

# The potassium paradox: Implications for soil fertility, crop production and human health

S.A. Khan\*, R.L. Mulvaney and T.R. Ellsworth

Department of Natural Resources and Environmental Sciences, University of Illinois at Urbana-Champaign, 1102 S. Goodwin Avenue, Urbana, IL 61801, USA.

\*Corresponding author: potassiumparadox@gmail.com

Accepted 5 June 2013; First published online 10 October 2013

Research Paper

## Abstract

Intensive fertilizer usage of KCl has been inculcated as a prerequisite for maximizing crop yield and quality, and relies on a soil test for exchangeable K in the plow layer to ensure that soil productivity will not be limited by nutrient depletion. The interpretive value of this soil test was rigorously evaluated by: (1) field sampling to quantify biweekly changes and seasonal trends, (2) characterizing the variability induced by air drying and the dynamic nature of soil K reserves and (3) calculating the K balance in numerous cropping experiments. These evaluations leave no alternative but to question the practical utility of soil K testing because test values cannot account for the highly dynamic interchange between exchangeable and non-exchangeable K, exhibit serious temporal instability with or without air drying and do not differentiate soil K buildup from depletion. The need for routine K fertilization should also be questioned, considering the magnitude and inorganic occurrence of profile reserves, the recycling of K in crop residues and the preferential nature of K uptake. An extensive survey of more than 2100 yield response trials confirmed that KCl fertilization is unlikely to increase crop yield. Contrary to the inculcated perception of KCl as a qualitative commodity, more than 1400 field trials predominately documented a detrimental effect of this fertilizer on the quality of major food, feed and fiber crops, with serious implications for soil productivity and human health.

**Key words:** soil K testing, soil K reserves, residue K recycling, KCl, potash fertilizer, agricultural sustainability, Cd bioaccumulation, Morrow Plots

## Introduction

In the modern era of industrialized agriculture, there is a prevalent view of intensive fertilizer inputs as a prerequisite for maximizing yield, and hence short-term profitability. Unfortunately, several decades of these inputs can have unintended consequences for the chemical, physical and biological functioning of the soil resource, and for air, water and food quality<sup>1–3</sup>.

Implicit to intensive K fertilization is the bank account philosophy of managing soil fertility, which emphasizes the need for fertilizer inputs to at least replace crop removal<sup>4</sup>. According to this philosophy, a major rationale for K fertilization is to maintain soil reserves without regard to the economic importance of yield response<sup>5–7</sup> or the overwhelming abundance of mineral K in most arable soils and subsoils, especially those dominated by 2:1 minerals<sup>8–12</sup>. These reserves were recognized long ago for their fundamental role in supplying K for plant uptake, such that K fertilization was considered unnecessary when residues were returned to the soil<sup>8,9</sup>. With the

entry of Canadian KCl into the world fertilizer market in the 1960s, the traditional approach to indigenous K fertility was displaced by growing reliance on a commercialized input.

Fertilizer K management originally utilized the sufficiency concept to predict yield response from exchangeable K in the plow layer<sup>13</sup>. An implicit assumption is that soil testing, typically carried out once in a 4-year interval, can adequately represent profile supplies of plant-available K. This assumption, no less relevant to the basic cation saturation ratio concept<sup>14–16</sup>, is highly questionable in view of evidence that the exchangeable fraction is in a highly dynamic and temporally variable equilibrium with a vast storehouse of non-exchangeable and mineral K<sup>10,17–21</sup> (see also supplemental references [1–3] for the online version of the paper). Since the 1970s, excessive K usage has been further intensified by the buildup-maintenance concept that inflates fertilizer consumption under the pretext of preventing yield reduction, and thus accentuates the economic interests of the fertilizer industry over those of the producer<sup>6,7</sup>.

Under the latter concept, the sole purpose of soil K testing is to quantify fertilizer inputs for building up exchangeable K to a critical level that precludes the possibility of yield response, while still more K is prescribed as maintenance to replace annual crop K removal.

To ascertain whether the usual approach for exchangeable K testing, with or without air drying, provides a reliable basis for fertilizer K management, the work reported herein was conducted to quantify: (1) temporal and seasonal variability in K test values obtained through biweekly sampling of surface soil with no recent history of KCl fertilization; (2) K test changes induced by air drying soils that differed in long-term KCl inputs; (3) non-exchangeable K released by successive extraction; (4) K balance in relation to soil K test changes for cropping experiments with static fertilizer K inputs; and (5) the fertilizer value of KCl in a systematic survey of peer-reviewed and university publications that encompass a global range of soil types, cropping practices and management systems in production settings. Based on these evaluations and the recycling of K from crop residues, we tested the null hypotheses that: (1) the usual approach to soil K testing is of no value for predicting fertilizer requirement or monitoring changes in K fertility, and (2) KCl fertilization will seldom lead to economic yield response or improve crop quality.

## Materials and Methods

### Seasonality study

To characterize seasonal changes in K test values, soil samples were collected at biweekly intervals between mid-March 1986 and 1990, from the University of Illinois South Farm at Urbana, IL. As detailed by Khan<sup>22</sup>, this sampling was done from six plots in a K rate study on a Drummer silty clay loam, classified as a fine-silty, mixed, superactive, mesic Typic Endoaquoll with montmorillonite and illite as the major 2:1 clay minerals<sup>23</sup>. The plots, each measuring 6 m wide and 24 m long with <1% slope, had been used as a corn (*Zea mays* L.) breeding nursery cropped in alternate years to soybean (*Glycine max* L. Merr.), and had been fertilized annually with KCl from 1970 to 1983, at rates of 0, 46, 93, 139, 186 and 232 kg K ha<sup>-1</sup>. Of the six plots sampled by Khan<sup>22</sup> for the seasonality study, the sole focus herein is on the plot that received no fertilizer P or K, but only a spring application of 160–180 kg N ha<sup>-1</sup> as NH<sub>4</sub>NO<sub>3</sub> when corn was grown between 1970 and 1990. Sampling followed a fixed protocol involving: (1) manual use of either a 2.5-cm diameter probe or an auger; (2) care to avoid previous sampling points; and (3) collection of a five-core composite (0–18 cm) from each of three locations representing northern, central and southern subplots. The composite samples, in polyethylene bags, were immediately transported to the laboratory, passed through a 4.75 mm screen and thoroughly homogenized.

Triplicate 1.2-g subsamples were analyzed for field-moist exchangeable K following the ammonium acetate (NH<sub>4</sub>C<sub>2</sub>H<sub>3</sub>O<sub>2</sub>)-extraction technique described by Knudsen *et al.*<sup>24</sup>, using a Jenway Model PFP 7 flame photometer (Jenway, Essex, UK). So as to express these analyses on an air-dry basis, soil moisture content was determined by air drying two additional 1.2-g subsamples for 48 h in a forced-air oven at 40°C. The remaining soil was transferred to a paper bag and subsequently air dried in the same oven for 10 days. The dried soil was crushed with a rolling pin to pass a 2 mm screen, mixed thoroughly in the bag and analyzed within 1 day for air-dried exchangeable K.

### Drying study

The effect of soil moisture level on the release of exchangeable K was investigated for the Drummer soil at Urbana where the seasonality study was conducted. After harvest in October 1989, a five-core composite was collected with a 2.5-cm diameter soil probe to a depth of 18 cm at three locations within each of the four plots where the annual K rate had been 0–139 kg ha<sup>-1</sup>, and the 15 cores collected from each plot were composited in polyethylene bags. The samples were transported to the laboratory, screened while field-moist to pass through a 4.75 mm sieve and spread to a depth of 2.5 cm on wooden trays. The trays were placed on laboratory benches for drying at approximately 20°C and 64% relative humidity, while air was continuously circulated across the samples that were periodically homogenized to ensure uniform moisture content. At 3-h intervals, triplicate samples from each tray were analyzed for moisture content and exchangeable K (expressed on an air-dried basis), until no further moisture loss was observed after 33 h. These analyses were also performed on a portion of each air-dried sample that had been oven-dried at 105°C. The percentage increase in exchangeable K upon air drying was calculated as  $100 \times (K_{AD} - K_{FM}) / K_{FM}$ , where the field-moist (FM) value was obtained at the initial soil moisture content and the air-dried (AD) value corresponds to a moisture content of approximately 40 g kg<sup>-1</sup>.

