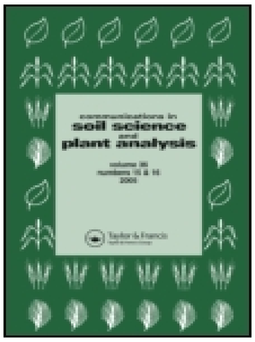

Communications in Soil Science and Plant Analysis

ISSN: 0010-3624 (Print) 1532-2416 (Online) Journal homepage: http://www.tandfonline.com/loi/lcss20

# Quantifying the Impact Factors of Different Forms of Potassium and Absorptions by Different Cotton Genotypes

Wenming He, Hongming He, Yang Cheng & Fang Chen

*Communications in Soil Science and Plant Analysis*, 46:2460–2474, 2015

ISSN: 0010-3624 print / 1532-2416 online
DOI: 10.1080/00103624.2015.1081927

Taylor & Francis
Taylor & Francis Group

# Quantifying the Impact Factors of Different Forms of Potassium and Absorptions by Different Cotton Genotypes

WENMING HE,[1,4] HONGMING HE,[2] YANG CHENG,[3] AND FANG CHEN[4]

[1]School of Chemistry and Environment, Jiaying University, Meizhou, Guangdong Province, China
[2]State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Northwest of Agriculture & Forestry University, and Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, Yangling, Shaanxi Province, China
[3]Civil and Environmental Engineering, Syracuse University, Syracuse, New York, USA
[4]Key Laboratory of Aquatic Botany and Watershed Ecology, Wuhan Botanical Garden, Chinese Academy of Sciences, Moshan, Wuchang, Wuhan, Hubei Province, China



*This study focuses on two genotypes of cotton and explores different factors that were able to affect the release of different forms of potassium (K) in the rhizosphere by considering a biogeochemical process integrating plants, soils, and microorganisms. The study indicated that both genotypes of cotton could effectively absorb exchangeable potassium (eK) under limited potassium (LK) supply, and cotton plants could use LK to sustain offspring, preferably under K-deficiency conditions. It was mainly due to its significantly greater active absorbing surface area of root and comparatively greater* $K^+$ *maximum uptake rate* ($I_{max}$)*, which caused more K accumulation in the high-efficiency genotype cotton (HEG). Although* $I_{max}$ *of the low-efficiency genotype cotton's (LEG's) was greater, K accumulation in LEG was less, which might be attributed to its significantly lower HEG and feedback inhibition on K taken up by greater K concentration in the plant. The lint yield had a significant positive correlation with boll number per plant, single boll weight, plant height, and number of fruit branches, which indicated that increasing these agronomic parameters is the base for increasing lint yield. There was a synergic action among humus, microorganisms, and K in the rhizosphere soil. The cation exchange capacity (CEC) of reduced soils was less under oxidized condition, due to collapse of the interlayer in response to increased layer charge upon structural Fe reduction. Crop yields can be increased when fertilizer K is applied according to proper ratio among different forms of potassium and humic acid in soils. The middle-high plant height, lower initial fruit branch, more fruit*

Received 6 December 2013; accepted 4 June 2015.
Address correspondence to Hongming He, State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Northwest Agriculture & Forestry University, and Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, Yangling, Shaanxi, China, 712100. E-mail: hongming.he@yahoo.com
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/lcss.

*branches, more bolls, and larger boll size should receive more attention during high-yielding cotton breeding.*

**Keywords** Environmental factor, path model, potassium, rhizosphere soil

## Introduction

Potassium (K) status is of great significance to crop growth, especially when plants are under severe environmental conditions (drought, low temperatures, saline soil, etc.) (Cakmak 2005; Kopittke 2012). Researchers have actively explored a variety of environmental factors (e.g., pH and organic matter) that influence the K status in the rhizosphere (Fernández et al. 2011; Hinsinger and Jaillard 1993; Wang et al. 2011). Different forms of K in the soil are interchangeable, and these transformations are determined by different factors, such as K-supplying capability of the soil and the weathering rate of mineral K (Balogh-Brunstad et al. 2008; Simonsson, Hillier, and Öborn 2009; Vanlauwe et al. 2002). Soil organic matter and inorganic ions produced by mineral weathering have significant influences on pH and oxidoreduction potential of the rhizosphere (Rausell-Colom et al. 1965), which in turn impacts the dynamic K ions in the plant root system (Øgaard and Hansen 2010). Root exudates, humic acid in soils, and silicate bacteria promote mineral weathering by reducing the oxidoreduction potential of the rhizosphere (Emerson et al. 2008; Hall et al. 2005; Han and Lee 2006; Sheng et al. 2008).

Although the impact of pH on the release of mineral K is not fully recognized, some researchers have found that the concentration of $H^+$ had certain impact on interlayer replacement of K. They have suggested that K release remains unchanged within a pH range of 4.0–8.0 (Chute and Quirk 1967; Rausell-Colom et al. 1965) and that the dissolution of K feldspar in organic acids under acidic conditions (pH 2.5) was far more significant than under neutral pH conditions (pH 7.0). Reaction between K (mica components) and $H^+$ could be intensified in the presence of $H^+$ (Drever and Stillings 1997; Newman 1969; Öborn et al. 2005). Exchangeable K could be replaced by ferrous ions ($Fe^{2+}$) and manganese ions ($Mn^{2+}$) in the soil clay complex (Barré et al. 2008; Dobermann et al. 1996). Potassium deficiencies have been found to occur in soils under continuous cropping where low amounts of fertilizer K were applied (Regmi et al. 2002; Rupa et al. 2001). Both specific and nonspecific root exudates can play an active role in improving the mineral nutrition in the rhizosphere. The increase in soil organic matter can help weaken the K-fixation capacity of the soil (Olk, Cassman, and Fan 1995; Sokolova 2011). Humic acid and fulvic acid play significant roles in decomposing K and promoting the release of K (Schnitzer and Kodama 1976; Tan 1980). Humic acid increased both the water-soluble K and the exchangeable K in the soil (Olk, Cassman, and Fan 1995).

