – completed 10/21/2011
Subtask: Measurement of Kfix modifying method to double added KCl to 4mM

Task: Field Moist vs Air Dry soil K measurements – completed 8/20/2013
Subtask: Collection of field moist soil samples
Subtask: Sample preparation, screening and removing subsamples to air dry
Subtask: Measurement of Kfix and XK on field moist (FM) and air dry (AD) materials

Task: Comparison of Kfix to Hartz Kfp method – completed 5/20/2014
Subtask: Measurement of Kfp by Hartz method

**Work directed to Objective 4**
See outreach activities summary

**DATA/RESULTS**

A brief description of the soils used in the various experiments, along with initial values for ammonium-acetate extractable K (XK) and K fixation potential (Kfix) are given in table 1.

**Table 1. Selected soil properties**

| Pedon Code | Soil/classification | Depth cm | XK mg kg$^{-1}$ | K fix mg kg$^{-1}$ |
|---|---|---|---|---|
| **DONA** | *Archerdale clay loam* | 9-28 | 113 | 19 |
| | *Pachic Haploxeroll* | 28-46 | 123 | 42 |
| | | 110-135 | 119 | 289 |
| **VSSA** | *Bruella sandy loam* | 0-12 | 65 | 235 |
| | *Ultic Palexeralf* | 12 30 | 45 | 377 |
| | | 30-44 | 32 | 259 |
| | | 60-79 | 67 | 208 |
| | | 79-100 | 53 | 231 |
| **KTRA** | *Columbia sandy loam* | 7-41 | 67 | 243 |
| | *Aquic Xerofluvent* | 41-61 | 49 | 348 |
| | | 96-135 | 36 | 318 |
| **DH2** | *Guard clay loam* | 20-40 | 63 | 422 |
| | *Duric Haplaquoll* | 40-60 | 79 | 500 |
| | | 80-100 | 52 | 404 |
| | | 100-120 | 50 | 503 |
| | | 120-140 | 34 | 450 |
| **224** | *Armona loam* | 0-10 | 59 | 384 |
| | *Fluventic Endoaquoll* | 10-50 | 78 | 564 |
| | | 50-100 | 48 | 740 |
| | | 100-120 | 92 | 475 |
| **225** | *Gepford clay* | 0-12 | 169 | 63 |
| | *Typic Natraquert* | 12-56 | 102 | 267 |
| | | 56-95 | 104 | 111 |
| **VSS E** | *San Joaquin silt loam* | 0-20 | 66 | 279 |
| | *Abruptic Durixeralf* | 100-120 | 81 | 642 |
| **KTR B** | *Columbia sandy loam* | 0-20 | 120 | 82 |
| | *Aquic Xerofluvent* | 120-140 | 65 | 604 |
| **VSN C** | *Redding gravelly loam* | 0-20 | 72 | 143 |
| | *Abruptic Durixeralf* | 40-60 | 54 | 526 |
| **KTR H** | *Sailboat silt loam* | 0-20 | 114 | 67 |
| | *Aquic Xerofluvent* | 40-60 | 84 | 473 |
| **KTR C** | *Sailboat silt loam* | 0-20 | 121 | 38 |
| | *Aquic Xerofluvent* | 120-140 | 96 | 325 |
| **KIMB 219** | *Kimberlina fine sandy loam* | 0-20 | 214 | -159 |
| | *Typic Torriorthent* | 40-60 | 86 | 278 |
| **CM F** | *Montpelier-Cometa complex* | 0-20 | 80 | 34 |
| | *Xeralfs* | 40-60 | 59 | 159 |
| **RM X** | *Redding gravelly loam* | 0-20 | 89 | -46 |
| | *Abruptic Durixeralf* | 40-60 | 40 | 26 |
| **CM N** | *Montpelier-Cometa complex* | 0-20 | 124 | -48 |
| | *Xeralfs* | 40-60 | 118 | -6 |
| **DOUG** | *Vina fine sandy loam* | 0-20 | 257 | -126 |
| | *Pachic Haploxeroll* | 40-60 | 116 | -36 |
| **KIMB 198** | *Kimberlina sandy loam* | 0-20 | 303 | -174 |
| | *Typic Torriorthent* | 40-60 | 149 | -54 |
| **RVB** | *Nord fine sandy loam* | 0-10 | 259 | -233 |
| | *Cumulic Haploxeroll* | | | |

<u>Objective 1</u>

**Incremental K Additions**

K was applied to soils at a rate equal to 2x Kfix values, followed by moist incubation for 24 hours and air drying, repeated four times for rates equal to 2x, 4x, 6x, and 8x Kfix values, along with one application at a rate equal to the CEC (one symmetry of K). XK, TPB-K, and Kfix were measured after each sequential addition, and used to estimate the K fixed by each soil. Figure 1 shows the resulting K fixation potential estimates for all soils, by method. As K additions increased, K fixation potential tended to reach a plateau, representing a maximum K fixation potential for each soil. Results for individual soils are presented in figure 2.

In some cases, it was clear that a maximum K fixation potential value had been reached (Fig. 2b,c,e), but for other soils, it is possible that even higher rates of K additions would have resulted in additional K fixation (Fig. 2a,d). The smectitic DON A Archerdale clay loam initially exhibited little-to-no K fixation throughout the profile, but at the symmetry rate of K additions, it exhibited significant K fixation (Fig. 2f), suggesting the possibility that K fixation potential was induced in this soil by the addition of a very large amount of K.