### Speciation study

Biweekly soil samples (0–18 cm) collected and air dried for the seasonality study in August and September were composited each year between 1986 and 1989 to represent the plot that had received N but no P or K fertilization since 1970. Following 1 M NH<sub>4</sub>C<sub>2</sub>H<sub>3</sub>O<sub>2</sub> extraction to determine exchangeable K, six successive digestions were performed to liberate non-exchangeable K with boiling 1 M HNO<sub>3</sub><sup>24</sup>. The digests were centrifuged, and the supernatant was analyzed for K by flame photometry as described previously.

Total K analyses were performed on samples composited from 1986 and 1989, by fusion of an oven-dried (105°C) portion with LiBO<sub>2</sub>·8H<sub>2</sub>O in a Pt crucible<sup>25</sup>.

The fused sample was dissolved in 0.04 M HNO<sub>3</sub> and analyzed by atomic emission spectroscopy using a Perkin Elmer Model 3110 spectrometer (Perkin Elmer, Norwalk, CT) and an air-C<sub>2</sub>H<sub>2</sub> flame.

### *Morrow Plots potassium balance study*

To ascertain whether the conventional approach to soil K testing reflects net K balance, exchangeable K was determined for surface (0–15 cm) samples collected in 1955 and 2005 from the Morrow Plots, where the world's longest continuous cropping experiment on the most productive soil order (Mollisols) has been conducted since 1876. The samples used in our work represent six unreplicated subplots currently designated as 3NA and 3NB under continuous corn, 4NA and 4NB under a 2-year rotation of corn and oats (*Avena sativa* L.) or soybean (since 1967) and 5NA and 5NB under a 3-year rotation of corn, oats and alfalfa (*Medicago sativa* L.) hay, where B- but not A-series subplots receive NPK fertilization that supplied 28–186 kg K ha<sup>-1</sup> in some but not all years. The soil is classified as Flanagan silt loam, a fine, smectitic, mesic Aquic Argiudoll with illite and smectite as the dominant 2:1 clay minerals<sup>26</sup>. Further details concerning the Morrow Plots and their management can be found in Khan et al.<sup>27</sup>.

A baseline for the study period was established using air-dried soil samples collected in the spring of 1955 prior to any application of KCl, which were obtained from an archival collection maintained by the University of Illinois in individually labeled air-tight glass containers. The 2005 samples consisted of triplicate soil cores that were collected just after harvest, air dried at 40°C and screened to <2 mm. Analyses for exchangeable K were performed in triplicate as described previously, by processing all samples in a single batch. To allow expression on a mass basis (kg ha<sup>-1</sup>), test values were multiplied by the corresponding bulk density, obtained from direct measurements in 2005, or by using pedo-transfer functions to estimate 1955 values. A more detailed description is available in Khan et al.<sup>27</sup>.

A K balance was constructed for 1955–2005, based on cumulative fertilizer input and crop removal. Morrow Plot records were utilized to document KCl inputs, whereas crop K removal was estimated using composition data from the Illinois Agronomy Handbook<sup>28</sup> in conjunction with yield and management records. The handbook values used for crop K composition are typical of university maintenance recommendations to replace K removed in alfalfa hay (20.8 kg Mg<sup>-1</sup>) or by corn (4.2 kg Mg<sup>-1</sup>), soybean (18.0 kg Mg<sup>-1</sup>) and oats (5.2 kg Mg<sup>-1</sup>) harvested for grain. The yield records used were expressed as dry tons acre<sup>-1</sup> for alfalfa, or as bushels acre<sup>-1</sup> at a market-standard moisture content of 155 g kg<sup>-1</sup> (15.5%) for corn (56 lb bushel<sup>-1</sup>), 130 g kg<sup>-1</sup> (13%) for soybean (60 lb bushel<sup>-1</sup>) and 140 g kg<sup>-1</sup> (14%) for oats (32 lb bushel<sup>-1</sup>). In the case of the unfertilized

(NA-series) subplots, crop K removal was intensified by the harvest of corn or oats stover until 1967, estimated at 331 kg K ha<sup>-1</sup> for continuous corn, 310 kg K ha<sup>-1</sup> for the corn–oats rotation, and 256 kg K ha<sup>-1</sup> for the corn–oats–hay rotation. To account for K removal in these residues, a harvest index of 0.5 was assumed for both crops<sup>29–32</sup>; and a K concentration of 13.5 (corn) or 15 (oats) kg Mg<sup>-1</sup> of dry matter<sup>33</sup>.

### *Potassium balance for other studies*

In a more comprehensive evaluation of exchangeable K testing for air-dried soil, a systematic review of the literature was performed to compile a global database of short- and long-term K response experiments involving fixed (static) fertilizer treatments and representing a wide range in soils, cropping and management practices. This review utilized the CAB citation index and reviews of relevant individual journals. Three attributes were critical in selecting these data sets: (1) soil test values for exchangeable K determined at the beginning and end of the study period; (2) fertilizer K inputs throughout the study period; and (3) yield or K removal data for all crop material harvested. In cases where soil K test data were reported as a mass-based concentration, a conversion was made to kg ha<sup>-1</sup> assuming a bulk density of 1.47 Mg m<sup>-3</sup>, which corresponds to the conventional weight of 2 million pounds (907 Mg) per acre (0.405 ha) for a plow layer 6 inches (15 cm) deep. When necessary, crop K removal was calculated from yield data by utilizing published K concentrations for grain<sup>28</sup> and/or stover<sup>33</sup>.

### *Fertilizer value of potassium chloride*

To ascertain the benefits of KCl fertilization for crop yield and quality, an extensive effort was made in surveying peer-reviewed and university data from published field studies not exceeding 10 years in duration. For the yield survey, 211 publications reporting statistical analyses of yield differences were utilized in calculating percentage response to KCl fertilization as 100 × (fertilized yield – unfertilized yield)/unfertilized yield. Qualitative impacts of this fertilizer were evaluated as positive, negative, none or variable, according to what was reported in 139 publications comparing a specific parameter of crop quality with and without the use of KCl. Major emphasis was placed on broad coverage of the scientific literature, encompassing food, feed and fiber crops grown under various management practices on a wide range of soil types throughout the world.

An effort was also made in utilizing the scientific literature to assess the impact of KCl fertilization on two key aspects of soil productivity: cation-exchange capacity (CEC) and microbial N cycling. Interest in these topics was motivated by K<sup>+</sup> fixation that promotes interlayer collapse of 2:1 clay minerals, and by the inhibitory effects of KCl on biological N<sub>2</sub> fixation and nitrification.

## Statistical analyses

Seasonality and linear trend analysis of the 4-year time series of air-dried test levels of exchangeable K ( $\text{kg ha}^{-1}$ ) was evaluated statistically as described by Lovell<sup>34</sup>. Paired *t*-tests were performed on samples collected post-harvest in October 1989 to monitor changes in soil test K upon air drying. Exchangeable K data obtained for the Morrow Plots were analyzed statistically with PROC MIXED in SAS<sup>35</sup>, such that the 2005 data provided a variance estimate for the standard error of mean values obtained as a five-core composite in 1955<sup>27</sup>. The step-down Bonferroni adjustment of *P* values<sup>36</sup> was performed with PROC MULTEST in SAS<sup>35</sup> for multiple comparison tests to evaluate net changes in exchangeable K between 1955 and 2005.

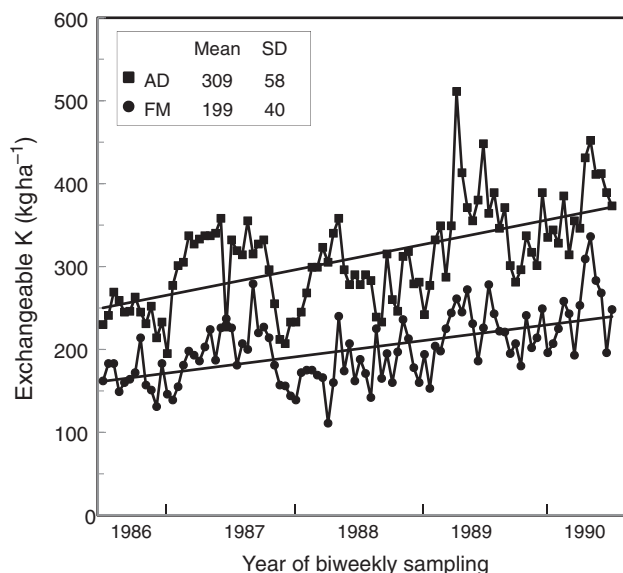
## Results and Discussion

### Evaluation of soil potassium testing

Soil testing is widely regarded as the best approach for making economical fertilizer recommendations or monitoring soil fertility changes in relation to management practices. If these objectives are to be properly met, soil sampling must be adequate to represent the field area under investigation, and test values should be calibrated to crop response and sufficiently stable that interpretations are unaffected by the time of sampling or the method of sample processing.