Researchers have developed various approaches to study K status changes in soil (Datta 2011; Song and Huang 1988; Yang, Zhang, and Ding 2012). Some of the widely used approaches include scanning electronic microscopy, thermal analysis, x-ray diffraction, and thermodynamic parameterization (Barré et al. 2008; Norrish 1961). The kinetics method on the basis of thermodynamic formula one and parabolic equations for K transformation include the batch equilibration method, flowing exchange method, and ion exchange resin method (Ballantine and Schneider 2009; Kalinowski and Schweda 1996; Rees, Pettygrove, and Southard 2013; Rochester 2007). The methods for studying K status changes in the rhizosphere soil include separation and measurement of rhizosphere soil, autoradiography, and testing of soil samples from root surface at different distances (screen spacing and slice sampling method) (Kuchenbuch and Barber 1987; Samal et al. 2010; Steingrobe and Claassen 2000). Obviously, previous studies were of great significance to improve our knowledge of K status changes in the rhizophere. However, studies on root exudates, including hydroponic culture and field experiments, often fail to disclose the internal mechanism(s) of K exchange. Most of these studies focus on qualitative analysis of one factor or multiple factors that affect the transformation of K status, instead of focusing on quantitative analysis of the process of equilibrium shifting (Banfield et al. 1999; Blaise, Bonde, and Chaudhary 2005; Lambers et al. 2009). How to enhance the exchange absorption of K ions by root system and improve the effectiveness of soil nutrients are some of the major concerns in studying the release of mineral K in the rhizosphere. This demands a systematic study and investigation to reach a rational conclusion.

This study focuses on two genotypes of cotton and explores different factors that were able to affect the release of different forms of K in the rhizosphere by considering a biogeochemical process integrating plants, soils, and microorganisms. The path model for exchangeable K was taken as an example. The model was aimed at determining the shift threshold of dynamic balance among water-soluble K (wsK), exchangeable K (eK), and nonexchangeable K (neK), $wsK \underset{\theta}{\overset{\varepsilon}{\rightleftarrows}} eK \underset{\omega}{\overset{\lambda}{\rightleftarrows}} neK$, which are under the influence of biogeochemical factors in the rhizosphere.

## Materials and Methods

To investigate the differences between rhizosphere soil and nonrhizosphere soil in nutrient supply and physiological mechanism, we carried out experiments on a rhizosphere soil and a nonrhizosphere soil using a high-efficiency genotype (HEG) cotton and low-efficiency genotype (LEG) cotton. The soil was a meadow soil with kaolinite, smectite, vermiculite, and hydromica as main constituents. Four treatments were used: control treatment (OPT), limited water treatment (LW, with 25% soil moisture), limited K treatment (LK, with 35% soil moisture, i.e., at normal level), and limited water and K treatment (LWK, with 25% soil moisture). The soil in each treatment weighed 8.5 kg. Fertilizer rates used in different treatments are listed in Table 1. All fertilizers were applied basally, except the carbamide fertilizers, which were applied 6.65 g at basal, seedling, and florescence stages, respectively. Planting effects of LEG and HEG are shown in Figure 1.

### *Sample Pretreatment*

Rhizosphere soil samples were collected by loosing the root zone soil, uprooting whole plant cotton, gently shaking off the root zone soil, and then carefully collecting the root-surface-adhering soil. The nonrhizosphere soil samples were collected at 10–15 cm deep from the soil surface.

**Table 1**
Fertilizing rates of different treatments (unit: g)

| Treatment | OPT | SW | SK | SWK |
|---|---|---|---|---|
| Urea | 6.65 | 6.65 | 6.65 | 6.65 |
| $Na_2PO_4 \cdot 2H_2O$ | 11.72 | 11.72 | 11.72 | 11.72 |
| KCl | 6.83 | 6.83 | 0 | 0 |
| $CaCO_3$ | 2.13 | 2.13 | 2.13 | 2.13 |
| $H_3BO_3$ | 1.00 | 1.00 | 1.00 | 1.00 |
| $ZnSO_4 \cdot 7H_2O$ | 1.87 | 1.87 | 1.87 | 1.87 |
| $MgSO_4 \cdot 7H_2O$ | 2.61 | 2.61 | 2.61 | 2.61 |

*Notes*. OPT, optimum fertilization treatment; SW, water limited; SK, K limited; SWK, water and K limited.

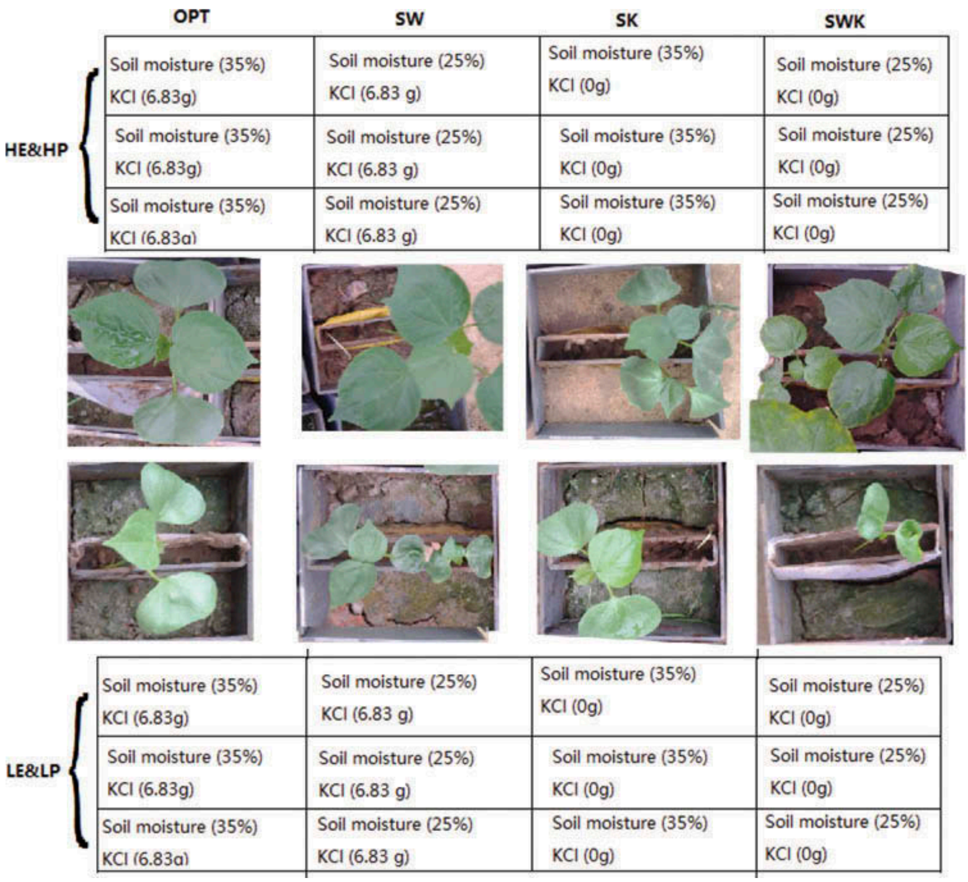


**Figure 1.** Cotton cultivation process different cropping treatments.

### *Soil and Plant Analyses*

Soil pH was measured in water (1:2.5 soil/water ratio) using a pH meter. Organic matter was determined by using the dichromate oxidation (Walkley 1947). Water-soluble K was determined in a 1:10 soil–distilled water extract ratio. Exchangeable K of soil was determined from the difference between 1.0 mol/L of ammonium acetate–extractable K ($NH_4OAc$-extractable K) and distilled water–extractable K. Nonexchangeable K in soil was determined from the difference between the boiling 1.0 mol/L of nitric acid–extractable K ($HNO_3$-extractable K) and 1.0 mol/L of $NH_4OAc$-extractable K. Total K was determined by liquating the soil samples with sodium hydroxide (NaOH). Clay mineralogy of the soil was determined by the x-ray diffraction method. The determination of K in plant and soil samples was performed using a flame photometer.