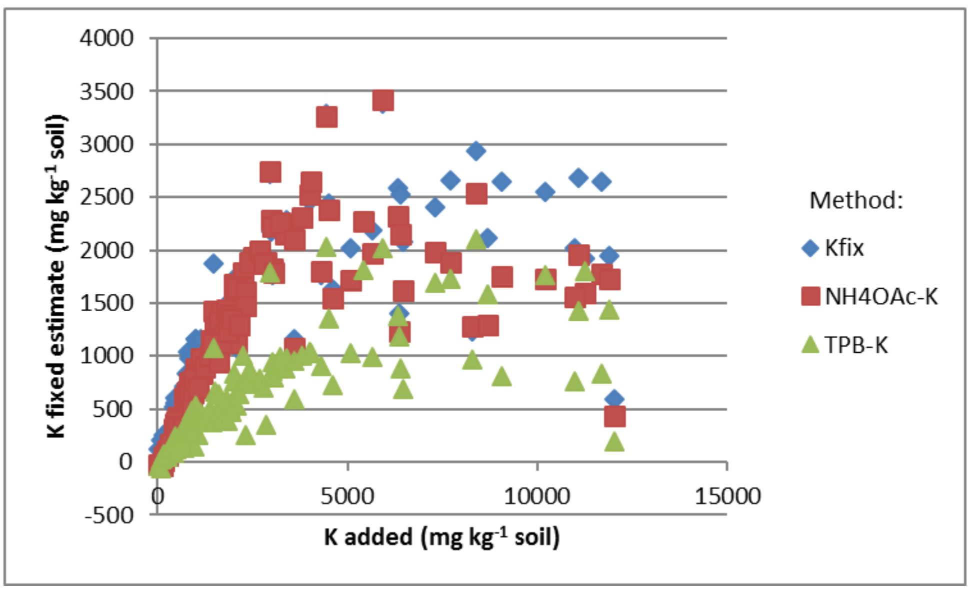


**Fig. 1. Relationship of estimated K fixed by Kfix, $NH_4OAc$-K, and TPB-K methods to K added.**

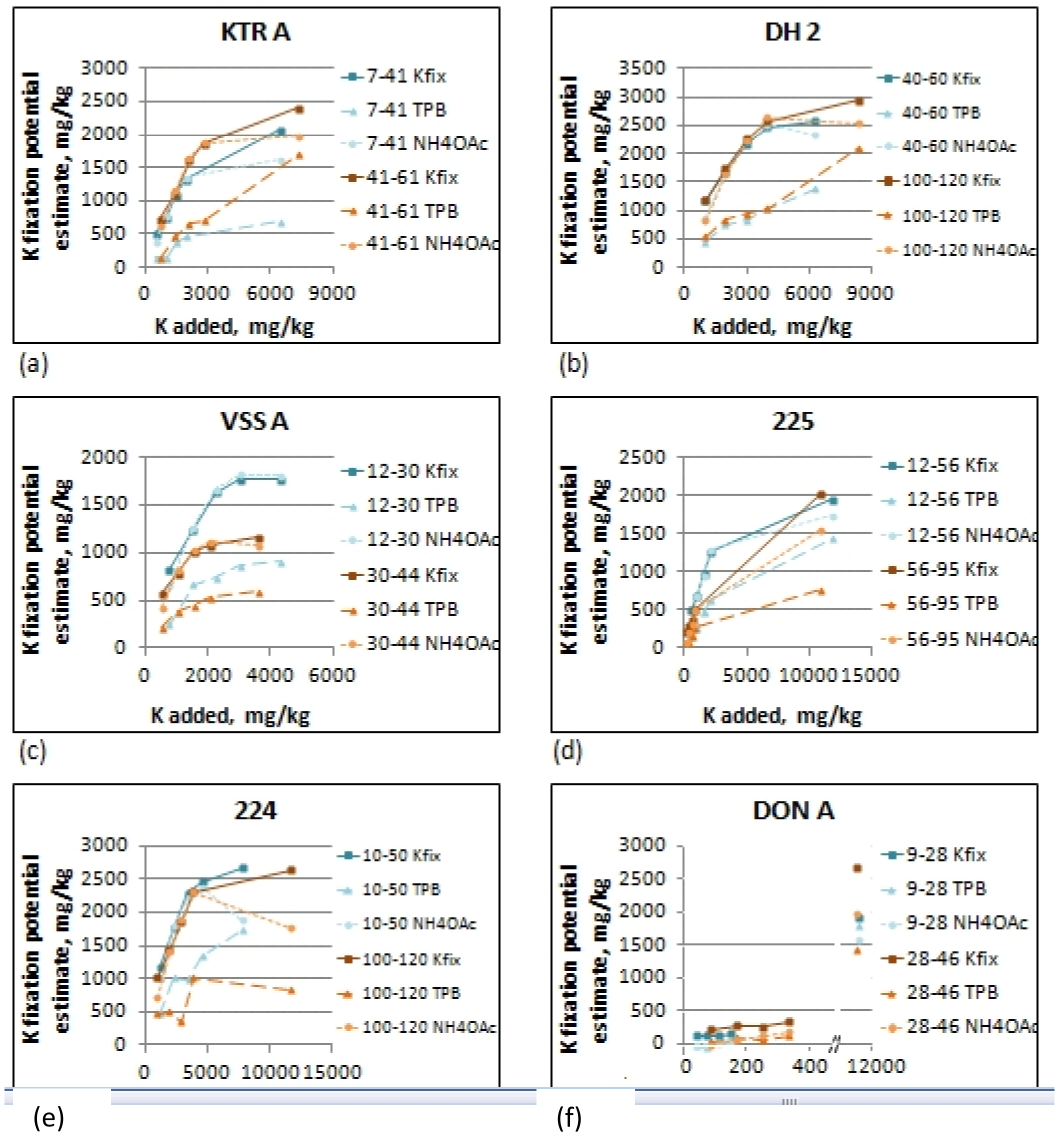


**Fig. 2. Estimated K fixation potential at increasing rates of applied K at selected depths for each soil, as estimated by Kfix, $NH_4OAc$-K, and TPB-K methods. Note the broken x-axis in 2(f).**

The initially determined Kfix value for these soils was significantly correlated with the maximum value of K fixation measured, but with only a moderately good linear fit (Fig. 3, $p<0.0001$, $R^2$ between 0.60 and 0.85 depending of the method used). Given this relationship, the Kfix value seems adequate as an index of a soil's true potential to fix K.

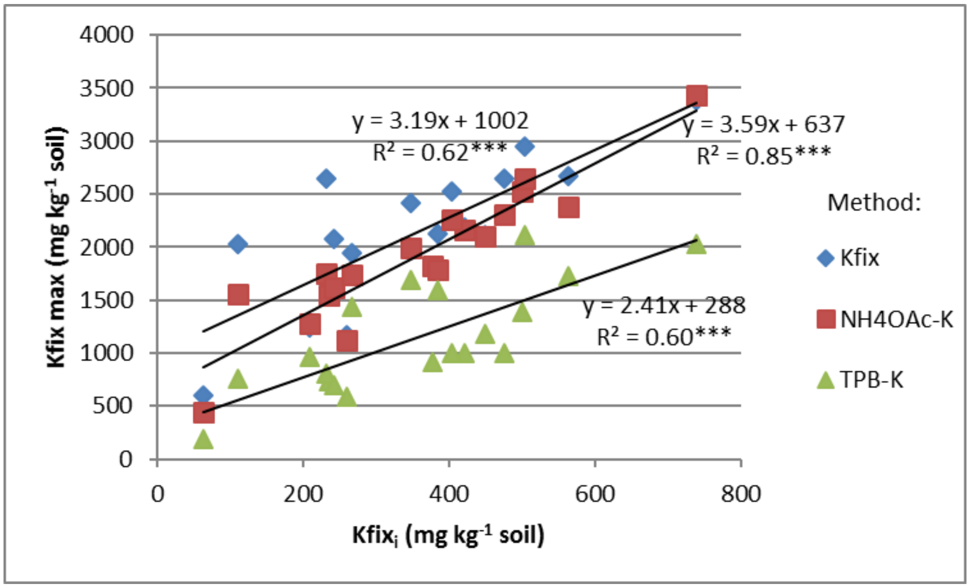


**Fig. 3. Comparison of Kfix max estimate with Kfix$_i$ value.**

The TPB-K method was roughly twice as efficient as the XK method in recovering added K, and the efficiency of both methods increased with added K, indicating a lower proportion of the larger additions of K were fixed in forms not available for plant uptake (Table 2). Figure 4 shows the percent of added K recovered by the two methods as a function of the rate added. Based on these results for the 2xKfix rate (closest to agronomically relevant rates), roughly 75% of added K was recovered for soils with Kfix values less than 200 mg kg$^{-1}$ by both methods. For soils with Kfix values greater than 200 mg kg$^{-1}$, the XK method recovered around 20%, and the TPB-K method recovered 60% of added K. Of the added K estimated to be fixed, approximately 50% was recovered by the TPB-K method but not by the XK method (Fig. 5). This pool of K is termed plant available non-exchangeable K (PANK).

**Table 2. Percent of added K recovered for soils with Kfix values of 200-600 mg kg$^{-1}$.**

| | XK % of added K recovered | | TPB-K % of added K recovered | |
|---|---|---|---|---|
| K added | Mean | Range | Mean | Range |
| 2x | 21% | 11-38% | 59% | 46-80% |
| 4x | 22% | 16-35% | 66% | 55-80% |
| 6x | 28% | 21-41% | 71% | 64-88% |
| 8x | 37% | 29-47% | 75% | 69-89% |
| Symm | 74% | 58-85% | 83% | 75-93% |

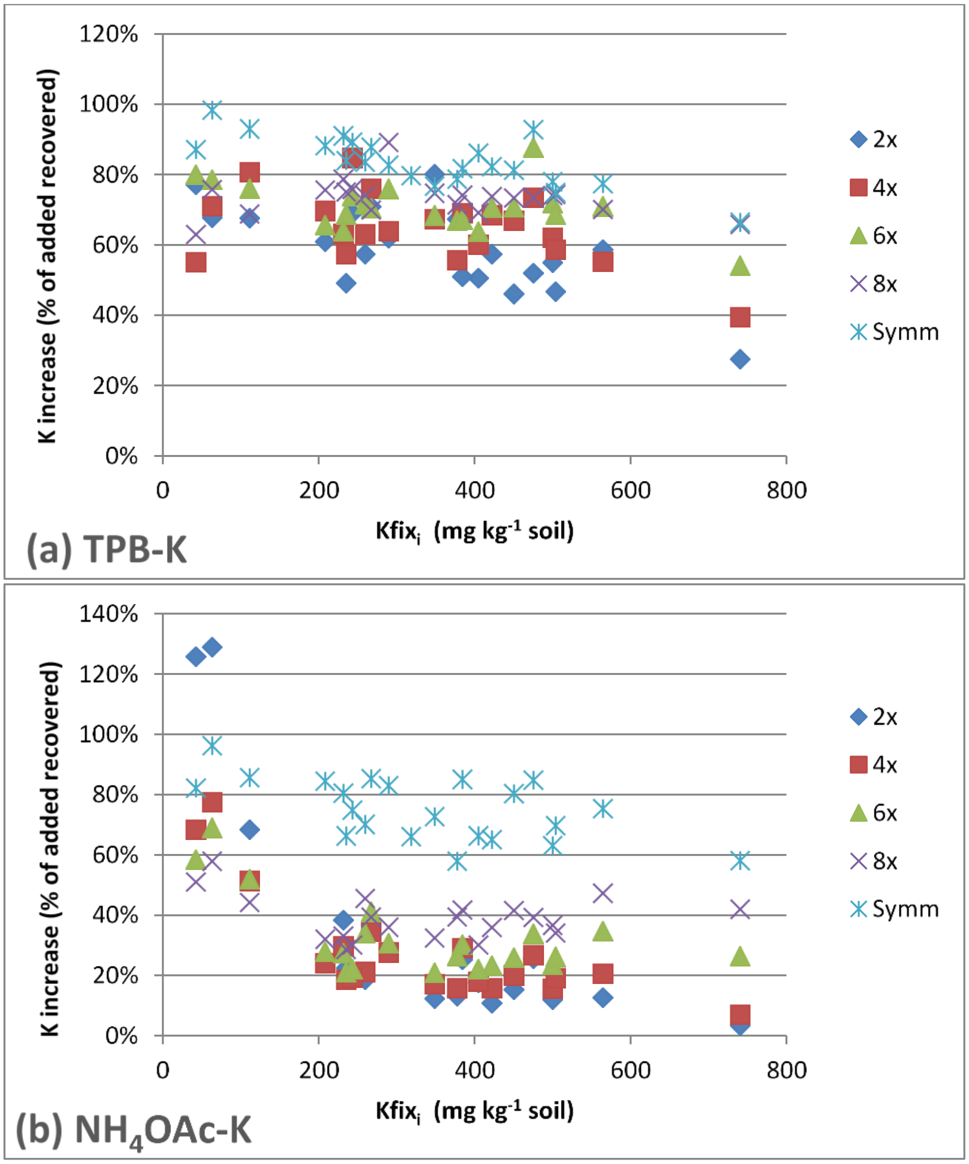


**Fig. 4. Percentage of added K recovered as a function of soil Kfix value, separated by increment of K added. Results for (a) TPB-K extraction and (b) XK extraction.**