In the modern era of input-intensive agriculture, soil testing is often done to measure exchangeable K, following the concept originated by Bray<sup>13</sup>. This prevalence reflects the major emphasis given to rapid methods of sample processing and analysis in commercial soil testing, despite an inherent complication that has long been recognized: K test values can change markedly when samples are air dried to expedite processing<sup>37,38</sup> (see also supplemental references [4–8] for the online version of the paper). A further complication arises because of variability associated with the time of sampling<sup>18,21</sup> (see also supplemental references [4] and [9] for the online version of the paper), which becomes a major source of error in soil testing for site-specific management<sup>39</sup>.

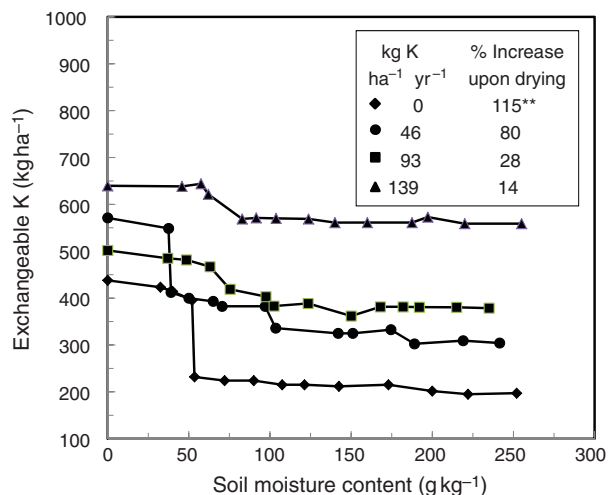
Both factors clearly contributed to the variability documented in Fig. 1 for a 4-year field study that involved biweekly sampling to monitor changes in exchangeable K test values with and without air drying. Any such changes would have been minimized because the work involved a single investigator utilizing a fixed protocol and experimental design, and a study site devoid of fertilizer K inputs for at least 14 years. By repeatedly imposing a dense sampling design on a single small research plot subject to minimal compaction from mechanical traffic, spatial variability was minimized so as to better quantify any occurrence of temporal variability.



**Figure 1.** Biweekly changes in exchangeable K for field-moist (FM) and air-dried (AD) samples (0–18 cm) collected on 96 dates between March 13, 1986 and March 15, 1990, from a Drummer soil under a corn (*Zea mays* L.)–soybean (*Glycine max* L. Merr.) rotation. No fertilizer P or K had been applied since 1970. Data points are a mean of nine determinations representing triplicate analyses performed on five-core composites collected from each of three subplots. Trendlines were generated by linear regression. SD, standard deviation.

Despite these precautions, Fig. 1 shows that soil K test levels, with or without air drying, varied drastically with the biweekly sampling strategy adopted throughout the study period, and the variation became more extensive as test values began to increase after harvest, during the usual sampling period for commercial soil testing in a temperate region such as the Midwestern USA. Statistical analyses were highly significant ( $P < 0.001$ ) in detecting a seasonality effect on exchangeable soil K, which is consistent with several previous field studies<sup>40,41</sup> (see also supplemental references [10–13] for the online version of the paper) that document greater test values during the winter months. This increase can be attributed to a high soil moisture content that promotes the leaching of K from crop residues and the conversion of non-exchangeable to exchangeable K through valence dilution. After seasonality adjustment, a highly significant ( $P < 0.001$ ) linear increase in exchangeable K was observed over the 4-year study period.

Drying was expected to decrease temporal variability by homogenizing soil samples; however, the data in Fig. 1 reveal no such effect as the coefficient of variation was nearly the same before and after air drying that escalated K test values by 55% on average. A major complication can also be found in the numerous incoherencies between field-moist and air-dried test values documented by Fig. 1, which precludes the use of a simple correction factor to compensate for air drying or the timing of sample



**Figure 2.** Potassium release curves for a Drummer soil cropped to a corn (*Zea mays* L.)–soybean (*Glycine max* L. Merr.) rotation, with or without annual application of 46–139 kg K ha<sup>-1</sup> as KCl. Field-moist samples (0–18 cm) were air dried to approximately 40 g kg<sup>-1</sup> in a forced-air oven at 40°C, followed by oven-drying at 105°C. Data points are a mean of triplicate determinations performed on five-core composites collected from each of three subplots. Error bars representing one standard deviation are shown, when they exceed the size of the data marker, for field-moist (FM) and air-dried (AD) test values. The percentage increase upon air drying was calculated as  $100 \times (K_{AD} - K_{FM}) / K_{FM}$ . \*\*, significant at  $P < 0.01$ .

collection. Both findings raise a serious concern that soil K testing by the usual approach is of no practical value, in contrast to the advocacy that is common in extension publications and presentations, trade magazines and popular articles<sup>28,42</sup>.

The same concern emerged when sample drying was evaluated by a one-time sampling of soils that ranged widely in K fertility, so as to eliminate the confounding effect of seasonality. The results (Fig. 2) follow the usual trend toward higher test values upon air drying; however, the increase tended to be greater as the fertility level decreased, further demonstrating the difficulties inherent in correcting air-dried test values to a field-moist basis. This finding reveals that air-dried K test values can easily be misinterpreted when utilized for predicting K fertilizer requirement under low fertility management or for monitoring buildup/depletion.

A more rigorous evaluation becomes possible when soil K test data span a prolonged period documented with a complete record of K inputs and outputs. The Morrow Plots serve as an ideal resource for this purpose, providing three cropping systems that include the corn–soybean rotation common throughout the Midwestern USA. With this rotation, and also with continuous corn, K removal from the Morrow Plots occurs only in grain, whereas the intensifying effect of forage production is present with a 3-year rotation of corn, oats and alfalfa hay.

As shown by Table 1, K test levels for the surface soil were invariably increased by 51 years of cropping. Remarkably, the largest increases, highly significant at  $P < 0.001$ , occurred in the absence of NPK fertilization, when the K balance was decidedly negative for continuous corn or the corn–oats–hay rotation. Equally remarkable is the substantial soil test increase observed for the unfertilized subplot in the two-crop rotation, despite K removal that totaled 1.4 Mg ha<sup>-1</sup>. These observations are consistent with the seasonality study discussed previously (Fig. 1), which showed an upward trend over time in air-dried and field-moist K test levels in the absence of fertilizer K inputs. No less troubling are the similar net changes documented by this soil test for the three subplots receiving NPK, regardless of whether fertilizer K inputs were above (continuous corn or corn–oats–hay) or below (corn–soybean) crop removal. The implication is that the K test cannot differentiate soil K buildup from depletion.

The latter flaw is also apparent from the sheer magnitude of the K test levels reported in Table 1 for the three unfertilized subplots, particularly those under continuous corn and the corn–oats–hay rotation. By 2005, following 130 years of K removal, test values for these subplots were within the range of critical levels calibrated for North America<sup>43</sup>, which would normally be interpreted as evidence of successful fertilizer K management.

To ascertain whether soil K testing is generally subject to the aforementioned difficulties, baseline changes in exchangeable K were compared with cumulative K balance compiled for numerous field experiments with and without K fertilization, encompassing a global range of soil orders, cropping systems and management practices. The resulting database (Table 2), consisting of 68 trials, provides no convincing evidence that soil test K reflects the net balance of K addition and removal. The most disturbing disparities involved 17 trials in which test levels were either constant or increased while crop K removal far exceeded fertilizer inputs or occurred in the complete absence of fertilization. Such obvious incongruities, paralleling what was found for the Morrow Plots (Table 1), leave little alternative but to question the validity of soil testing for exchangeable K, and this concern is especially relevant to the developing world, where soil K removal has been intensified by many centuries of grain and biomass harvest. To make matters worse, Table 2 shows that K test values sometimes decreased with a positive K balance, which according to the usual interpretation would justify unnecessary K fertilization. The implication is that soil K testing does not provide a scientific basis for fertilizer K management.