### *Determination of Soil Properties*

Pot experiments with two cotton genotypes as indicator crops were carried out to study K status of the different soils. X-ray fluorescence spectroscopy (Axios Advanced pw4400) and x-ray fluorescence (WD-XRF) were used for the analysis of the total content of mineral elements [e.g., sodium (Na), magnesium (Mg), aluminum (Al), silicon (Si), iron (Fe), calcium (Ca), etc.] in the rhizosphere soil and the nonrhizosphere soil. The components of organic matter were measured by the potassium dichromate method and marked as soil organic matter (SOM). When testing TC/NPOC(total carbon) and total nitrogen (TN) in soil solution, deionized water and soil sample (screened by 0.047-mm < R < 0.5-mm sieve) were mixed and lixiviated using the 20 ml / 14 g ratio, and then (after 36 h) filtered by filter membrane (Whatman GF/C-1822–047-0.45 μm). The filtrate was measured at 1073 K using XTA module of Multi N/C 2100.

## Results

### *Impact of Environmental Parameters on Potassium Status*

Environmental parameters were sampled and tested to examine the K status of two cotton genotypes (HEG and LEG). All the experimental data obeyed normal distribution. The coefficient of variation (CV) of measured datasets was mostly catergorized into weak variations [CV < 0.1, e.g., chemical index of alteration (CIA), Al, Si, K, Fe, carbonate ($CO_3$), saf, sodium (Na), P, ba, Mg, Na/K, Ca, sulfur (S), pH, and eK], followed by medium variations [0.1 < CV < 1.0, e.g., humic acid in soil that can be extracted by NaOH solution (0.1 mol/L, pH = 3) (NHA), TC, SOM], and strong variations (CV > 1, e.g., the quantity of K-solubilizing bacteria).

Environmental parameters had different impacts on K utilization by the cotton plant. Forms of K changed between rhizosphere soil and nonrhizosphere soil of cotton. The pH of the nonrhizosphere soil was larger than that of the rhizosphere soil (Figure 2A). It can be explained by the fact that root secretion and allelopathy produce large quantities of organic acids and soil colloids that could change the pH of the soil. Soil water is the largest contributor to oxidoreduction potential of rhizosphere soil. Acidic soils contained less K in

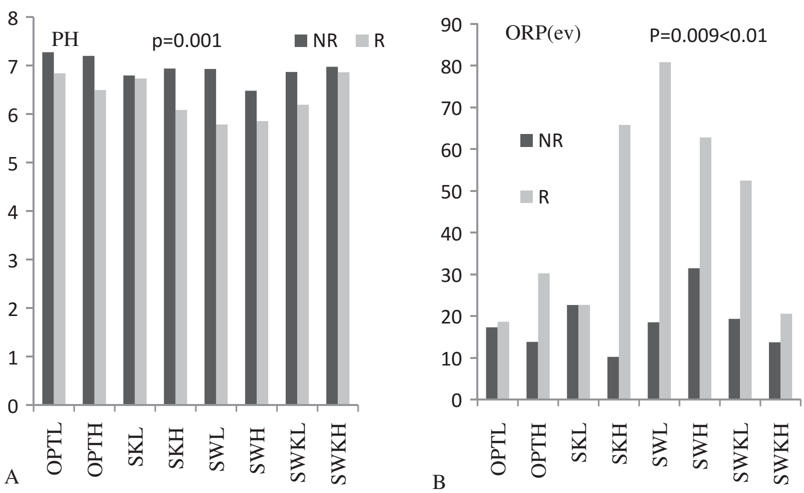


**Figure 2.** Oxidoreduction potential (ORP) and potential hydrogen (pH) of cotton rhizosphere soil and nonrhizosphere soil under different experimental treatments (R, rhizosphere soil; NR, nonrhizosphere soil; S, limited of; W, water; K, potassium; OPT, optimum fertilization treatment; H, HEG; L, LEG).

all fractions than the less weathered soils. The clay fractions exhibited mostly mica, vermiculite, smectite, and kaolinite. The oxidoreduction potential (ORP, eV) of rhizosphere soil is greater than that of nonrhizosphere soil (Figure 2B). The oxidoreduction potentials (ORP, eV) of rhizosphere soils treated by LW and LK of HEG and LEG cotton were greater than that of nonrhizosphere soil. The cation exchange capacity (CEC) of reduced soils was less under oxidized condition, due to collapse of the interlayer in response to increased layer charge upon structural Fe reduction.

The values of wsK in nonrhizosphere soil were 6.8 (41.3/6.1), 4.8 (88.8/18.6), and 2.1 times the valves in treatments LK and LW in rhizosphere soils of HEG cotton, and in treatment LWK in the rhizosphere soil of LEG cotton, respectively. The values of neK in nonrhizosphere soil were 3.0 (121.6/39.2), 2.6 (99.7/38.7), and 2.0 times the values in LK and LWK in rhizosphere soils of LEG cotton and in LW in rhizosphere soil of LEG cotton, respectively. Similarly, the values of eK in nonrhizosphere soil were 6.4 (40.3/6.3), 5.2 (27.5/5.2.7), and 2.4 times the values in treatment LW in rhizosphere soil of LEG cotton, LK in rhizosphere soil of HEG cotton, and LW in rhizosphere soil of HEG cotton. HEG cotton can effectively absorb wsK in LK and LW treatments and absorb eK in LK treatment. LEG cotton can effectively absorb neK in LK and LWK treatments and absorb eK in LK treatment (Figure 3).

The values of SOM reached 8.12% and 5.89% in the nonrhizosphere soil and the rhizosphere soil, respectively. Total carbon (TC) content in the nonrhizosphere soil was greater than that in the rhizosphere soil in normal, LW and LK, and TC treatments, while the treatment LWK showed the opposite effect. Water treatment is a major factor affecting water-soluble N in the soil. Soluble TN increased significantly in LW and LWK treatments. The TC/NPOC and TN test on soil solution revealed that the TN in the rhizosphere soil was greater than that of the nonrhizosphere soil (Figure 4).