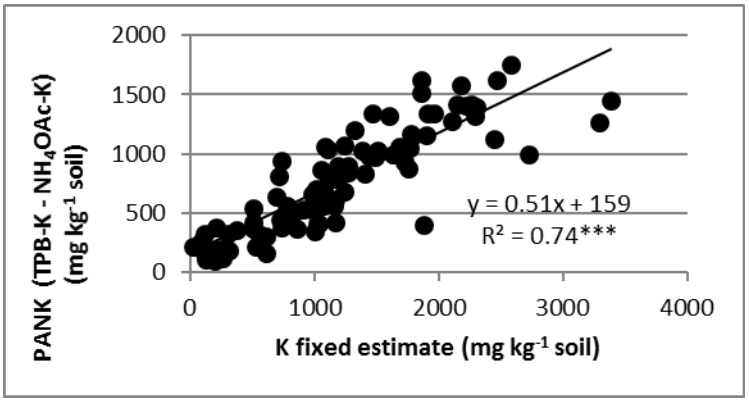


**Fig. 5. Plant-available nonexchangable K compared to K fixed as estimated by Kfix method for 2x through 8x incremental additions.**

**Greenhouse pot study**

To compare laboratory methods of plant-available K to actual plant uptake, annual ryegrass (*Lolium multiflorum*) was grown in 15cm diameter pots in a greenhouse in 12 different soil types and at four rates of K fertilization (0, 50, 250, and 1000 mg kg$^{-1}$). N and P were supplied in excess as both soluble and controlled release forms. Grass was seeded at 1.5 grams per pot, and clipped at 1cm above soil surface at 3, 6, and 9 weeks after germination. Oven dry weight of aboveground biomass (yield) was recorded (Fig. 6), and tissue K was measured by acetic acid extraction (Table 3). Additionally, total K by aqua regia digestion was measured for each of these soils (Table 4).

**Table 3. Ryegrass K uptake by rate**

| | | Total uptake (mg) | | | |
|---|---|---|---|---|---|
| Pedon | Depth | K rate (mg/kg soil): | | | |
| Code | (cm) | 0 | 50 | 250 | 1000 |
| VSS E | 0-20 | 239 | 304 | 590 | 1069 |
| VSS E | 40-60 | 340 | 374 | 587 | 747 |
| DH 2 | 0-20 | 558 | 633 | 810 | 957 |
| DH 2 | 40-60 | 153 | 145 | 348 | 689 |
| KTR A | 0-20 | 662 | 679 | 907 | 1042 |
| KTR A | 40-60 | 369 | 452 | 648 | 961 |
| DON A | 0-20 | 681 | 774 | 895 | 959 |
| DON A | 40-60 | 287 | 333 | 519 | 831 |
| RM X | 0-20 | 154 | 183 | 435 | 1043 |
| RM X | 40-60 | 60 | 126 | 359 | 970 |
| DOUG | 0-20 | 324 | 383 | 550 | 791 |
| DOUG | 40-60 | 96 | 144 | 325 | 707 |

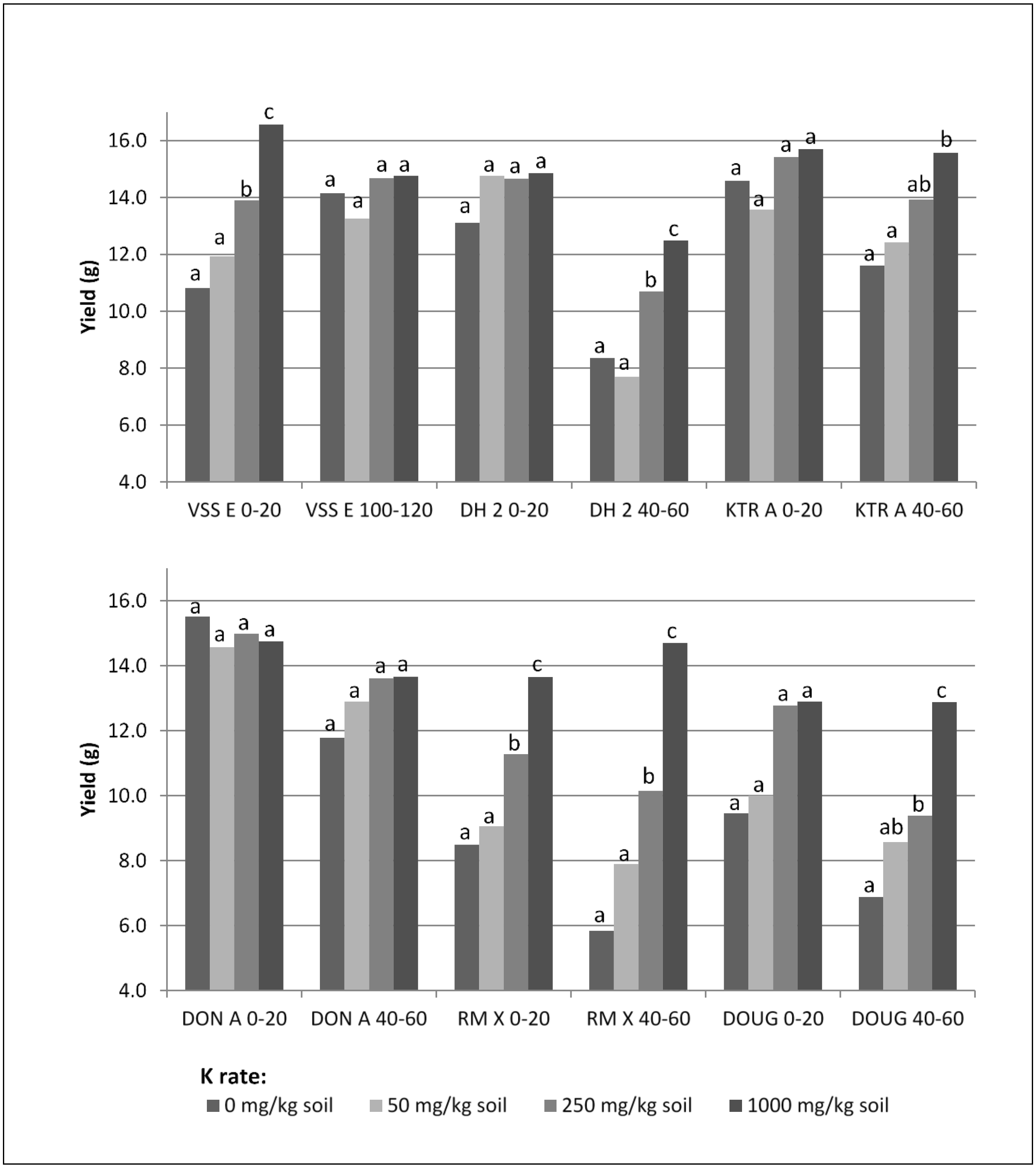


**Fig. 6. Total yield by K rate for each of the 12 soil materials used. For each soil, letters indicate significantly different means at the 5% probability level as determined by the Tukey HSD method.**

**Table 4. Soil descriptions and K properties**

| Pedon Code | Soil/Classification | Depth (cm) | XK (mg kg$^{-1}$) | TPB-K (mg kg$^{-1}$) | TotK (mg kg$^{-1}$) | Kfix (mg kg$^{-1}$) |
|---|---|---|---|---|---|---|
| **VSS E** | *San Joaquin silt loam* | 0-20 | 79 | 189 | 2100 | 241 |
| | *Abruptic Durixeralf* | 100-120 | 95 | 183 | 3950 | 632 |
| **DH 2** | *Guard clay loam* | 0-20 | 194 | 553 | 2820 | 58 |
| | *Duric Haplaquoll* | 40-60 | 116 | 234 | 2810 | 420 |
| **KTR A** | *Columbia sandy loam* | 0-20 | 167 | 770 | 4500 | -26 |
| | *Aquic Xerofluvent* | 40-60 | 88 | 300 | 3940 | 243 |
| **DON A** | *Archerdale clay loam* | 0-20 | 269 | 558 | 4000 | -70 |
| | *Pachic Haploxeroll* | 40-60 | 159 | 234 | 2840 | 225 |
| **RM X** | *Redding gravelly loam* | 0-20 | 87 | 130 | 830 | -45 |
| | *Abruptic Durixeralf* | 40-60 | 40 | 66 | 880 | 14 |
| **DOUG** | *Vina fine sandy loam* | 0-20 | 301 | 395 | 1430 | -186 |
| | *Pachic Haploxeroll* | 40-60 | 144 | 155 | 740 | -60 |

Significant yield response at the 5% probability level was determined by the Tukey HSD test, and results are included for each soil and depth in Figure 6. The Cate-Nelson method was used to determine critical values for K below which a K response would be anticipated. This was done for each method of K measurement. Critical values were: for XK, 167 mg/kg soil; for TPB-K, 419 mg/kg soil; and for TotK, 1663 mg/kg soil. These critical values were then compared to the observed levels at which a significant response to K occurred.