This dilemma is inherent to a one-time measurement of exchangeable K, which can never represent the highly dynamic effect of soil moisture on the interchange with vastly larger soil pools that occur in the form of non-exchangeable and mineral K<sup>80</sup>. The dynamic nature of soil K is no less relevant in refuting the central assumption implicit to soil K testing, namely, that plant K availability

**Table 1.** Soil potassium test changes and potassium balance for the Morrow Plots, 1955–2005.

Rotation <sup>1</sup>	Fertilizer treatment <sup>2</sup>	Exchangeable K <sup>3</sup>			Cumulative		
		Initial <sup>4</sup>	Final <sup>5</sup>	Net change	K added	K removed	Net K input
----- kg ha <sup>-1</sup> -----							
C–C	None	242 (4)	403 (33)	161***	0	892	– 892
	NPK	242 (4)	354 (22)	112***	2231	1692	539
C–O(S)	None	218 (4)	304 (25)	86***	0	1706 <sup>6</sup>	– 1706
	NPK	218 (4)	327 (26)	109***	1934	2136 <sup>7</sup>	– 202
C–O–H	None	217 (6)	382 (18)	165***	0	1088 <sup>8</sup>	– 1088
	NPK	217 (6)	332 (27)	115***	3114	2865 <sup>9</sup>	249

\*\*\* Significant at  $\alpha=0.001$  by the step-down Bonferroni procedure.

<sup>1</sup> C, corn (*Zea mays* L.); H, alfalfa (*Medicago sativa* L.) hay; O, oats (*Avena sativa* L.); S, soybean (*Glycine max* L. Merr.). Since 1967, the two-crop rotation has involved soybean instead of oats.

<sup>2</sup> NPK, nitrogen–phosphorus–potassium fertilization using urea (168 [1955–1966] or 224 [since 1967] kg N ha<sup>-1</sup> yr<sup>-1</sup> for corn, 28 kg N ha<sup>-1</sup> yr<sup>-1</sup> for oats), triple superphosphate (0–96 kg P ha<sup>-1</sup> yr<sup>-1</sup>) and KCl (0–186 kg K ha<sup>-1</sup> yr<sup>-1</sup>). No amendment was applied before 1955.

<sup>3</sup> Determined by NH<sub>4</sub>C<sub>2</sub>H<sub>3</sub>O<sub>2</sub> extraction<sup>24</sup> of air-dried samples.

<sup>4</sup> Mean values reported from triplicate determinations of a single archived five-core composite soil sample (0–15 cm). Standard deviations shown in parentheses.

<sup>5</sup> Mean values reported from triplicate determinations performed on each of three replicate soil samples (0–15 cm). Standard deviations shown in parentheses.

<sup>6</sup> Estimated as 44% by corn, 7% by oats and 49% by soybean.

<sup>7</sup> Estimated as 49% by corn, 3% by oats and 48% by soybean.

<sup>8</sup> Estimated as 54% by corn, 25% by oats and 21% by alfalfa hay.

<sup>9</sup> Estimated as 26% by corn, 65% by oats and 9% by alfalfa hay.

is directly related to exchangeable K in the surface soil. Table 2 leaves no doubt that plant K uptake must originate from other sources, and is consistent with previous evidence that soil K reserves contribute considerable quantities of plant-available K<sup>10,11,20,75,78,81–83</sup> (see also supplemental references [14–26] for the online version of the paper).

These reserves were once recognized to be a major source of K-supplying power for the highly productive soils that dominate the Corn Belt, as well as for most other areas of the continental USA<sup>8,9,84</sup>. The importance of the non-exchangeable fraction as a storehouse for exchangeable and soluble K is documented by Table 3, which shows the magnitude of this fraction by six successive determinations performed on surface samples of a soil cropped for 17–20 years with no K input. Initial recoveries were three- to fivefold higher for non-exchangeable than exchangeable K, followed by a gradual decline toward a stable level of 240–300 kg ha<sup>-1</sup>, with approximately 3000 kg ha<sup>-1</sup> as the cumulative recovery of non-exchangeable K. The resilient behavior of soil K is further revealed, in that 4 years of crop K removal had no consistent effect on soil concentrations of exchangeable, non-exchangeable or total K, implicating the mineral fraction as an important source of buffering. These findings are to be expected, considering what has long been known about the availability and dynamics of non-exchangeable and mineral K, based on chemical extraction<sup>19,85–87</sup> (see also supplemental references [22] and [27–30] for the online version of the paper), exhaustive

cropping<sup>81,86,88,89</sup> (see supplemental references [8], [15] and [16] for the online version of the paper) and electro dialysis<sup>83,90</sup>.

The importance of non-exchangeable and mineral K for plant uptake is by no means unique to micaceous clays, which are subject to biological weathering in the rhizosphere<sup>91–94</sup> (see also supplemental references [28] and [31] for the online version of the paper). Sand- and silt-sized muscovite and biotite can also be a major source of plant-available K, as demonstrated conclusively by Mengel *et al.*<sup>83</sup> in studies with 14 loess-derived Alfisols. These primary minerals, and also K feldspars, are believed to account for the high K-supplying power of sandy Ultisols of the Atlantic Coastal Plain<sup>82,95–97</sup>, while non-exchangeable K reserves can even be important for growing a shallow-rooted crop such as pineapple on the basaltic Andisols of Hawaii<sup>81</sup>.

Soil K reserves are much greater for the profile than the plow layer<sup>12,62,95,97,98</sup> (see also supplemental references [32–34] for the online version of the paper), and can be more fully exploited by many agricultural crops with a well-developed rooting system. The importance of subsoil K is clearly apparent from K/Rb isotope dilution studies demonstrating that the extent of uptake is directly proportional to rooting depth<sup>99–101</sup>. This uptake is largely concentrated in the vegetative biomass<sup>33,102</sup>, and enriches the surface soil when inorganic K leaches from plant shoots or residues<sup>8,9,81,102–106</sup> (see supplemental references [35–45] for the online version of the paper).