Compared to the control treatment, K deficiency enhanced the transport of K from senescence leaves to functional leaves and young leaves, such that there was an increase in the recycle of K in the cotton plant. As we know, reproductive organs are the biggest and final sink for K in cotton plant, but main stem likely acted as a reserving and transferring

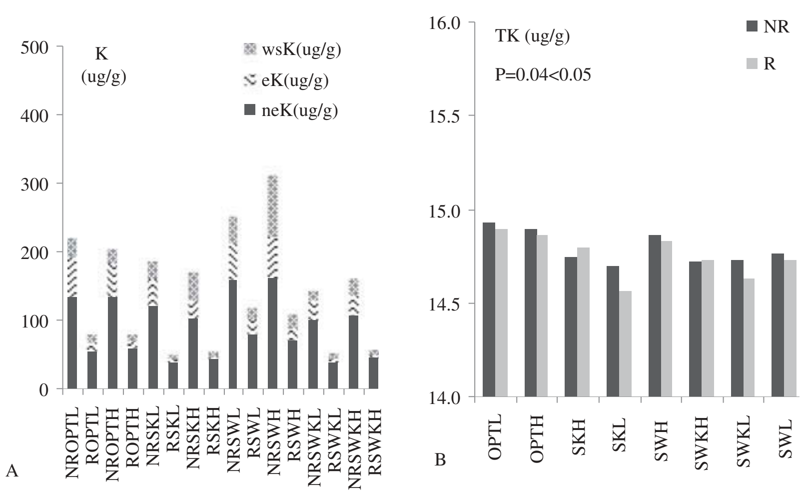


**Figure 3.** Comparisons of different forms of potassium of cotton in rhizosphere soil and nonrhizosphere soil under different experimental treatments.

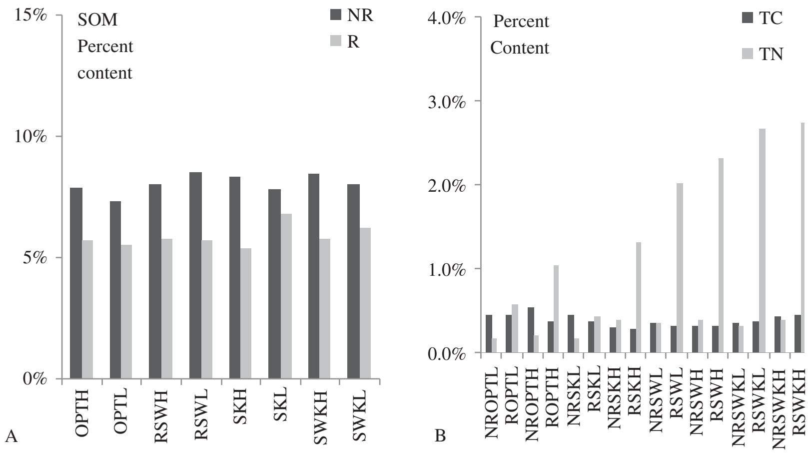


**Figure 4.** Soil organic matter in soil solution (SOM), total carbon (TC), and total nitrogen (TN) in soil solution of cotton rhizosphere soil and nonrhizosphere soil under different experimental treatments.



organ for potassium. The ratio of K partitioning in reproductive organs was increased by K deficiency. As shown in Figure 5, the K% content in cotton leaves decreased, but there was quite a variability in that effect. In leaves, stem, and reproductive organs, the K content were changed from 2.5, 3.96, and 2.87% to 3.2, 1.91, and 1.92%, respectively. In the HEG, K content in stem (except wadding stages) and main stem leaf was obviously lower than in the LEG. The K% content in leaves, branches, and leaves was high and in stem branches, especially in the main stem, it was low. Potassium percentage in the LEG cotton was lower in the early stage, but significantly greater in the later stages. When compared with other parts of the cotton plant, the variation of K concentration in seed and fiber with K availability was much less. These results indicated that cotton plant could use limited K to sustain offspring, preferably under K-deficiency conditions.

Strong correlations exist between general K and environmental factors in the rhizosphere soil and nonrhizosphere soil (Table 2). There was a strong negative correlation between K and Na, Mg, $CO_3$, Na/K, sa, and saf, and strong positive correlation between K and Al, Si, Fe, CIA, chloride (Cl), and bromide (Br). The quantities of zinc (Zn) and Cl, which were much greater in the rhizosphere soil than in the nonrhizosphere soil, were strongly and positively correlated with K in the rhizosphere soil. The values of wsK, neK, and eK were significantly or very significantly correlated with the types of extraction solvent, temperature, HA, Ca, P, S, chromium (Cr), nickel (Ni), soil soluble TN, CIA, and Na/K (Table 3). The pH value of the soil had a strong positive correlation with SOM, Ni, and soluble total carbon (TC) but a strong negative correlation with S, TN, and ORP.

### *Evaluating Potasium Efficiency of Two Cotton Genotypes using Path Analysis*

A path analysis model for K absorption in cotton fields was constructed to quantify the dynamic equilibrium of K absorption of two genotype cottons (HEG, LEG). For the selection of parameters for path analysis, soil chemical and mineralogical constraints were considered and after the correlation analysis (Pearson), the parameters that