Each method was between 70-80% accurate in correctly predicting the presence or absence of a yield response to additional K, and no method was consistent in over-estimating or under-estimating the potential for a yield response. The TPB-K method was the most frequently accurate, with a correct prediction in 29 of 36 cases, followed by uptake and XK measurements at 27 of 36, and TotK at 26 of 36. TotK was the least similar to the other methods, with an opposite prediction from all other methods in eight cases. TotK, when wrong, was also on average off by more than the other methods, both as an absolute value and as a proportion. By this metric, TPB-K was closest to the critical value when in error, followed by XK, and TotK. Some individual soils proved problematic for one or multiple methods.

All soils with initial TPB-K values above the critical value of 419 mg/kg (DON A 0-20cm, KTR A 0-20cm, and DH 2 0-20 cm) behaved as predicted by each method of K analysis, showing no significant response to K additions at any level.

For soils with TPB-K values between 50 and 100% of the critical value, DOUG 0-20cm and DON A 40-60cm each failed to show a significant response to K fertilization, contrary to the predictions for both soils by the TPB-K critical value and for DON A 40-60cm by the XK critical value. In both cases an apparent response was not significant by the Tukey method due to relatively high variability between replicates (Fig. 1). Grass grown in KTR

A 40-60cm fit predictions by the XK and TPB critical values, with the 1000 mg $kg^{-1}$ treatment producing a significantly greater yield than the 0 and 50 mg $kg^{-1}$ treatments. DH 2 40-60cm, with a high measured K fixation potential, exhibited a strong response to K additions at the 250 and 1000 mg $kg^{-1}$ rates. With the addition of 250 mg $kg^{-1}$, the critical values for all methods incorrectly predicted that K levels should be sufficient and that additional K would not impact yield. This result, and uptake at each level increasing by significantly less than the amount of K added indicate that the K fixation potential of this soil impacted the ability of the grass to access portions of the K added.

For soils with TPB-K less than 50% of the critical value, DOUG 40-60cm, RM X 0-20cm, and RM X 40-60cm all represented non-K-fixing soil materials with low to very low TPB-K, XK, and TotK values. True to these properties, all three showed significant yield responses to both the 250 and 1000 mg $kg^{-1}$ treatments. VSS E 0-20cm responded significantly to K at both the 250 and 1000 mg $kg^{-1}$ rates, despite all methods predicting no response between the two rates. The moderate Kfix value for this soil did not appear to impact K availability, as increase in uptake were consistently on par or greater than added K. VSS E 40-60cm, despite low XK and TPB-K values and a very high Kfix value did not respond to K at any treatment level. This soil had very high TotK values, so it is hypothesized that some of this structural K became slowly available over the course of the study.

Linear regression of yield and uptake with measured K properties showed that yield was best correlated with TotK, followed by TPB-K. Uptake was best correlated with TPB-K. (Table 5).

**Table 5. Correlation coefficients (r) for linear regression of variables**

| | Yield | K uptake | TPB + added K | XK + added K | Kfix - added K | TotK + added K |
|---|---|---|---|---|---|---|
| Yield | 1.0000 | 0.8706*** | 0.6692*** | 0.5204** | -0.3579* | 0.7465*** |
| Total K uptake | 0.8706*** | 1.0000 | 0.8966*** | 0.7885*** | -0.7159*** | 0.6090*** |
| TPB + added K | 0.6692*** | 0.8966*** | 1.0000 | 0.9300*** | -0.8496*** | 0.5425*** |
| XK + added K | 0.5204** | 0.7885*** | 0.9300*** | 1.0000 | -0.9015*** | 0.3245* |
| Kfix - added K | -0.3579* | -0.7159*** | -0.8496*** | -0.9015*** | 1.0000 | -0.0623 |
| TotK + added K | 0.7465*** | 0.6090*** | 0.5425*** | 0.3245* | -0.0623 | 1.0000 |

* ** *** Correlation (r) significant at p<0.05, 0.01, or 0.0001, respectively.

Objective 2

**Estimation of soil profile exchangeable K and K fixation for soils in regional model categories**

For most annual crops, soil K fertility is evaluated using a sample collected from the surface 15 to 30 cm (6-12 inches). For deeper rooted crops, such as cotton and grapes, assessment of soil K fertility is more difficult, as plants may or may not obtain significant amounts of K from the subsoil, and because rooting depth and geometry is not well known. We have found that plant-available K (measured as XK) tends to decrease with depth, and K fixation capacity (as measured by Kfix) tends to increase with depth in some soils formed from granitic parent material. This suggests that evaluating the K soil fertility of rootzones for deep-rooted crops may be difficult.

We have used our XK and Kfix profile data to calculate mean soil K levels in 12 soil profiles by two weighting methods: (1) weighting according to the depth increment represented by each sample, and (2) weighting according to published grape root depth distribution data (Fig. 7). The distribution function shown in Fig. 7 is based on root counts made in 240 California vineyard locations (Smart et al., 2006). The equation for the distribution is $Y=1-\beta^d$, where Y is the proportion of roots from the surface to depth d (in cm), and $\beta = 0.9826 \pm 0.0068$.

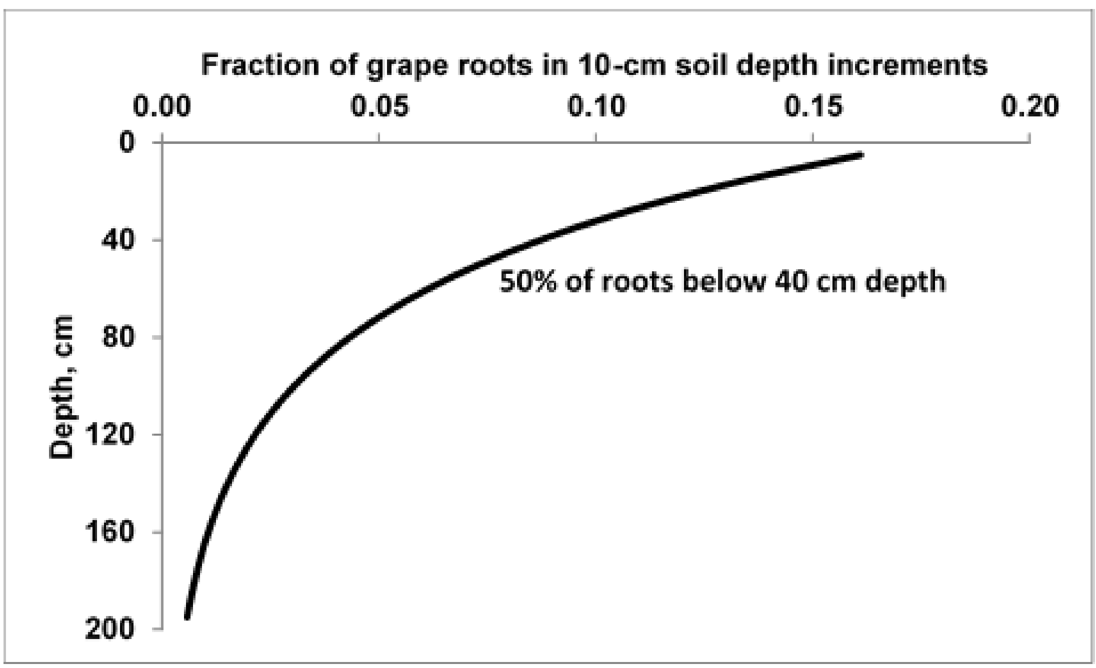


**Fig. 7. Grape root depth distribution function used to estimate weighted mean XK and Kfix values in Table 6. Based on measurements (n=240) by Smart et al. (2006).**

The soil profile samples used for our calculations were collected from the Lodi winegrape district across a broad range of soil types and at depths up to two meters .

Support for soil sample collection and initial characterization was provided by the Lodi Winegrape Commission.

In some soil samples with high XK and no K-fixing minerals, our Kfix laboratory method gave a negative value, i.e., “negative K fixation capacity”.  To calculate mean soil profile values of Kfix, where Kfix <0, Kfix was set to zero. Values of XK and Kfix were calculated for each depth sampled in a profile. To obtain a profile mean value, values for individual depths were weighted according to thickness of depth (method 1) or according to the hypothetical fraction of grape roots in that depth increment (method 2). The resulting soil profile mean XK and Kfix values are shown in Table 6.

Results for Objective 2

1. The 12 profiles we have chosen to present here were sampled to depths ranging from 90 to 170 cm. In 11 of the 12 profiles, the surface layer had higher XK and lower Kfix than the profile mean values.
2. Nine of the 12 sites would be judged as K deficient based on the surface sample XK level and using a typical agronomic crop critical level of 80-100 mg K/kg soil. Also the profile weighted mean XK values are very low (<70 mg/kg in 11 of 12 profiles).
3. Samples of 6 of the 12 sites showed little or no K fixation capacity (Kfix<50 mg/kg) in the surface depth increment; but 4 of those profiles had much higher Kfix in the subsurface and therefore have high mean profile values of Kfix.
4. Weighting by a published grape root distribution function in comparison to weighting by sampling depth increment gave a 41% lower mean profile Kfix and a 20% lower mean profile XK.
5. Mean profile Kfix values when expressed as a percentage of K fixed in our laboratory procedure (rather than on a soil weight basis) are all lower than the 60% level suggested by Miller et al. (1997) as the level of K fixation above which very high application rates of K fertilizer should be considered for cotton. Percent fixation values for Kfix for the 9 strongly K-fixing profiles range from 29 to 54% (weighting method 1) or 19 to 38% (weighting method 2).
6. The weighted profile values of Kfix are consistent with our soil regional model categories (O’Geen et al. 2008) in 10 of the 12 selected profiles. Two of the profiles do not fit our regional model categories.  These are the CM-F site (mapped as a Kaseberg soil) and the VSN-C site (mapped as a Redding gravelly loam). Based on landscape position and other considerations, we placed these sites in “Region 4”, and as such, we would expect them to be low in K-rich weatherable minerals and lacking in K fixation capacity. However, both of these profiles showed strong K fixation capacity below the surface sampled depth.