**Table 2.** Soil potassium test changes in relation to potassium balance, as reported for static plot experiments.

Location	Soil order <sup>1</sup>	Cropping system <sup>2</sup>	Study period	Sampling depth	Exchangeable K <sup>3</sup>			Cumulative			Reference(s)
					Initial	Final	Net change	K added	K removed	Net K input	
					----- kg ha <sup>-1</sup> -----						
USA				cm							
Alabama	Ultisols (fsl <sub>4</sub> , scl <sub>2</sub> , sil <sub>1</sub> )	C-Ct (7)	1954–1969	0–15	113	104	–9	0	332	–332	44–46
					113	229	115	1488	513	975	
Illinois	Mollisols (sil)	C–S (2)	1982–1987	0–18	322	335	13	0	290	–290	47
					322	476	154	334	325	9	
	Entisols (sil)	C–S	1994–1996	0–20	288	253	–35	0	325	–325	48
					316	317	1	335	330	5	
	Mollisols (sil)	C–S	1994–1996	0–20	280	283	3	0	270	–270	
					314	339	26	335	282	52	
Indiana	Mollisols (sil)	C–S–W <sub>w</sub> –C	1964–1983	0–20	93	112	19	0	506	–506	49
					178	422	243	2790	723	2067	
Iowa	Mollisols (cl)	C–S	1976–1989	0–15	10(3)	10(3)	(0)	0	501	–501	50
					10(3)	19(7)	9(4)	1207	600	607	
	Mollisols (l)	C–S	1979–1989	0–15	40(4)	17(7)	–22(7)	0	474	–474	51
					37(2)	61(4)	24(2)	1478	481	998	
Michigan	Alfisols (ls)	C–C	1974–1982	0–22	266	260	–6	335	284	51	52
					601	598	–3	1595	276	1319	
Minnesota	Mollisols (cl)	C–C (2)	1974–1981	0–20	227	302	75	0	258	–258	53, 54
					237	315	78	372	267	105	
Missouri	Alfisols (sil)	W <sub>s</sub> –W <sub>s</sub>	1963–1989	0–20	400	303	–97	0	87	–87	55
		C–C	1963–1989	0–20	414	364	50	0	50	–50	
Nebraska	Mollisols (sicl)	C–C	1973–1984	0–15	598	77(3)	17(5)	156	471	–315	6, 56
					598	83(1)	23(3)	720	486	234	
New Jersey	Ultisols (l)	A–A	1953–1961	0–30	131	105	26	0	412	–412	57
					222	660	438	3357	2006	1351	
North Carolina	Ultisols (s)	Cb–Cb	1954–1965	0–15	53	9	–44	0	215	–215	58
					53	53	0	2231	2202	29	
Oklahoma	Mollisols (l)	W <sub>w</sub> –W <sub>w</sub>	1938–2001	0–15	508	414	–94	0	1219	–1219	59–61
					464	548	84	1843	1201	584	
Virginia	Ultisols (sil)	C <sub>s</sub> –C <sub>s</sub>	1966–1971	0–15	224	85	–139	0	411	–411	62
					224	124	–100	336	440	–104	
China	Inceptisols	W <sub>w</sub> –C <sup>d</sup>	1990–2005	0–20	28(4)	5(3)	–23(1)	0	718	–718	63, 64
					30(3)	24(8)	–5(5)	1500	1089	411	
	Inceptisols (sl)	C–C	1993–2004	0–20	206	223	17	0	480	–480	65, 66
					206	235	29	259	650	–391	
England	Alfisols (sicl)	B–B <sup>5</sup>	1856–1974	0–23	313	219	–94	0	1221	–1221	67
					313	305	–8	5040	4294	746	
	Inceptisols (sl)	Sb–W <sub>w</sub> –B	1965–1982	0–25	162	132	–30	0	580	–580	68
					162	265	102	1992	1160	832	
	Alfisols (sicl)	W <sub>w</sub> –W <sub>w</sub>	1966–1992	0–23	323	271	–52	0	675	–675	69
					1326	1236	–90	2430	1431	999	

Table 2. (Cont.)

Location	Soil order <sup>1</sup>	Cropping system <sup>2</sup>	Study period	Sampling depth	Exchangeable K <sup>3</sup>			Cumulative			Reference(s)
					Initial	Final	Net change	K added	K removed	Net K input	
Denmark	Alfisols (s)	W <sub>w</sub> -Rcl-B-Gcl	1949-1972	0-20	65	52	-13	0	456	-456	70
					188	172	-15	1584	1584	0	
					98	62	-36	0	696	-696	
Germany	Alfisols (sl)	W <sub>w</sub> -Rcl-B-Gcl	1949-1972	0-20	152	122	-30	1584	2160	-576	71
					158	123	-35	0	4531	-4531	
					158	131	-27	5127	7039	-1912	
India	Mollisols (sl)	Po-P-W <sub>s</sub> -Rc-B	1977-1984	0-20	170	179	9	0	568	-568	72
					496	448	-48	1792	1256	536	
					8(8)	7(0)	-1(8)	0	3952	-3952	
New Zealand	Inceptisols (ls)	C-W <sub>w</sub> -Cp <sup>4</sup>	1971-1996	0-15 <sup>6</sup>	9(6)	9(8)	(2)	2860	5642	-2782	73
					194	148	-46	0	1508	-1508	
					194	167	-27	2460	2393	67	
Nigeria	Alfisols (sc <sub>1</sub> , ls <sub>2</sub> )	A-A <sup>4</sup>	1971-1974	0-20	216	225	9	0	571	-571	75
					216	394	178	786	758	28	
					381	198	-183	0	197	-197	
Philippines	Alfisols (sc <sub>1</sub> , ls <sub>2</sub> )	C-C <sup>4</sup> (3)	1966-1968	0-15	381	228	-153	168	239	-71	76
					381	228	-153	168	239	-71	
					381	228	-153	168	239	-71	
Poland	Inceptisols (sic)	Ri-Ri	1968-1986	0-20	521	13(5)	-38(6)	0	578 <sup>7</sup>	-578	77
					521	15(6)	-36(5)	950	759 <sup>7</sup>	191	
					209	24(9)	4(0)	0	580 <sup>7</sup>	-580	
Poland	Vertisols (c)	Ri-Ri	1968-1986	0-20	209	39(3)	18(4)	950	799 <sup>7</sup>	151	77
					209	39(3)	18(4)	950	799 <sup>7</sup>	151	
					938	57(3)	-36(5)	0	531 <sup>7</sup>	-531	
Poland	Vertisols (c)	Ri-Ri	1968-1986	0-20	938	62(6)	-31(2)	950	677 <sup>7</sup>	273	77
					938	62(6)	-31(2)	950	677 <sup>7</sup>	273	
					938	62(6)	-31(2)	950	677 <sup>7</sup>	273	
Scotland	Alfisols (ls)	Ry-Ry	1963-1995	0-25	107	200	93	0	1254	-1254	69
					320	300	-20	2574	2310	264	
					113	147	33	0	1584	-1584	
Scotland	Spodosols (ls)	Po-B-Rcl-W <sub>w</sub> -Ry	1963-1995	0-25	327	363	37	2574	3069	-495	78
					327	363	37	2574	3069	-495	
					72	20	-52	448 <sup>9</sup>	1608	-1160	
Scotland	Spodosols (ls)	Pr-Pr <sup>8</sup>	1969-1998	0-15	55	24	-31	1969 <sup>9</sup>	3158	-1189	78
					55	24	-31	1969 <sup>9</sup>	3158	-1189	

<sup>1</sup> Surface texture designated parenthetically as c (clay), cl (clay loam), fsl (fine sandy loam), l (loam), ls (loamy sand), s (sand), sc (sandy clay), scl (sandy clay loam), sic (silty clay), si (silty clay loam), sil (silt loam) and sl (sandy loam). Subscripts indicate the number of soils studied with a given texture.

<sup>2</sup> A, alfalfa (*Medicago sativa* L.); B, barley (*Hordeum vulgare* L.); C, corn (*Zea mays* L.); Cb, coastal bermudagrass (*Cynodon dactylon* L. Pers.); Ce, cereal; Cp, cowpea (*Vigna unguiculata* L.); C<sub>s</sub>, silage corn (*Zea mays* L.); Ct, cotton (*Gossypium hirsutum* L.); Gcl, grass-clover; L, ley; P, pea (*Pisum* L.); Pm, pearl millet (*Pennisetum glaucum* L. R. Br.); Po, potato (*Solanum tuberosum* L.); Pr, perennial ryegrass (*Lolium perenne* L.); Rc, root crop; Rcl, red clover (*Trifolium pratense* L.); Ri, rice (*Oryza sativa* L.); Ry, rye (*Secale cereale* L.); S, soybean (*Glycine max* L. Merr.); Sb, sugarbeet (*Beta vulgaris* L.); Sp, sweet potato (*Ipomoea batatas*); W<sub>s</sub>, spring wheat (*Triticum aestivum* L.); W<sub>w</sub>, winter wheat (*Triticum aestivum* L.). Values in parentheses indicate the number of separate trials summarized.

<sup>3</sup> Parentheses indicate digital uncertainty in estimating data reported in figures.

<sup>4</sup> All crops were grown annually.

<sup>5</sup> Prior to 1901, the cropping system was W<sub>w</sub>-W<sub>w</sub> (1856-1875) or Po-Po (1876-1901).

<sup>6</sup> Assumed as the depth for sampling surface soil.

<sup>7</sup> Rice grain was assumed to contain 0.04 g K kg<sup>-1</sup> at a moisture content of 140 g kg<sup>-1</sup> <sup>79</sup>.

<sup>8</sup> Cropped to cereals between 1982 and 1987, with 4 years of barley, 1 year of oats (*Avena sativa* L.) and 1 year of winter wheat.

<sup>9</sup> Includes atmospheric K deposition.