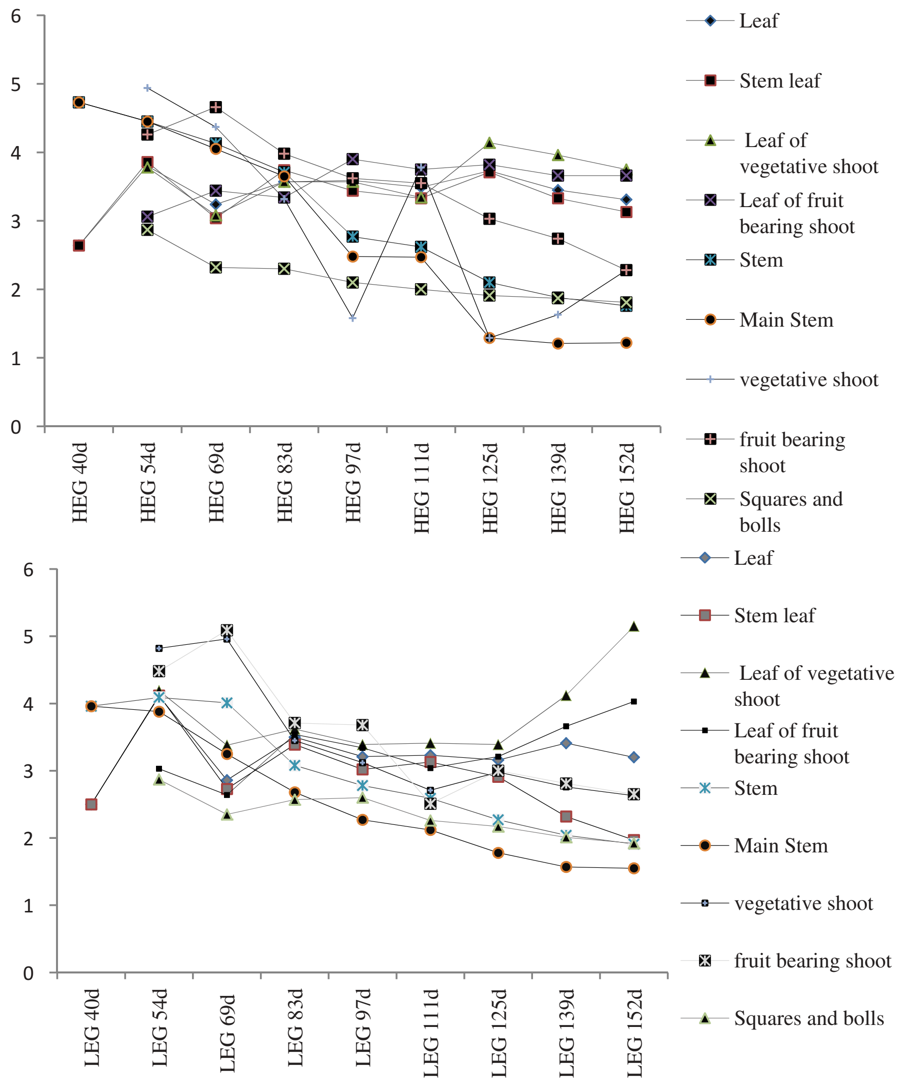


**Figure 5.** Changes of K percentage in the organs of cotton in their growth stages.

exhibited a relatively high correlation coefficient to K (in this case wsK, neK, and eK) were selected for the path analysis. For purpose of model construction, experimental datasets were standardized and correlation coefficients. The parameters were categorized into direct and indirect correlations. Path coefficients were derived by multivariate linear regression (Figure 6).

In the path model, the direct effects of soil properties on the ZeK were represented by single-headed arrows, while correlation coefficients between soil properties were represented by double-headed arrows. Direct and indirect effects in the path analysis were derived from (i) multiple linear regressions of soil properties on the ZeK (Z means standardization) and (ii) simple correlation coefficients between soil properties. Direct and indirect effects were indicated by value and marked with ±. The direct effects of soil properties on the ZeK were termed path coefficients and were

**Table 2**
Correlation between total K and environmental factors

| Environmental factor | K |
|---|---|
| Na | −0.47a |
| Mg | −0.50a |
| $CO_3$ | −0.62a |
| ICV | −0.59a |
| Na/K | −0.67a |
| Sa | −0.60a |
| Saf | −0.58a |
| Al | 0.79a |
| Si | 0.45a |
| Fe | 0.58a |
| CIA | 0.56a |
| Cl | 0.36b |
| Br | 0.29b |

*Note*. Statistical probabilities of a and b: A, $P < 0.01$; b, $P < 0.05$.

**Table 3**
Correlation between three different forms of K and environmental factors

| Environmental factor | wsK | neK | eK |
|---|---|---|---|
| SOM | $0.58^a$ | $0.80^b$ | $0.74^b$ |
| wsK | $0.54^a$ | $0.65^b$ | $0.68^b$ |
| After weathered eK | $0.53^a$ | $0.79^b$ | $0.74^b$ |
| After weathered wsK | $0.51^a$ | $0.67^b$ | $0.70^{\mathrm{b}}$ |
| After weathered nek | $0.53^a$ | $0.69^b$ | $0.65^b$ |
| Na | $-0.55^a$ | | $-0.55^a$ |
| Ca | $-0.55^a$ | $-0.83^b$ | $-0.78^b$ |
| P | | $-.54^a$ | $-0.56^a$ |
| S | $-0.56^a$ | $-0.86^b$ | $-0.83^b$ |
| Cr | $0.58^a$ | $0.62^a$ | $0.59^a$ |
| Ni | $0.59^a$ | $0.70^b$ | $0.68^b$ |
| CIA | | $0.56^a$ | $0.51^a$ |
| Na/K | $-0.52^a$ | $-0.66^b$ | $-0.67^b$ |
| TN | | $-0.64^b$ | $-0.62^a$ |
| wsK | | $0.77^b$ | $0.73^b$ |
| neK | | | $0.98^b$ |

*Note*. Statistical probabilities of a and b: A, $P < 0.01$; b, $P < 0.05$.

standardized partial regression coefficients for each of the soil properties in the multiple linear regressions against the ZeK. Indirect effects of soil properties on the ZeK were determined from the product of the simple correlation coefficient between soil properties and the path coefficient (i.e., one two-headed arrow and one single-headed

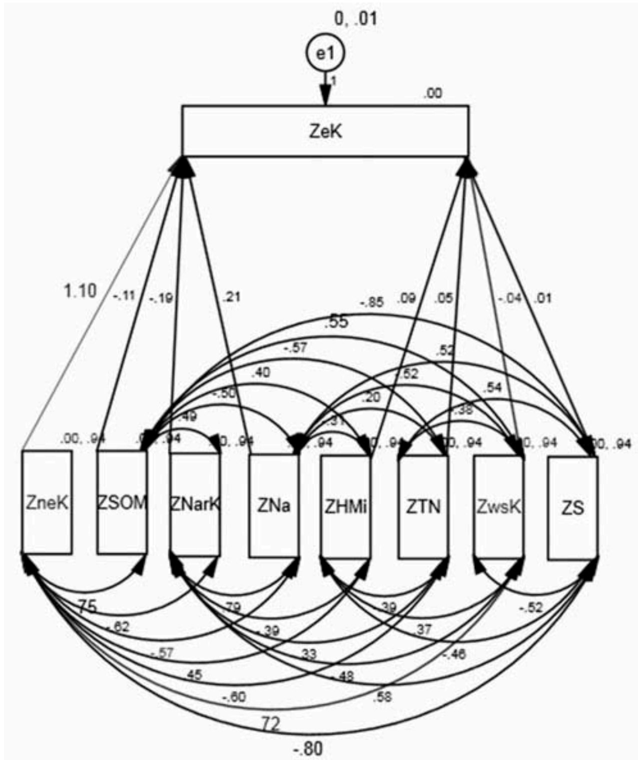


**Figure 6.** Path model of exchangeable potassium (eK).

arrow). The correlation between the ZeK and a soil property was the sum of the entire path connecting two variables, as described by

$$r_{neK,eK} = P_{eK,neK} + r_{neK,SOM}P_{eK,SOM} + r_{neK,Na/K}P_{eK,Na/K} + r_{neK,Na}P_{eK,Na} + r_{neK,HMi}P_{eK,HMi} + r_{neK,TN}P_{eK,TN} + r_{neK,wsK}P_{eK,wsK} + r_{neK,S}P_{eK,S}$$