**Table 6. Mean soil profile exchangeable K and K fixation capacity estimated by two weighting methods.**

| Soil profile or pedon code | Soil region (O'Geen et al. 2008) | Surface sample depth | Profile sampling depth | Form of K† | Surface depth sample | **Profile mean K** (depth-weighted) | **Profile mean K** (root distrib-weighted)‡ |
|---|---|---|---|---|---|---|---|
| | | *cm* | *cm* | | *------------- mg K/kg soil* | | *------------* |
| CM F | 4 | 0-20 | 90 | **XK** | 88 | 62 | 53 |
| | | | | **Kfix** | 0 | 311 | 177 |
| CM N | 4 | 0-20 | 120 | **XK** | 63 | 43 | 32 |
| | | | | **Kfix** | 0 | 44 | 15 |
| DH 2 | 2A | 0-20 | 140 | **XK** | 124 | 41 | 27 |
| | | | | **Kfix** | 82 | 323 | 186 |
| DON A | 1 | 0-2 | 170 | **XK** | 683 | 104 | 73 |
| | | | | **Kfix** | 0 | 126 | 43 |
| KTR A | 2A | 0-7 | 150 | **XK** | 286 | 48 | 45 |
| | | | | **Kfix** | nd | 288 | 222 |
| KTR B | 2A | 0-8 | 145 | **XK** | 51 | 63 | 69 |
| | | | | **Kfix** | 31 | 389 | 296 |
| KTR C | 2A | 0-7 | 140 | **XK** | 139 | 44 | 42 |
| | | | | **Kfix** | 0 | 276 | 147 |
| KTR H | 2A | 0-20 | 120 | **XK** | 82 | 47 | 34 |
| | | | | **Kfix** | 127 | 334 | 231 |
| RM X | 4 | 0-20 | 120 | **XK** | 53 | 29 | 21 |
| | | | | **Kfix** | 0 | 40 | 15 |
| VSN C | 4 | 0-20 | 90 | **XK** | 78 | 51 | 46 |
| | | | | **Kfix** | 122 | 417 | 283 |
| VSS A | 3 | 0-12 | 100 | **XK** | 65 | 42 | 28 |
| | | | | **Kfix** | 235 | 226 | 179 |
| VSS E | 3 | 0-20 | 120 | **XK** | 77 | 47 | 31 |
| | | | | **Kfix** | 212 | 359 | 222 |

†XK= K extracted with 1M $NH_4OAc$. Kfix=K fixation capacity per Murashkina et al. 2007a.

‡Based on root depth distribution for grapes, Smart et al., 2006.

Objective 3
**16 day K incubation**

After additions of K equal to Kfix and moist incubation with for 1, 2, 4, 8, and 16 days, XK, TPB-K, and Kfix were measured on moist and air-dried materials. Even after adding K equal to the Kfix values for these soils, they all continued to fix additional K, though at levels lower than for the untreated soils. In other words, the added K did not fully satisfy the K fixation potential of these soils (Fig. 7).

K extracted by both $NH_4OAc$ (XK) and NaTPB (TPB-K) increased after K addition, but by some amount less than the K that had been added in solution. This indicates that these soils fixed a portion of the added K, and some of this fixed K was removed from the pool of plant-available K as measured by NaTPB extraction.

Kfix values were independent of the duration of incubation. Changes to the fixation potential of these soils after the addition of K appeared to all take place in the first 24 hours. $NH_4OAc$-K and TPB-K values behaved less consistently. There was an apparent slight downward trend in $NH_4OAc$-K with time for some, but not all samples, and an apparent slight upward trend in TPB-K for some, but not all samples.

For all soil samples analyzed, Kfix values for moist samples were lower than for their dried counterparts (Fig. 8). This indicates that air drying results in an increase in the potential for soils to fix potassium. Air drying did not have a consistent effect on XK.

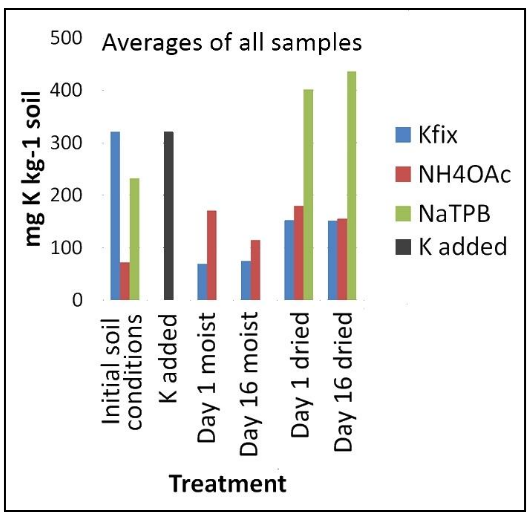


**Fig. 7. Soil K fixation, ammonium acetate K, and tetraphenyl boron K – average of all soil samples.**

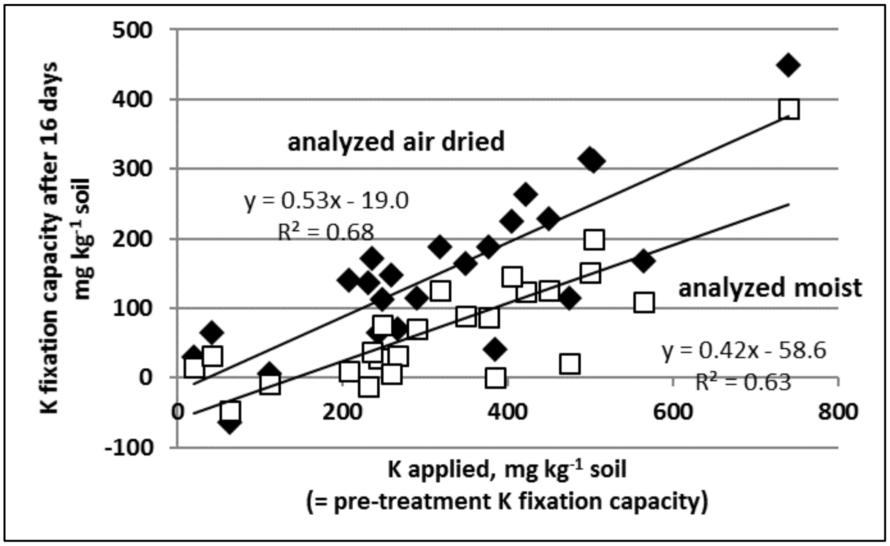


**Fig.8. Change in soil K fixation capacity following KCl application, for samples analyzed without drying (squares) or after air drying (diamonds). Applying K to samples in amounts equal to initial Kfix reduced K fixation, but not to zero.**

**Field Moist vs Air Dry soil K measurements**

Kfix and XK were measured for selected samples before and after a single drying event of field moist samples. Data from the trial is summarized in table 6. Field-moist and air-dry values are compared for Kfix in figure 9 and for XK in figure 10.

The Kfix value increased with drying for all K-fixing soils by an average of about 55 ppm (figure 1). However, for non-K-fixing soils, the change in Kfix was not consistent, and there was no discernible relationship between Kfix values and the magnitude of change. The change in Kfix did not correlate with XK values.

The change in XK was small (less than 20 ppm) for most samples. Those samples with high XK values were less likely to show a large change in XK with drying, whereas drying increased XK for most low XK soils and most K-fixing soils (figure 2). As was the case for Kfix, the change in XK was less consistent for non-K-fixing soils. It is hypothesized that the effect of drying may be a function of mineralogy (vermiculite in K-fixing soils), explaining the more consistent results for K-fixing soils.