**Table 3.** Speciation of potassium in surface (0–18 cm) samples collected in August and September between 1986 and 1989 from a Drummer soil under a corn–soybean rotation with no P or K fertilization since 1970.<sup>1</sup>

Year	Exchangeable K <sup>2</sup>	Non-exchangeable K recovered in six successive extractions <sup>3</sup>							Total K <sup>4</sup>
		Ext. 1	Ext. 2	Ext. 3	Ext. 4	Ext. 5	Ext. 6	Ext. 1–6	
		-----kg ha <sup>-1</sup> -----							
1986	240 (16)	1048 (54)	616 (58)	463 (37)	351 (8)	252 (37)	239 (28)	2969	42,271 (682)
1987	244 (18)	932 (47)	588 (43)	407 (35)	435 (16)	351 (16)	308 (24)	3021	ND
1988	224 (23)	1120 (50)	700 (56)	476 (8)	336 (32)	379 (21)	267 (8)	3278	ND
1989	276 (25)	987 (24)	627 (35)	448 (16)	358 (14)	299 (29)	269 (16)	2988	42,208 (680)

<sup>1</sup> 160–180 kg N ha<sup>-1</sup> applied for corn production in 1986 and 1988. All values reported as a mean of triplicate determinations performed on a sample composited from 45 to 75 cores collected in August and September of each year. Standard deviations shown in parentheses.

<sup>2</sup> Determined by extraction with 1 M NH<sub>4</sub>C<sub>2</sub>H<sub>3</sub>O<sub>2</sub> (pH 7)<sup>24</sup> after air drying at 40°C.

<sup>3</sup> Determined after extraction of exchangeable K, by boiling with 1 M HNO<sub>3</sub><sup>24</sup>.

<sup>4</sup> Determined by fusion with LiBO<sub>2</sub>·8H<sub>2</sub>O, followed by dissolution in 1 M HNO<sub>3</sub><sup>25</sup>. ND, not determined.

### Fertilizer value of potassium chloride

Besides being abundant in soils and plant residues, K is notable as the only macronutrient dominated by inorganic forms in both the soil and plant, and thus availability is not dependent upon microbial transformations. Uptake occurs much more readily for K<sup>+</sup> than for Ca<sup>2+</sup> or Mg<sup>2+</sup> because of greater membrane permeability further enhanced at low concentrations by active diffusion, while specialized transport systems selective for K rapidly distribute this nutrient in the plant<sup>33,107</sup>. Under these circumstances, and considering the ubiquitous nature of K, it becomes clear why many years can be required to induce fertilizer K response in long-term static plot experiments<sup>59,60,71,77,108</sup> (see also supplemental references [46–52] for the online version of the paper). On the basis of such findings, there is little reason to expect economically viable crop response to shorter periods of K fertilization that limit check-plot depletion, and a far lower likelihood of response in a production setting where the entire field shares the same history of regular fertilizer K inputs.

This view was indeed confirmed by compiling a global database of crop response to KCl from 2121 short-term field trials conducted by public universities or experiment stations. The resulting database is too extensive to be accommodated herein but is available in the online supplement as Table S4 (for the online version of the paper). As hypothesized, KCl fertilization was often ineffective for increasing productivity, according to non-significant responses that occurred in approximately 76% of the total trials surveyed. The inherent capability for plant uptake of soil K is manifestly evident from studies in which shallow-rooted crops growing on sandy soils were non-responsive to K fertilization<sup>109–112</sup>, and often made fertilizer K superfluous when deeper rooted crops had access to profile K supplies in more productive soils. Unfortunately, KCl usage in the latter case has long been exacerbated by a buildup-maintenance philosophy that

promotes intensive fertilizer K inputs without regard to huge soil K reserves or their recycling through crop residues.

To ascertain the value of K fertilization, those trials showing a statistically significant response to KCl fertilization, accounting for 24% of the total database, are presented herein in Table 4. Most of the responses were positive and occurred on coarse-textured, organic or highly weathered soils inherently low in K-supplying power (231 site-years); when the above-ground residues were removed (191 site-years); with crops having a shallow or low-density rooting system (62 site-years); and/or when subsoil rooting was restricted (12 site-years). In the absence of such factors, there is very little reason to expect a significant yield response to KCl fertilization.

The input-intensive approach to fertilizer K management can have negative economic consequences for producers, which are apt to go unnoticed unless fertilizer response is determined relative to yield in the absence of fertilization. These consequences are to be expected considering the ample evidence in Table S4 (for the online version of the paper) that KCl inputs are often ineffective for increasing yield, but will be more serious when yield is depressed. The latter effect has indeed been observed, and was significant in field studies with corn<sup>38,144,148,192</sup>, soybean<sup>120,125,131,175</sup>, wheat (*Triticum aestivum* L.)<sup>186</sup>, sugarbeet (*Beta vulgaris* L.)<sup>139</sup>, sugarcane (*Saccharum officinarum* L.)<sup>127</sup>, alfalfa<sup>145</sup>, peanut (*Arachis hypogaea* L.)<sup>109,191</sup>, rape (*Brassica napus* L.)<sup>176</sup> and cowpea (*Vigna unguiculata* L.)<sup>166</sup>. In several of these studies, the loss of yield was intensified by increasing the rate of KCl application<sup>38,109,120,125,175,192</sup>, and in some cases the higher rate transformed significant yield gain to loss<sup>127,186</sup>.

Yield reductions due to KCl fertilization, as documented in Table 4, can be explained by the high salt index of this fertilizer, which has been implicated as a detrimental factor for crop germination and growth<sup>193–195</sup> and microbial processes<sup>196,197</sup>. More serious consequences can occur because of the anion supplied by KCl.

**Table 4.** Significant yield responses to KCl fertilization in field studies documented by a survey of 211 peer-reviewed and university publications involving ≤10 years of KCl application at a fixed rate.<sup>1</sup>