where $r_{ij}$ was the simple correlation coefficient between the ZeK and a soil property, $P_{ij}$ was the path coefficient between the ZeK and a soil property, and $r_{ij}P_{ij}$ was the indirect effect of a soil property on the ZeK. In the path model, "e1" above ZeK was an uncorrelated residue (e) that represents the unexplained part of an observed variable in the path model was calculated as (Zhang et al. 2005)

$$e = (1 - R^2)^{0.5} = 0.01$$

where $R^2$ was the coefficient of determination of the multiple regression equation between the ZeK and the eight soil properties (neK, SOM, Na/K, Na, HMi, TN, wsK, and S). Backward regression analysis was performed with the ZeK as the dependent variable and the eight soil properties as independent variables. Backward regression was a multiple regression procedure in which all the independent variables were entered into the regression equation at the beginning, and variables that do not contribute significantly to the fit of the regression model were successively eliminated until only statistically significant variables remain. Path coefficients range from large to small as Z(neK) > Z($CO_3$) > Z(pH) > Z(E) > Z(Na) > Z(Mg) > Z(S) > Z(K) > Z(PHA) > Z(SOM) > Z(CIA) > Z(HMi) > Z(TN) > Z(Na/K) > Z(wsK).

There was a dynamic balance between neK and wsK (ZneK and ZwsK). S was concomitant with K (ZS). Na in the soil has significant impact on the K absorption of cotton (ZNarK, ZNa, NarK represents total Na/K) as Na and K have similar chemical properties, and isomorphism was likely to occur in their crystal structures. SOM, HMi, and TN in the rhizosphere soil change and the range, path, and rate of K absorption.

### *Evaluating Potassium Efficiency of Two Cotton Genotypes using Path Analysis*

Dynamics of K forms and their transformation in soils under two genotype cottons (HEG, LEG) are controlled by different threshold values. Quantification of this dynamics is significant for fertilizer K application in actual practice.

The dynamics indicated that when wsK in soil solution was lower than the equilibrium threshold value (in LK treatment), eK was likely to change into wsK; the equilibrium was reached at the point calculated by function. LEG equilibrium threshold value was 65–70 mg·kg$^{-1}$, while the HEG equilibrium threshold value was 40–45 mg·kg$^{-1}$. Both cotton genotypes can effectively absorb eK in LK. In the soil under LEG cotton treated by LK, the eK changed into wsK, when the wsK in soil solution was lower than 65–70 mg·kg$^{-1}$. In the soil under HEG cotton treated by LK, eK changed into wsK, when the wsK in soil solution was lower than 40–45 mg·kg$^{-1}$. The total absorbed K was only 0.94–2.16% of soil K, but the quantity of eK absorbed was 21–32% in the LK soil. Soil with a moisture content of 35% reduced the fixed K by 2–29 mg·kg$^{-1}$ vis-à-vis the soil that had 25% moisture content. The soil K fixation was increased after dry and humid alternation. Crop yields can be increased when fertilizer K is applied according to proper ratio among different forms of K and humic acid in soils. It also can explain why the cotton genotypes growing in soils with poor fertility can produce similar yields as those in soils with good fertility.

For LEG cotton, equilibrium thresholds calculated from the dynamic equilibrium of K in the rhizosphere soil were greater. This showed that in the LK treatment, K absorption by crops was difficult. However, the vitality of HEG was strong under sufficient water conditions. When K level was not less than 40–45 mg·kg$^{-1}$, HEG cotton could continuously absorb K and transport it to various organs. Under drought conditions, HEG increased rhizosphere secretion, silicate bacteria, and acidity. It enhanced the conversion of eK to wsK, and accelerated the movement of eK to wsK, so as to promote K absorption. It has been reported in literature that a significant portion of K (70–90%) required by plants comes from the nonexchangeable pool in the absence of easily supplied K, thus indicating the beneficial role of the fixed K (Rupa et al. 2001; Wang et al. 2011). For HEG cotton, the thresholds of dynamic equilibrium of K in the rhizosphere soil were low, which resulted in easy K absorption by crops. That is why the HEG cotton could survive in drought conditions.

HEG cotton could effectively utilize wsK in LK and OPT treatments and effectively utilize eK in LK treatment, while LEG cotton could effectively utilize eK only in LK and LWK treatments and effectively utilize eK in LWK treatment. Figure 7 shows the differences in K uptake among HEG and LEG. The results showed that HEG at 6- or 7-leaf stage had significantly greater biomass and K accumulation than LEG. It was mainly due to its significantly greater active absorbing surface area of root and comparatively greater $I_{max}$, which caused more K accumulation in HEG plant. Despite LEG's greater $I_{max}$ between the two cotton, K accumulation in LEG was less, which might be attributed to its significantly lower HEG and feedback inhibition on K uptake by greater K concentration

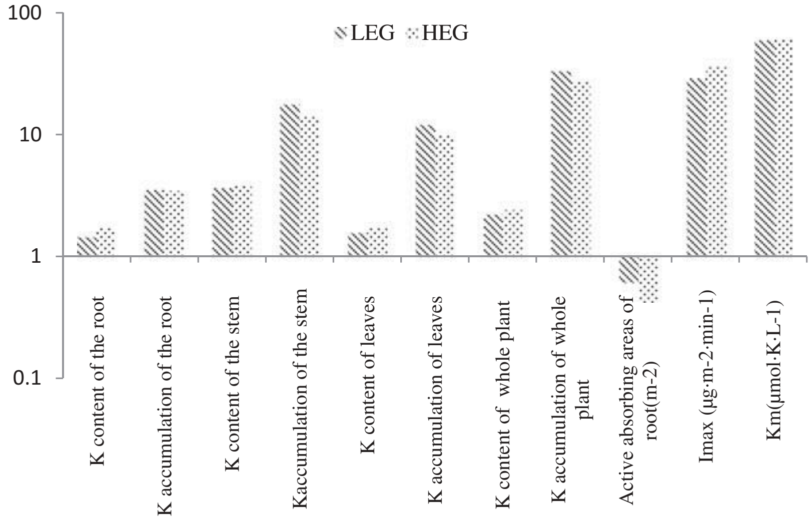


**Figure 7.** K-uptake kinetic parameters and distribution of K in different organs of cotton.



in the plant. HEG cotton can absorb and utilize humic acids in the rhizosphere soil, while LEG cotton can increase the content of organic matter by root exudates and microbial action, improve soil structure, and promote the root system to absorb wsK.

## Discussion and Conclusion

The significance of the study lies in quantifying the K status changes and complex relations among correlation factors. This can help provide guidance to practical production and realize the shift of dynamic balance among different forms of K by controlling corresponding environmental factors, ultimately improving the efficiency of fertilizer K application.