**Table 6. Soil Properties – Field Moist v. Air Dry**

| Code | Soil/Classification | Depth (cm) | Kfix Field Moist (mg kg$^{-1}$) | Kfix Air Dry (mg kg$^{-1}$) | XK Field Moist (mg kg$^{-1}$) | XK Air Dry (mg kg$^{-1}$) |
|---|---|---|---|---|---|---|
| VSS E | *San Joaquin silt loam* | 0-20 | 177 | 279 | 59 | 66 |
| | *Abruptic Durixeralf* | 100-120 | 613 | 642 | 51 | 81 |
| KTR B | *Columbia sandy loam* | 0-20 | 1 | 82 | 123 | 120 |
| | *Aquic Xerofluvent* | 120-140 | 523 | 604 | 51 | 65 |
| VSN C | *Redding gravelly loam* | 0-20 | 87 | 143 | 74 | 72 |
| | *Abruptic Durixeralf* | 40-60 | 499 | 526 | 50 | 54 |
| KTR H | *Sailboat silt loam* | 0-20 | 39 | 67 | 113 | 114 |
| | *Aquic Xerofluvent* | 40-60 | 406 | 473 | 72 | 84 |
| DH 2 | *Guard clay loam* | 0-20 | 17 | 104 | 157 | 160 |
| | *Duric Haplaquoll* | 40-60 | 282 | 365 | 81 | 103 |
| KTR C | *Sail boat silt loam* | 0-20 | 5 | 38 | 125 | 121 |
| | *Aquic Xerofluvent* | 120-140 | 324 | 325 | 65 | 96 |
| KIMB 219 | *Kimberlina fine sandy loam* | 0-20 | -103 | -159 | 213 | 214 |
| | *Typic Torriorthent* | 40-60 | 262 | 278 | 68 | 86 |
| KTR A | *Columbia sandy loam* | 0-20 | -60 | -31 | 160 | 156 |
| | *Aquic Xerofluvent* | 40-60 | 244 | 266 | 111 | 107 |
| CM F | *Montpelier-Cometa complex* | 0-20 | 13 | 34 | 80 | 80 |
| | *Xeralfs* | 40-60 | 54 | 159 | 37 | 59 |
| DON A | *Archerdale clay loam* | 0-20 | -98 | -81 | 244 | 250 |
| | *Pachic Haploxeroll* | 40-60 | 110 | 155 | 39 | 90 |
| RM X | *Redding gravelly loam* | 0-20 | -24 | -46 | 93 | 89 |
| | *Abruptic Durixeralf* | 40-60 | -2 | 26 | 37 | 40 |
| CM N | *Montpelier-Cometa complex* | 0-20 | -24 | -48 | 137 | 124 |
| | *Xeralfs* | 40-60 | -102 | -6 | 166 | 118 |
| Dougan | *Vina fine sandy loam* | 0-20 | -98 | -126 | 247 | 257 |
| | *Pachic Haploxeroll* | 40-60 | 3 | -36 | 68 | 116 |
| KIMB 198 | *Kimberlina sandy loam* | 0-20 | -169 | -174 | 318 | 303 |
| | *Typic Torriorthent* | 40-60 | -29 | -54 | 106 | 149 |
| RVB | *Nord fine sandy loam* | 0-10 | -206 | -233 | 270 | 259 |
| | *Cumulic Haploxeroll* | | | | | |

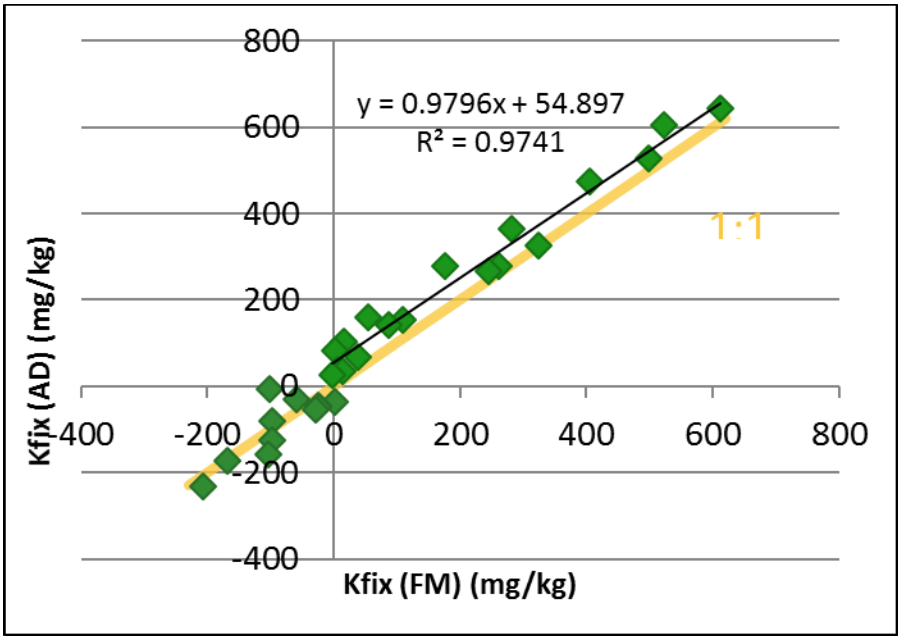


**Fig. 9. Air-dried (AD) vs field-moist (FM) Kfix values. Regression is for Kfix>0 only.**

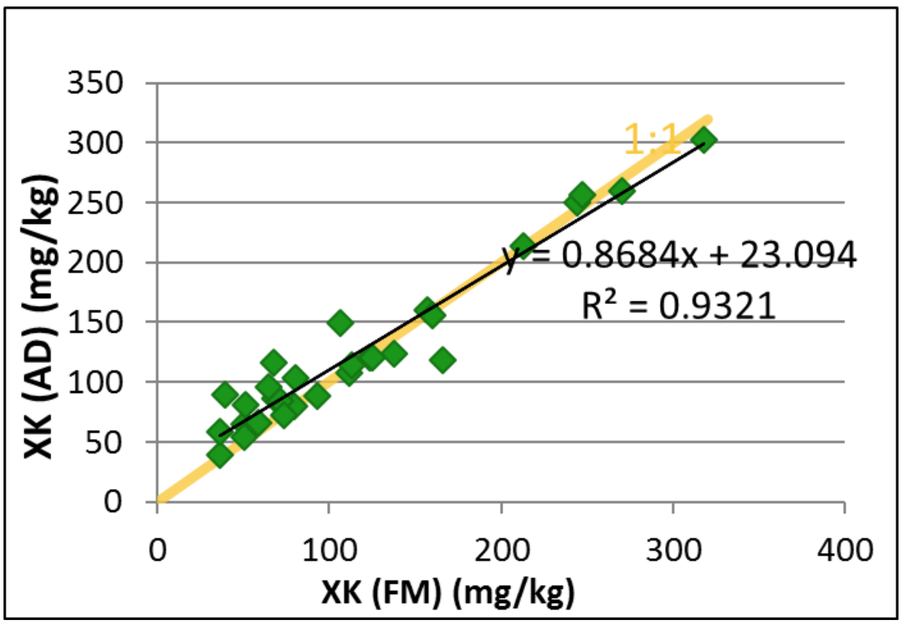


**Fig. 10. Air-dried (AD) vs field-moist (FM) XK values**

**Multiple cycles of wetting and drying**

Multiple cycles of wetting and drying after an initial application of K equal to the Kfix value did not significantly affect the values of Kfix, $NH_4OAc$-K, or TPB-K, as shown in figure 11. The changes in K fixation potential that were produced by a single drying event were not enhanced by additional drying cycles.

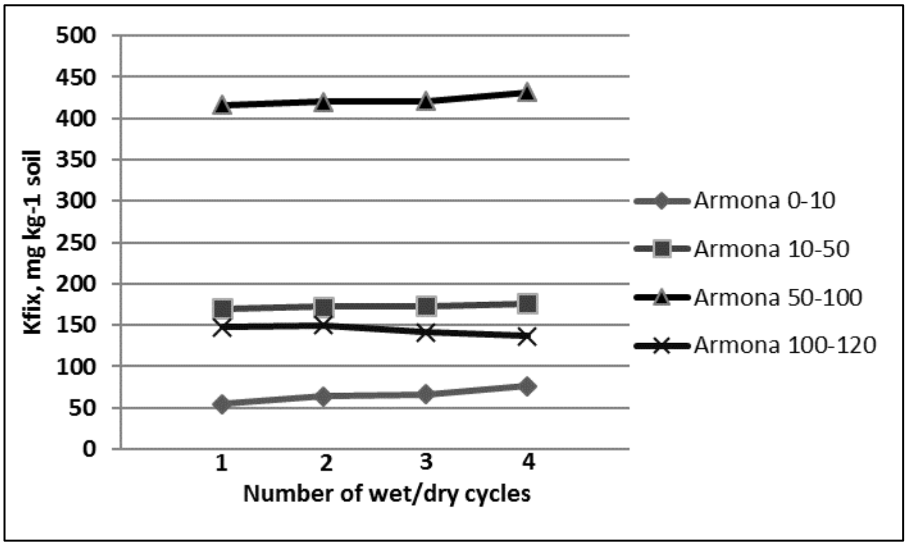


**Fig. 11. Kfix values for the Armona loam soil (224) after 1, 2, 3, and 4 cycles of wetting and drying. Soil Kfix did not change significantly with additional wet/dry cycles.**

**4mM Kfix method trial**

Comparing Kfix values from the standard procedure (Murashkina et al., 2007a) to a modified version of the method in which K is added at double the original rate (4mM instead of 2mM) showed that the two approaches are significantly correlated ($R^2$=0.87, $p<0.0001$), with a slope of 1.655. Doubling the rate of added K increased the amount fixed by 165% on average.