Location	Soil order <sup>2</sup>	Exchangeable K <sup>3</sup> kg ha <sup>-1</sup>	K applied (as KCl) kg ha <sup>-1</sup> yr <sup>-1</sup>	Site-years studied <sup>4</sup>	Cropping system <sup>5</sup>	Yield without fertilizer K <sup>6</sup> Mg ha <sup>-1</sup>	Yield response to K <sup>7</sup>		Reference
							Lowest	Highest	
							-----%-----		
North America									
Canada									
Manitoba	Mollisols (scl)	50–310 (15)	0–200	15	A <sup>o</sup>	16.7	59* (50)	174* (200)	113
Ontario	Alfisols (sl)	NR	0–126	4	O–Po	19.8	24* (126)	24* (126)	114
USA									
Alabama	Ultisols (sil)	42	0–150	3	Bg <sup>o</sup> –S	2.6	27* (75)	44* (150)	115
	Ultisols (fsl, sil)	25–42 <sup>s</sup> (20)	0–112	6	Tf, Wc <sup>o</sup>	3.6	25 <sup>ns</sup> (28)	46* (112)	116
Alaska	Inceptisols (sil)	256	0–186	2	Sbg <sup>o</sup>	3.2	–15 <sup>ns</sup> (112)	31* (186)	117
Arkansas	Alfisols (sil)	112 (16)	0–75	3	S	2.8	8* (75)	8* (75)	118
	Alfisols (fsl)	213–269 (15)	0–84	6	Ct	2.1	10* (28)	22* (84)	119
	Alfisols (sil)	NR	0–1175	8	S	2.7	–21* (1175)	–9 <sup>ns</sup> (587)	120
California	Mollisols (sl)	65 <sup>s</sup>	0–480	3	Ct	2.(4)	11** (120)	31*** (480)	121
	Alfisols (l)	67 <sup>s</sup> (20)	0–100	3	Ri <sup>o</sup>	7.(8)	5* (63)	7* (100)	122
Colorado	Mollisols (cl)	335 <sup>s</sup> (15)	0–750	16	A <sup>o</sup>	52.7	6* (375, 750)	6* (375, 750)	123
Connecticut	Inceptisols (fsl)	121 <sup>7</sup>	0–448	6	Rc <sup>o</sup>	10.7	7* (448)	12* (224)	124
Delaware	Ultisols (sil)	207	0–223	20	S	2.0	–30* (223)	–11* (56)	125
Florida	Spodosols (fs)	45–52 <sup>s</sup> (15)	0–200	1	S–Vg	4.0	6 <sup>ns</sup> (50)	15* (200)	126
	Histosols	43 (30)	0–560	1	Sc <sup>o</sup>	97.2	–4** (560)	6** (280)	127
	Ultisols (lfs)	17–150 <sup>s</sup> (15)	0–418	2	C–(S or Ar <sup>o</sup> )	9.5	19* (209)	21* (418)	128
Georgia	Ultisols (sl)	NR	0–188	3	Bg <sup>o</sup>	9.5	11* (47)	14* (188)	129
	Ultisols (fs)	30 (15)	0–168	6	Pn	2.3	17* (34)	34* (168)	130
	Ultisols (ls, sl)	41–182	0–224	9	Pn	4.(2)	–4* (224)	–1 <sup>ns</sup> (121)	109
	Ultisols (s)	NR	0–186	30	S	1.7	–30* (186)	–30* (186)	131
	Entisols (ls)	10 <sup>s</sup> (25)	0–56	3	C–Pn	3.5	47* (56)	47* (56)	132
Idaho	Mollisols (gl)	92–112 <sup>s</sup> (20)	0–415	5	A <sup>o</sup> –Po	24.8	20* (415)	21* (208)	133
Illinois	Alfisols (sil)	60–86 (15)	0–224	2	Sg–C	4.1	2 <sup>ns</sup> (28)	60** (224)	38
	Alfisols (sil)	63–161 (15)	0–224	2	C	4.9	20** (28)	118** (112)	134
	Inceptisols (sil)	166 (15)	0–112	1	C	8.3	–1 <sup>ns</sup> (28)	7* (56)	
Indiana	Alfisols (fs)	51 <sup>s</sup> (18)	0–372	3	A <sup>o</sup>	3.7	32** (93)	54** (372)	135
	Alfisols (sil)	74 <sup>s</sup> (18)	0–372	2	A <sup>o</sup>	5.1	15* (93)	21* (372)	
Iowa	Mollisols (sl-sil)	141–491 (15)	0–335	9	A <sup>o</sup>	4.3	1 <sup>ns</sup> (74, 112)	12* (335)	136
	Alfisols (sil)	62–190 (15)	0–140	5	A <sup>o</sup> –C	5.7	10* (28)	16* (112)	38
Kansas	Alfisols (sil)	45–108 <sup>s</sup> (15)	0–140	6	(A <sup>o</sup> or Bt <sup>o</sup> )–Sr	6.(0)	10* (70, 140)	10* (70, 140)	137
Kentucky	Ultisols (sil)	NR	0–372	3	Tf/Wc <sup>o</sup>	5.1	0 <sup>ns</sup> (372)	7* (140)	138
Michigan	Alfisols (sl, l)	77–242 (15)	0–335	7	A, Rcl, Sbg <sup>o</sup>	4.1	8 <sup>ns</sup> (19)	33* (335)	136
	Alfisols (l)	NR	93–186	1	Sb	50.7 <sup>10</sup>	–6* (186)	–6* (186)	139
Minnesota	Alfisols (sil)	102–142 (15)	0–140	2	A <sup>o</sup> –C	5.2	10 <sup>ns</sup> (28)	25* (140)	38
	Entisols (fs)	122 (15)	0–140	1	A <sup>o</sup> –C	3.9	–18* (140)	3 <sup>ns</sup> (28)	
	Histosols	37 (15)	0–140	1	C–C	2.4	38* (140)	46* (84, 112)	
	Mollisols (ls, sil)	111–198 (15)	0–140	2	A <sup>o</sup> –C	4.6	16* (28)	37** (140)	

Mississippi	Entisols (sil)	NR	0–112	2	<u>C–Ct</u>	1.3	17* (37)	31* (112)	140
	Inceptisols (fsl)	289–465 (15)	0–112	8	<u>Ct</u>	1.0	9* (112)	9* (112)	141
	Entisols (si)	115 <sup>s</sup> (15)	0–204	2	<u>Ct</u>	1.2	7* (68)	13* (204)	142
	Inceptisols (fsl)	138–159 <sup>s</sup> (15)	0–112	11	<u>Ct</u>	1.1	5* (112)	5* (112)	143
Nebraska	Entisols <sub>1</sub> , Mollisols <sub>15</sub>	91–609 <sup>s</sup> (20)	0–40	16	<u>C–S</u>	14.4	–3* (40)	–3* (40)	144
New Mexico	Entisols (fsl)	NR	0–56	3	<u>A<sup>o</sup></u>	16.6	–2* (56)	–2* (56)	145
North Carolina	Ultisols (fsl)	12 <sup>s</sup>	0–112	3	<u>C–S</u>	0.35	131* (11)	342* (112)	146
North Dakota	Mollisols (l)	570–940	0–99	4	<u>B</u>	2.7	1 <sup>ns</sup> (24)	4* (99)	147
Ohio	Mollisols (sicl)	NR	0–360	2	<u>C</u>	9.2	–20*** (90)	–19*** (360)	148
	Alfisols (sil)	190	0–74	6	<u>C–S</u>	3.0	1 <sup>ns</sup> (37)	7* (74)	149
Pennsylvania	Alfisols (sicl)	32 (15)	0–112	6	<u>Og<sup>o</sup></u>	4.0	21* (56)	29* (112)	150
	Alfisols <sub>4</sub> (sil), Ultisols <sub>2</sub> (sil)	61–140 (15)	0–525	16	<u>A<sup>o</sup></u>	2.(8)	66* (175)	72* (350)	151
	Mollisols	> 391	0–71	20	<u>O</u>	2.5	3* (35, 71)	3* (35, 71)	152
Tennessee	Mollisols (fsl)	NR	0–186	1	<u>C</u>	5.0	–2 <sup>ns</sup> (149)	18* (19)	153
	Alfisols (sil)	198–444 (15)	56–112	6	<u>Ct</u>	1.8 <sup>10</sup>	5* (112)	5* (112)	154
Texas	Ultisols (fs, fsl)	NR	0–278	6	<u>Bg<sup>o</sup></u>	10.3	24* (139, 278)	24* (139, 278)	155
Utah	Mollisols (sil)	59–77 <sup>s</sup> (30)	0–224	2	<u>Po</u>	37.4	15* (224)	15* (224)	156
Virginia	Ultisols (sl)	55 (15)	0–372	6	<u>S</u>	1.8	25* (372)	25* (372)	157
	Ultisols (cl)	66–121	0–112	2	<u>S</u>	1.6	85* (28)	139* (112)	158
Wisconsin	Mollisols (sil)	142 (15)	0–1120	3	<u>A<sup>o</sup></u>	6.5	22* (56)	53* (672)	159
	Alfisols (sil)	124 (15)	0–1792	2	<u>A<sup>o</sup></u>	8.3	11 <sup>ns</sup> (1344)	32* (448)	160
	Mollisols (sil)	167 (15)	0–896	1	<u>A<sup>o</sup></u>	6.2	14* (896)	22* (448)	161
	Mollisols (sil)	142 (15)	0–672	2	<u>A<sup>o</sup></u>	5.8	34* (224)	37* (672)	162
	Entisols (ls)	72–90 <sup>s</sup>	0–372	4	<u>Po</u>	34.8	17* (93)	25* (280)	163
South America									
Brazil	Oxisols	46 <sup>s</sup>	0–168	9	<u>Ri–Ri</u>	1.1	9* (42)	19** (126)	164
	Oxisols (ls)	20–52 <sup>s</sup> (20)	0–199	2	<u>S</u>	1.(5)	65* (33)	111* (133)	165
Peru	Ultisols	55 <sup>s</sup> (15)	0–120	6	<u>Ri–Cp<sup>o</sup></u>	2.1	4 <sup>ns</sup> (20)	22* (80)	166
	Ultisols	55 <sup>s</sup> (15)	0–120	4	<u>Ri–Cp<sup>o</sup></u>	0.8	–24* (20)	25* (120)	166
Venezuela	Oxisols (scl)	38 <sup>s</sup>	0–135	2	<u>S</u>	1.0	8 <sup>ns</sup> (9)	173* (108)	167
Europe									
Macedonia	Entisols	83 <sup>s</sup> (20)	0–100	2	<u>Po</u>	33.3	13** (100)	13** (100)	168
Africa									
Madagascar	Oxisols (sl)	55 <sup>s</sup> (20)	0–75	5	<u>S</u>	0.5	278** (25)	422** (50, 75)	169
Nigeria	Oxisols (ls-sl)	31–817 <sup>s</sup> (15)	0–75	9	<u>Ct</u>	1.9	35* (25)	42* (75)	170
	Alfisols, Ultisols (ls)	39–78 <sup>s</sup> (15)	0–40	20	<u>Gn</u>	1.4	24* (20)	31* (40)	171
	Inceptisols (ls)	20–66 <sup>s</sup> (15)	0–40	20	<u>Gn</u>	1.1	20* (20)	22* (40)	171
Asia									
Bangladesh	Inceptisols (scl)	20 <sup>s</sup>	28–37	1	<u>Sa</u>	1.3 <sup>10</sup>	8* (37)	8* (37)	172
	Entisols (scl)	78–86 <sup>s</sup> (30)	0–180	2	<u>Sc<sup>o</sup></u>	74.8	6* (45, 135)	9* (70, 90)	173
	Inceptisols (sicl)	133 <sup>s</sup> (20)	66–133	1	<u>Ra<sup>o</sup></u>	24.0 <sup>10</sup>	8* (100)	12* (133)	174
India	Vertisols	NR	9–150	2	<u>S</u>	3.1 <sup>10</sup>	–7* (37)	–3* (19)	175
	Inceptisols (sl)	223	0–33	1	<u>R<sup>o</sup></u>	1.1	–20* (33)	–20* (33)	176
	Alfisols, Inceptisols	22–60 <sup>s</sup> (15)	0–156	6	<u>W<sub>w</sub><sup>o</sup></u>	4.(8)	3 <sup>ns</sup> (156)	6** (104)	177
	Inceptisols (s-sl)	56–158 <sup>s</sup>	0–84	28	<u>Po<sup>o</sup></u>	12.1	15* (42)	22* (84)	178
	Inceptisols (ls, sil)	NR	0–66	4	<u>Ri<sup>o</sup></u>	5.3	6* (33)	11* (66)	179
				4	<u>W<sub>w</sub><sup>o</sup></u>	3.0	12* (33)	24* (66)	179