First, rhizosphere bacteria can secrete some acid-causing substances, reduce pH, and directly dissolve K in the soil. Polysaccharides can damage K feldspars to some extent. Silicate bacteria can produce acids during liquid culture, reduce pH, reduce oxidoreduction potential (ORP), and in turn promote K release. The nutrient, energy, and signal exchanges in the rhizosphere soil can change the water content, nutrient supply of the soil, absorption efficiency of root system, as well as the status of microorganisms. On the one hand, $H^+$ accelerates the dissolution of minerals by acid reduction; on the other hand, hydroxonium ion can replace K in mineral crystal lattice because of its similarity to K ions and then release $K^+$.

Second, the lint yield had a significant positive correlation with boll number per plant (r = 0.94), single boll weight (r = 0.33), plant height (r = 0.28), and number of fruit branches (r = 0.27), which indicated that increasing these agronomic parameters is the basis for increasing lint yield. The path analysis showed that the direct effect of boll number per plant was the greatest on lint yield with a path coefficient of 0.90, followed by single boll weight with the path coefficient as 0.37. Path analysis of properties and cotton production is shown in Table 4. The table shows that the direct effect of boll number per plant was the greatest on lint yield with a path coefficient of 0.90, followed by single boll weight with the path coefficient as 0.37 (He and Chen 2013). In conclusion, middle-high plant height, initial fruit branch, number of fruit branches and bolls, and boll size should receive more attention during high-yielding cotton breeding.

**Table 4**
Path analysis of properties and cotton production

| Characteristic | Director path coefficient | Indirector path coefficient | | | | | |
|---|---|---|---|---|---|---|---|
| | | Boll number per plant | Single boll weight | Seed index | Lint percentage | Number of fruit branches | Initial fruit branch |
| Boll number per plant | 0.90 | — | 0.02 | 0.00 | 0.01 | 0.00 | 0.00 |
| Single boll weight | 0.37 | 0.06 | — | −0.01 | −0.09 | 0.00 | 0.00 |
| Seed index | −0.02 | 0.04 | 0.15 | — | −0.05 | 0.00 | 0.00 |
| Lint percentage | 0.21 | 0.05 | −0.17 | 0.00 | — | 0.00 | 0.00 |
| Number of fruit branches | 0.01 | 0.25 | −0.02 | 0.00 | 0.02 | — | 0.01 |
| Initial fruit branch | −0.02 | −0.12 | 0.03 | 0.00 | −0.04 | 0.00 | — |

Third, because the mineral nutrition of plants was affected by interactions among plants, soils, and microorganisms, the path model should be used to conduct quantitative analysis on the interactions among plants, soils, and microorganisms as a whole, so as to obtain more objective and correct conclusions. This study was of great importance in aspects such as exploring the absorption of different forms of K in the rhizosphere soil, finding out the adaptability of root system to soil nutrient, selecting the genotype cotton with high efficiency in nutrient absorption and predicting nutrient absorption in the soil.

## Funding

We acknowledge with gratitude the research grants kindly provided by the Hundred-talent Project of the Chinese Academy of Sciences (Dr. He, H.M., 2011009), the National Science Foundation of China (No. 41072137), the Innovation Frontier Project of the Institute of Soil and Water Conservation of the Chinese Academy of Sciences (10502), Key Research Program of the Chinese Academy of Sciences (Grant No. KZZD-EW-04), Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDB03020300), and State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau (10501-192). Datasets were provided by Data-Sharing Network of Earth System Science (www.geodata.cn), Center for Loess Plateau Data-Sharing Network, China.

## References

Ballantine, K., and R. Schneider. 2009. Fifty-five years of soil development in restored freshwater depressional wetlands. *Ecological Applications* 19:1467–80. doi:10.1890/07-0588.1.

Balogh-Brunstad, Z., C. K. Keller, B. T. Bormann, R. O'Brien, D. Wang, and G. Hawley. 2008. Chemical weathering and chemical denudation dynamics through ecosystem development and disturbance. *Global Biogeochemical Cycles* 22:1–11. doi:10.1029/2007GB002957.

Banfield, J. F., W. W. Barker, S. A. Welch, and A. Taunton. 1999. Biological impact on mineral dissolution: Application of the lichen model to understanding mineral weathering in the rhizosphere. *Proceedings of the National Academy of Sciences* 96:3404–11. doi:10.1073/pnas.96.7.3404.

Barré, P., C. Montagnier, C. Chenu, L. Abbadie, and B. Velde. 2008. Clay minerals as a soil potassium reservoir: Observation and quantification through x-ray diffraction. *Plant and Soil* 302:213–20. doi:10.1007/s11104-007-9471-6.

Blaise, D., A. Bonde, and R. Chaudhary. 2005. Nutrient uptake and balance of cotton + pigeonpea strip intercropping on rainfed Vertisols of central India. *Nutrient Cycling in Agroecosystems* 73:135–45. doi:10.1007/s10705-005-0073-5.

Cakmak, I. 2005. The role of potassium in alleviating detrimental effects of abiotic stresses in plants. *Journal of Plant Nutrition and Soil Science* 168:521–30. doi:10.1002/(ISSN)1522-2624.

Chute, J., and J. Quirk. 1967. Diffusion of potassium from mica-like clay minerals. *Nature* 213:1156–57. doi:10.1038/2131156a0.

Datta, S. 2011. Potassium dynamics and status in Indian soils. *Karnataka Journal of Agricultural Sciences* 24:25–44.

Dobermann, A., K. Cassman, P. S. Cruz, M. Adviento, and M. Pampolino. 1996. Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice systems, II: Effective soil K-supplying capacity. *Nutrient Cycling in Agroecosystems* 46:11–21. doi:10.1007/BF00210220.

Drever, J., and L. Stillings. 1997. The role of organic acids in mineral weathering. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 120:167–81. doi:10.1016/S0927-7757(96)03720-X.

Emerson, D., L. Agulto, H. Liu, and L. Liu. 2008. Identifying and characterizing bacteria in an era of genomics and proteomics. *Bioscience* 58:925–36. doi:10.1641/B581006.

Fernández, F. G., S. M. Brouder, J. J. Volenec, C. A. Beyrouty, and R. Hoyum. 2011. Soybean shoot and root response to localized water and potassium in a split-pot study. *Plant and Soil* 344:197–212. doi:10.1007/s11104-011-0740-z.

Hall, K., J. M. Arocena, J. Boelhouwers, and Z. Liping. 2005. The influence of aspect on the biological weathering of granites: Observations from the Kunlun Mountains, China. *Geomorphology* 67:171–88. doi:10.1016/j.geomorph.2004.09.027.

Han, H., and K. Lee. 2006. Effect of co-inoculation with phosphate and potassium solubilizing bacteria on mineral uptake and growth of pepper and cucumber. *Plant Soil and Environment* 52:130.

He, W., and F. Chen. 2013. Evaluating status change of soil potassium from path model. *Plos One* 8: e76712.