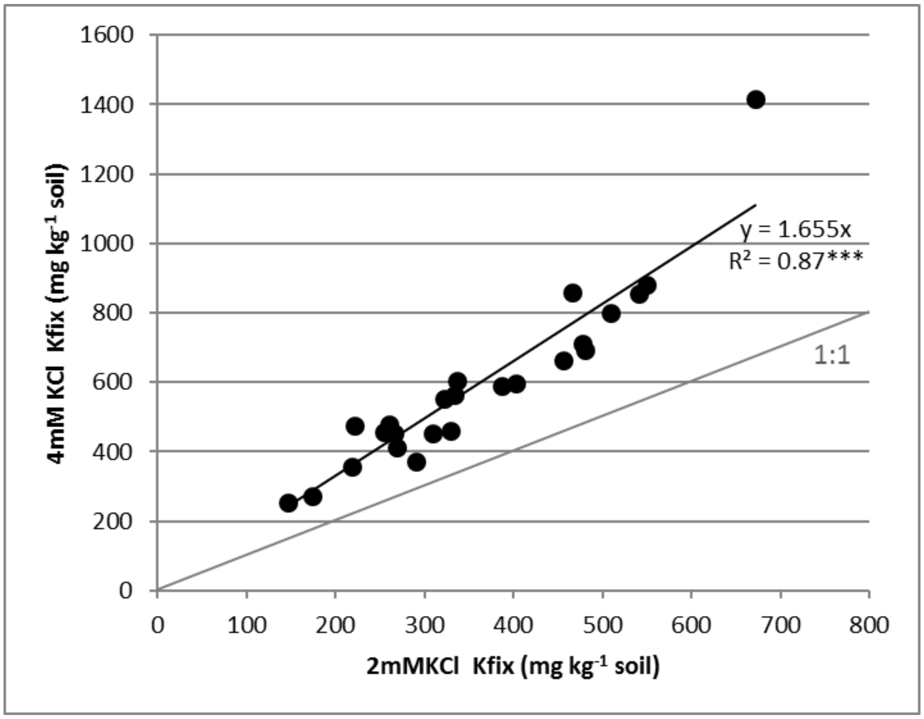


**Fig. 12. Comparison of the use of 4mM and 2mM KCl in the Kfix method.**

**Comparison of Kfix to Hartz Kfp method**

The Kfix method was also compared to the Kfp method of Hartz et al. (2002). Both are simplified versions of the Cassman et al. (1990) method, differing in that the Kfp method maintains an air-drying step and adds K at half the rate added in the Kfix method. Results (Fig. 13) show a correlation between the methods, but the Kfp method approaches 100% of added K fixed more quickly than the Kfix method, resulting in a non-linear, plateauing relationship. Though the drying event likely impacts the K fixed (as observed in previously discussed experiments), in this case the difference between the methods seems most clearly related to the lower rate of K applied in the Kfp method, resulting in that method “maxing out” with lower rates of K fixation potential than is the case for the Kfix method.

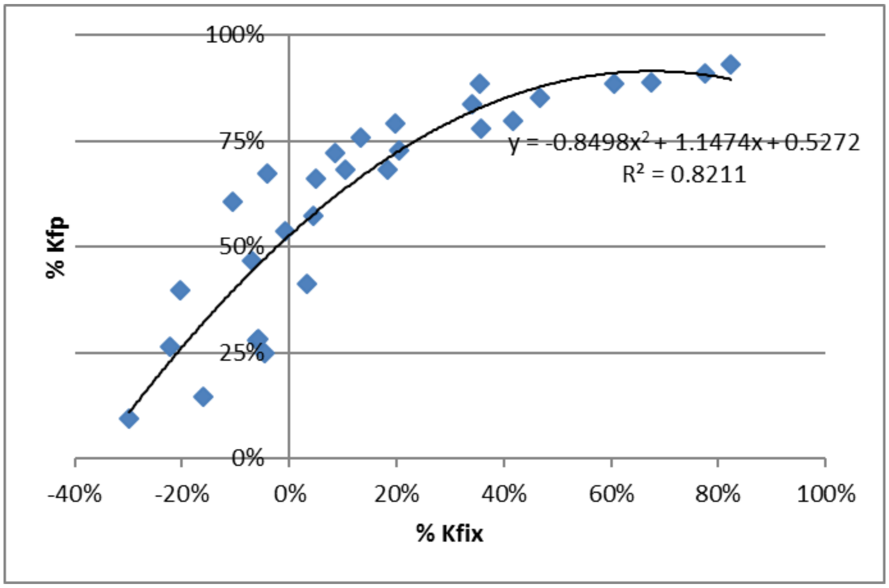


**Fig. 13. Comparison of the Kfp method to the Kfix method. Kfp approaches 100% more quickly than Kfix, plateauing at around 90%.**

## DISCUSSION AND CONCLUSIONS

Sufficiency levels for annual ryegrass in our pot study were 167 mg $kg^{-1}$ for XK and 419 mg $kg^{-1}$ for TPB-K. These levels were not perfect in predicting yield responses to K applications, but the TPB-K method was most accurate, and best correlated with measured uptake. Based on the efficiency results from the incremental additions of K, in order to increase soil test levels of XK and TPB-K to these levels, K should be applied at 1.33 times the desired increase for soils with Kfix<200 mg $kg^{-1}$ for both methods. For soils with Kfix>200, K should be added at 1.67 times the desired increase for TPB-K, and 5 times the desired increase for XK. Adjustments are not necessary for non-K-fixing soils. These numbers are estimates based on our set of soils, and some variation in response by soil is to be expected.

As a caution, given the limited correlation of Kfix values to observed growth response in the pot study, further refinement of these methods and recommendations is necessary.

An important question for crop managers is whether subsoil test K levels should be considered in evaluating soil fertility and fertilizer management of deep-rooted crops; also whether high subsoil K fixation capacity justifies higher rates of K fertilization. We developed a weighted whole soil-profile value of both XK and Kfix. We used a published continuous grape root distribution function (i.e., proportion of roots vs. depth) to estimate mean profile available K and K fixation values. This is undoubtedly an overly simplistic approach to weighting by roots. It does not take into account the effect of gravel lenses, stoniness and impermeable layers on root distribution. Also, in the case of grapes and other woody perennial species, the impact of interrow vegetation should be considered. K transport to roots is influenced both by plant demand and by K fixation and release in the soil (Karpinets and Greenwood, 2003). Researchers have successfully modeled K uptake (e.g., Barber, 1995) but have not included soil K fixation as a factor. It is very expensive to conduct K fertilizer field trials that elucidate the impact of soil K fixation, root distribution, interrow vegetation, use of drip irrigation, etc. Multiparameter mechanistic models of K dynamics are more cost-effective (Karpinets and Greenwood, 2003), and their development for use in these more complicated environments would be helpful.

In K-fixing soils, drying consistently results in an increase in K fixation capacity relative to moist samples, both with and without K additions previous to the drying event. Relative to field moist conditions, Kfix increased by an average of 55 mg $kg^{-1}$. Changes in XK, however, were less consistent.

When alternate methods are used to measure K fixation potential, a higher rate of added K results in a higher estimate of K fixation. In order to differentiate strongly K-fixing soils, it is important to use a method that adds K at a rate high enough to not be entirely fixed by these soils.

Additions of K to K-fixing soils results in a new distribution of K across the various pools of soil K. Some of the added K remains exchangeable, some becomes non-exchangeable, but still plant available, and some is fixed in a non-plant-available form. A portion of K added sequentially to soils continues to be fixed, with the fraction fixed decreasing with each addition, meaning that K fixation potential is only partially satiated by K additions, and a single application of K at a high rate in K-fixing soils will not remove the potential for continued fixation of applied K in the future.

K management in K-fixing soils is a complex task, influenced by a variety of soil properties. The sum of this work provides several critical insights into the dynamics of K in these soils, and some rules of thumb for adjusting K applications in K-fixing soils. Broadly, this work demonstrates that K fertility cannot be assumed to be simple in any setting, and even soils with similar soil K test levels may behave very dissimilarly in practice.

## PROJECT IMPACTS

The main achievement of this project has been to provide information to Certified Crop Advisers and analytical laboratories on the relevance of soil K fixation to K soil fertility and crop production in the Central Valley of California.

The research has shown that soils low in available K can be found in several parts of the San Joaquin Valley. Fixation of applied K in a non-exchangeable and partially unavailable form is found in the SJV in soils derived from granitic parent material, especially on the east side of the valley. K fixation is less often found in the surface 0-20 cm soil depth but often is quite strongly present in the subsoil. For deeper rooted crops, strong soil K fixation may be an important limiting factor in providing adequate K nutrition. Our research has clearly shown that even when very large amounts of K fertilizer (thousands of pounds of $K_2O$/acre) are applied to K-fixing soils, the K fixation capacity is only partially satisfied. However, our greenhouse pot experiment comparing K-fixing and non-K fixing soils (both with low initial K as measured by the conventional agricultural soil test) did not show clearly that “more K is needed” in the K-fixing soils. A soil test, tetraphenyl boron, was helpful in distinguishing these soils, but it is not a practical test for commercial analytical laboratories.

Our simple “1 hour” K fixation test (Kfix) is a variation of a previously published test that required a 7-day incubation (Cassman et al. 1990). In our research here, the 1-hr test was correlated well with another variation of the Cassman test used by Hartz et al.(2002); However the Hartz et al. method is less sensitive at very high (>50%) K fixation levels, beyond which it plateaus, compared to our Kfix method. Our Kfix method is suitable for commercial laboratory usage; however interpretation of the resulting value and generation of a fertilizer recommendation will likely be crop-specific. It may be that use of the Kfix soil test in combination with our regional soil model (O’Geen et al., 2008) will help in identifying situations where K fixation is a limiting factor to crop production.