Hinsinger, P., and B. Jaillard. 1993. Root-induced release of interlayer potassium and vermiculitization of phlogopite as related to potassium depletion in the rhizosphere of ryegrass. *Journal of Soil Science* 44:525–34. doi:10.1111/ejs.1993.44.issue-3.

Kalinowski, B. E., and P. Schweda. 1996. Kinetics of muscovite, phlogopite, and biotite dissolution and alteration at pH 1–4, room temperature. *Geochimica et Cosmochimica Acta* 60:367–85. doi:10.1016/0016-7037(95)00411-4.

Kopittke, P. M. 2012. Interactions between Ca, Mg, Na, and K: Alleviation of toxicity in saline solutions. *Plant and Soil* 352:353–62. doi:10.1007/s11104-011-1001-x.

Kuchenbuch, R., and S. Barber. 1987. Yearly variation of root distribution with depth in relation to nutrient uptake and corn yield. *Communications in Soil Science and Plant Analysis* 18:255–63. doi:10.1080/00103628709367816.

Lambers, H., C. Mougel, B. Jaillard, and P. Hinsinger. 2009. Plant-microbe-soil interactions in the rhizosphere: An evolutionary perspective. *Plant and Soil* 321:83–115. doi:10.1007/s11104-009-0042-x.

Newman, A. 1969. Cation exchange properties of micas. *Journal of Soil Science* 20:357–72. doi:10.1111/ejs.1969.20.issue-2.

Norrish, K. T. 1961. Low-angle x-ray diffraction studies of the swelling of montmorillonite and vermiculite. *Clays and Clay Minerals* 10:123–49. doi:10.1346/CCMN.

Öborn, I., Y. Andrist-Rangel, M. Askegaard, C. Grant, C. Watson, and A. Edwards. 2005. Critical aspects of potassium management in agricultural systems. *Soil Use and Management* 21:102–12. doi:10.1079/SUM2005297.

Øgaard, A. F., and S. Hansen. 2010. Potassium uptake and requirement in organic grassland farming. *Nutrient Cycling in Agroecosystems* 87:137–49. doi:10.1007/s10705-009-9320-5.

Olk, D., K. Cassman, and T. Fan. 1995. Characterization of two humic acid fractions from a calcareous vermiculitic soil: Implications for the humification process. *Geoderma* 65:195–208. doi:10.1016/0016-7061(95)94048-9.

Rausell-Colom, J., T. Sweatman, C. Wells, K. Norrish, E. Hallsworth, and D. Crawford. 1965. Studies in the artificial weathering of mica. *Experimental Pedology* 40–72.

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* 44:741–48. doi:10.1080/00103624.2013.748129.

Regmi, A., J. Ladha, H. Pathak, E. Pasuquin, C. Bueno, D. Dawe, P. Hobbs, D. Joshy, S. Maskey, and S. Pandey. 2002. Yield and soil fertility trends in a 20-year rice-rice-wheat experiment in Nepal. *Soil Science Society of America Journal* 66:857–67. doi:10.2136/sssaj2002.8570.

Rochester, I. J. 2007. Nutrient uptake and export from an Australian cotton field. *Nutrient Cycling in Agroecosystems* 77:213–23. doi:10.1007/s10705-006-9058-2.

Rupa, T., S. Srivastava, A. Swarup, and D. Singh. 2001. Potassium supplying power of a Typic Ustochrept profile using quantity/intensity technique in a long-term fertilized plot. *Journal of Agricultural Science* 137:195–204. doi:10.1017/S0021859601001216.

Samal, D., J. L. Kovar, B. Steingrobe, U. S. Sadana, P. S. Bhadoria, and N. Claassen. 2010. Potassium uptake efficiency and dynamics in the rhizosphere of maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), and sugar beet (*Beta vulgaris* L.) evaluated with a mechanistic model. *Plant and Soil* 332:105–21. doi:10.1007/s11104-009-0277-6.

Schnitzer, M., and H. Kodama. 1976. The dissolution of micas by fulvic acid. *Geoderma* 15:381–91. doi:10.1016/0016-7061(76)90042-2.

Sheng, X. F., F. Zhao, L. Y. He, G. Qiu, and L. Chen. 2008. Isolation and characterization of silicate mineral-solubilizing *Bacillus globisporus* Q12 from the surfaces of weathered feldspar. *Canadian Journal of Microbiology* 54:1064–68. doi:10.1139/W08-089.

Simonsson, M., S. Hillier, and I. Öborn. 2009. Changes in clay minerals and potassium fixation capacity as a result of release and fixation of potassium in long-term field experiments. *Geoderma* 151:109–20. doi:10.1016/j.geoderma.2009.03.018.

Sokolova, T. A. 2011. The role of soil biota in the weathering of minerals: A review of literature. *Eurasian Soil Science* 44:56–72. doi:10.1134/S1064229311010121.

Song, S., and P. Huang. 1988. Dynamics of potassium release from potassium-bearing minerals as influenced by oxalic and citric acids. *Soil Science Society of America Journal* 52:383–90. doi:10.2136/sssaj1988.03615995005200020015x.

Steingrobe, B., and N. Claassen. 2000. Potassium dynamics in the rhizosphere and K efficiency of crops. *Journal of Plant Nutrition and Soil Science* 163:101–6. doi:10.1002/(ISSN)1522-2624.

Tan, K. 1980. The release of silicon, aluminum, and potassium during decomposition of soil minerals by humic acid. *Soil Science* 129:5–11.

Vanlauwe, B., J. Diels, O. Lyasse, K. Aihou, E. Iwuafor, N. Sanginga, R. Merckx, and J. Deckers. 2002. Fertility status of soils of the derived savanna and northern guinea savanna and response to major plant nutrients, as influenced by soil type and land use management. *Nutrient Cycling in Agroecosystems* 62:139–50. doi:10.1023/A:1015531123854.

Walkley, A. 1947. A critical examination of a rapid method for determining organic carbon in soils: Effect of variations in digestion conditions and of inorganic soil constituents. *Soil Science* 63:251–64. doi:10.1097/00010694-194704000-00001.

Wang, H. Y., Q. H. Shen, J. M. Zhou, J. Wang, C. W. Du, and X. Q. Chen. 2011. Plants use alternative strategies to utilize nonexchangeable potassium in minerals. *Plant and Soil* 343:209–20. doi:10.1007/s11104-011-0726-x.

Yang, W., M. Zhang, and G. Ding. 2012. Effect of transgenic Bt cotton on bioactivities and nutrients in rhizosphere soil. *Communications in Soil Science and Plant Analysis* 43:689–700. doi:10.1080/00103624.2012.644008.

Zhang, H., J. Schroder, J. Fuhrman, N. Basta, D. Storm, and M. Payton. 2005. Path and multiple regression analyses of phosphorus sorption capacity. *Soil Science Society of America Journal* 69:96–106.