## OUTREACH ACTIVITIES SUMMARY

### Presentations at professional meetings (and in conference proceedings) for crop consultants, certified crop advisers, cooperative extension and other practitioners

Pettygrove, S., A.T. O’Geen, and R.J. Southard. 2011. K fixation and significance for crop production. p. 106-109. Proceedings of the Western nutrient management conference. Reno, NV. 3-4 March 2011. International Plant Nutrient Institute. (Also an oral presentation at Conference) https://community.ipni.net/site/wera.nsf/home.xsp.

Pettygrove, S., R.J. Southard, and G. Rees. 2011. Relationship of soil K fixation and other soil properties to fertilizer K rate requirement. p. 22-26. In Proceedings 19th Annual Fertilizer Research and Education Program Conference. Tulare, CA. 16-17 Nov. 2011. CA. California Dept. Food & Agriculture. Sacramento, CA. (Also an oral presentation at Conference)

Rees, G.L., G.S. Pettygrove, and R.J. Southard. 2012. Estimating Plant-available K in K-fixing Soils. p. 47-50. Proceedings of the California Plant and Soil Conference. Visalia, CA. 7-8 Feb. 2012. CA. American Society of Agronomy California Chapter. (Also an oral presentation at Conference) http://calasa.ucdavis.edu/files/134945.pdf

Pettygrove, G.S. Potassium in Vegetable Production: Soil Fertility and Plant Nutrition Aspects. Nutrient Management Conference. Salinas, CA, 26 February 2013. http://cemonterey.ucanr.edu/files/162231.pdf

### Presentations and proceedings at professional academic/scientific meetings

Rees, G.L., R.J. Southard, and G.S. Pettygrove. 2011. Estimating availability of applied K in K-fixing soils. Abstract 127-6. ASA-CSSA-SSSA International Meetings.

San Antonio TX. 10-16, October 2011. American Society of Agronomy, Madison WI. (Also presented as a poster at Meeting) http://a-c-s.confex.com/crops/2011am/webprogram/Paper64193.html.

Rees, G.L., R.J. Southard, and G.S. Pettygrove. 2012. Estimation of Potassium Availability by Incremental Additions of K to K-Fixing Soils. Abstract 151-13. ASA-CSSA-SSSA International Meetings. Cincinnati, OH. 21-24 October 2012. American Society of Agronomy, Madison WI. (Also presented as a poster at Meeting) https://scisoc.confex.com/crops/2012am/webprogram/Paper73017.html

Southard, R.J. 2013. Soil Mineralogy and Potassium Dynamics in California's Central Valley. Abstract 287-6. ASA-CSSA-SSSA International Meetings. Tampa, FL. 3-6 November 2013. American Society of Agronomy, Madison WI. (Also an oral presentation at Meeting) https://scisoc.confex.com/scisoc/2013am/webprogram/Paper81448.html

Rees, G.L., R.J. Southard, and G.S. Pettygrove. 2013. Measurement of Potassium Fixation Potential On Air-Dried Vs. Field-Moist Soil Materials. Abstract 283-9. ASA-CSSA-SSSA International Meetings. Tampa, FL. 3-6 November 2013. American Society of Agronomy, Madison WI. (Also presented as a poster at Meeting) https://scisoc.confex.com/scisoc/2013am/webprogram/Paper78800.html

**Publications for practitioners**

Pettygrove, S., A.T. O'Geen, and R. Southard. 2011. Potassium fixation and its significance for California crop production. Better Crops 95(4):16-18.

**Research publications**

Rees, G.L., G.S. Pettygrove, and R.J. Southard. 2013. Estimating plant-available potassium in potassium-fixing soils. *Communications in Soil Science and Plant Analysis* 44:741-748.

**FACTSHEET**

**Title: Relationship of soil K fixation and other soil properties to fertilizer K rate requirement**
**Grant agreement Number: 10-D012-00-A06**

**Project Leader**: G. Stuart Pettygrove, Cooperative Extension Specialist, Emeritus, Department of Land, Air & Water Resources, One Shields Ave. University of California CA 95616. (gspettygrove@ucdavis.edu, 530-304-1007)

**Project Collaborators**: Randal J. Southard (Professor of Soil Science) and Gordon L. Rees (graduate student), Department of Land, Air and Water Resources, University of California, One Shields Ave, Davis, CA 95616

**Years: 2011-2014**

**Location: UC Davis, CA Central Valley**

**Counties: Butte, Fresno, San Joaquin, Yolo**

**Highlights:**

- Soils continued to fix K even after K equal to the measured K fixation potential was added.
- Drying K-fixing soils resulted in an increase in K fixation potential, both before and after additions of K.
- In order to increase soil test K values by a given amount, K must be applied at rates between 133% and 500% that amount. These numbers vary by soil and by method of soil test used.

**Introduction:** Soils of the Central Valley and bordering uplands display a wide range in the properties that determine K fertilizer requirements. Soil K fixation, which is associated with persistent crop K deficiencies, is found in some soils on the east side of the Central Valley that are derived from granitic parent material and contain the silicate layer mineral vermiculite. During the past 40 years, UC researchers have demonstrated the significance of K fixation for cotton and processing tomato production in the Central Valley (Miller et al., 1997; Hartz et al., 2008). In a UC field experiment (Cassman et al., 1989), 86% of the 1540 lb K2O/acre applied in a 3-yr period was fixed beyond extraction by $NH_4^+$, and cotton plants remained marginally deficient.

We expanded on previous UC research that investigated the relationship between soil mineralogy and K-fixation behavior in San Joaquin Valley soils used primarily for cotton production. Important findings were the dominant role of silt and fine sand fractions in K-fixation in soils in our study that were derived from Sierran granites (Murashkina et al. 2007b) and the observation that some soils that contain little vermiculite fix K, probably due to the presence of tetrahedrally substituted smectite (Murashkina et al. 2008). More recently, we have identified soils with high K fixation potential in winegrape vineyards in the Lodi district. Research supported by the Lodi Winegrape Commission is in progress to determine whether higher rates of K fertilizer are needed on K-fixing vineyard soils in that district than on non K-fixing soils.

Although several UC researchers have examined K fertilizer responsiveness in K-fixing and non K-fixing soils (Cassman et al., 1990; Cassman et al., 1992; Gulick et al., 1989), additional work is needed to develop practical laboratory methods for determining the K fertilizer requirements of such soils. We have developed a 1-hr incubation method for measuring soil K fixation potential (Murashkina et al., 2007a). Other researchers have shown that a modified version of an older test -- sodium tetraphenylboron, $NaBPh_4$ -- is useful for estimating the portion of fixed K that is plant-available (Cox et al., 1999). To be useful to growers in California, these tests must be correlated with K fertilizer response. In research funded by the California Department of Food & Agriculture Fertilizer Research & Education Program, we are using soils previously collected from the Lodi winegrape district and San Joaquin Valley cotton fields to determine whether our regional model categories (O'Geen et al. 2008) are informative with respect to K fertilizer requirement and whether the two analytical procedures described above predict the rate of K required to achieve sufficiency levels.

**Methods/Management:** A variety of K-fixing and non-K-fixing soils were analyzed for soil K status using ammonium acetate extractable K (XK), sodium tetraphenylboron plant-available K (TPB-K), aqua regia total K, and K fixation potential (Kfix). These soils were then used in a variety of experiments, including incubations with K at several rates and for multiple lengths of time, comparisons of K measurements for field-moist vs. air-dried samples, and a greenhouse pot study measuring growth and K uptake of annual ryegrass at multiple K rates.

**Findings:** Sufficiency levels for annual ryegrass in our pot study were 167 mg $kg^{-1}$ for XK and 419 mg $kg^{-1}$ for TPB-K. These levels were not perfect in predicting yield responses to K applications, but the TPB-K method was most accurate, and best correlated with measured uptake. Based on the efficiency results from the incremental additions of K, in order to increase soil test levels of XK and TPB-K to these levels, K should be applied at 1.33 times the desired increase for soils with Kfix<200 mg $kg^{-1}$ for both methods. For soils with Kfix>200, K should be added at 1.67 times the desired increase for TPB-K, and 5 times the desired increase for XK. Adjustments are not necessary for non-K-fixing soils. These numbers are estimates based on our set of soils, and some variation in response by soil is to be expected.

As a caution, given the limited correlation of Kfix values to observed growth response in the pot study, further refinement of these methods and recommendations is necessary.

In K-fixing soils, drying consistently results in an increase in K fixation capacity relative to moist samples, both with and without K additions previous to the drying event. Relative to field moist conditions, Kfix increased by an average of 55 mg $kg^{-1}$. Changes in XK, however, were less consistent.

Additions of K to K-fixing soils results in a new distribution of K across the various pools of soil K. Some of the added K remains exchangeable, some becomes non-exchangeable, but still plant available, and some is fixed in a non-plant-available form. A portion of K added sequentially to soils continues to be fixed, with the fraction fixed decreasing with each addition, meaning that K fixation potential is only partially satiated by K additions, and a single application of K at a high rate in K-fixing soils will not remove the potential for continued fixation of applied K in the future.

K management in K-fixing soils is a complex task, influenced by a variety of soil properties. The sum of this work provides several critical insights into the dynamics of K in these soils, and some rules of thumb for adjusting K applications in K-fixing soils. Broadly, this work demonstrates that K fertility cannot be assumed to be simple in any setting, and even soils with similar soil K test levels may behave very dissimilarly in practice.

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