Table 4. (Cont.)

Location	Soil order <sup>2</sup>	Exchangeable K <sup>3</sup>	K applied (as KCl)	Site-years studied <sup>4</sup>	Cropping system <sup>5</sup>	Yield without fertilizer K <sup>6</sup>	Yield response to K <sup>7</sup>		Reference
							Lowest	Highest	
Indonesia	Alfisols (sl)	125	0–156	3	<u>Sc</u> <sup>9</sup>	103.6	11* (125)	19* (188)	180
	Aridisols (sl)	160 (15)	0–75	3	<u>W<sub>w</sub></u> <sup>9</sup>	4.7	10* (50)	14* (75)	181
	Inceptisols (sl)	138	0–166	4	<u>Po</u> <sup>9</sup>	28.4	17* (42)	38* (166)	182
	Inceptisols (sl)	75 <sup>8</sup>	62–187	8	<u>Po</u> <sup>9</sup>	21.3 <sup>10</sup>	17* (124)	21* (187)	183
	Oxisols	51 <sup>8</sup>	0–75	1	<u>C</u>	0.5	400* (25)	600* (75)	184
	Oxisols	NR	0–105	1	<u>P</u>	0.2	1 <sup>ns</sup> (26)	11* (105)	185
	Ultisols (c)	55 <sup>8</sup> (12)	23–83	6	<u>Cp–Ri–S</u> <sup>9</sup>	6.3 <sup>10</sup>	37* (83)	37* (83)	105
Pakistan	Aridisols (cl)	135 <sup>8</sup> (15)	0–148	1	<u>Ri–W<sub>w</sub></u> <sup>9</sup>	2.5	–14 <sup>ns</sup> (111)	23* (37)	186
		160 <sup>8</sup> (15)	0–148	1	<u>F–W<sub>w</sub></u> <sup>9</sup>	2.1	–12* (148)	16* (37)	
	Aridisols (sicl)	125 <sup>8</sup> (25)	0–199	1	<u>W<sub>w</sub></u> <sup>9</sup>	3.6	11 <sup>ns</sup> (33)	29** (133–199)	187
Turkey	Vertisols (c)	560–750 <sup>8</sup>	0–199	2	<u>Ct</u>	2.6	12* (66)	27* (133)	188
Vietnam	Ultisols	8 <sup>8</sup> (20)	0–133	9	<u>Cs</u>	2.8	454* (33)	546* (133)	189
Australasia									
Australia	Alfisols <sub>4</sub> , Entisols <sub>5</sub> , Inceptisols <sub>1</sub> (s)	19–37 <sup>8</sup> (10)	0–60	10	<u>Cn</u>	1.(2)	25* (15)	51* (60)	190
Mauke	Ultisols (cl)	NR	0–132	1	<u>Pn</u>	1.2	–16* (132)	–16* (132)	191

\* \*\* \*\* \*\* Significant at  $\alpha=0.05, 0.01$  and  $0.001$ , respectively; ns, not significant.

<sup>1</sup> A complete listing of all studies surveyed can be found in Table S4, for the online version of the paper.

<sup>2</sup> Surface texture designated parenthetically as c (clay), cl (clay loam), fs (fine sand), fsl (fine sandy loam), gl (gravelly loam), l (loam), lfs (loamy fine sand), ls (loamy sand), s (sand), scl (sandy clay loam), si (silt), sicl (silty clay loam), sil (silt loam) and sl (sandy loam). Subscripted values indicate the number of soils studied that represent a specific order.

<sup>3</sup> Air-dried data reported. Values in parentheses indicate sampling depth in cm. NR, not reported.

<sup>4</sup> Values take into account the number of genotypes studied and/or the use of multiple tillage systems.

<sup>5</sup> A, alfalfa (*Medicago sativa* L.); B, barley (*Hordeum vulgare* L.); Bg, bermudagrass (*Cynodon dactylon* L. Pers.); Bt, birdsfoot trefoil (*Lotus corniculatus* L.); C, corn (*Zea mays* L.); Cn, canola (*Brassica napus* and *campestris*); Cp, cowpea (*Vigna unguiculata* L.); Cs, cassava (*Manihot esculenta*); Ct, cotton (*Gossypium hirsutum* L.); F, fallow; Gn, groundnut (*Arachis hypogaea* L.); O, oat (*Avena sativa* L.); Og, orchardgrass (*Dactylis glomerata* L.); P, pea (*Pisum sativum* L.); Pn, peanut (*Arachis hypogaea* L.); Po, potato (*Solanum tuberosum* L.); R, rape (*Brassica napus* L.); Ra, radish (*Raphanus sativus* L.); Rc, reed canarygrass (*Phalaris arundinacea* L.); Rcl, red clover (*Trifolium pratense* L.); Ri, rice (*Oryza sativa* L.); S, soybean (*Glycine max* L. Merr.); Sa, safflower (*Carthamus tinctorius* L.); Sb, sugarbeet (*Beta vulgaris* L.); Sbg, smooth brome grass (*Bromus inermis* Leyss.); Sc, sugarcane (*Saccharum officinarum* L.); Sg, small grain; Tf, tall fescue (*Festuca arundinacea* Schreb.); Vg, vegetables; Wc, white clover (*Trifolium repens* L.); W<sub>w</sub>, winter wheat (*Triticum aestivum* L.). Underscoring indicates the crop(s) studied for K response.

<sup>6</sup> Data for legumes were obtained from fertilization with P but not K, whereas data for non-legumes were obtained from fertilization with N or N and P but not K. Parentheses indicate digital uncertainty in estimating data reported in figures. When otherwise reported, grain yields were adjusted to market-standard moisture content.

<sup>7</sup> Estimated as  $100 \times (\text{fertilized yield} - \text{unfertilized yield}) / \text{unfertilized yield}$ . Values in parentheses indicate the rate of K application in  $\text{kg ha}^{-1} \text{yr}^{-1}$ . Application of N or N and P was constant throughout the range of K rates cited.

<sup>8</sup> Values expressed as  $\text{mg kg}^{-1}$ .

<sup>9</sup> Above-ground residues removed.

<sup>10</sup> Yield when the lowest K rate was applied with N or N and P.

Many leguminous crops are sensitive to  $\text{Cl}^-$  toxicity, including soybean<sup>120,131</sup> and alfalfa<sup>159,160,198</sup>, and  $\text{Cl}^-$  can reduce soil N availability by inhibiting nitrification in soils<sup>195,196,199,200</sup> (see also supplementary references [53–55] for the online version of the paper) and by acting as a competitive anion that suppresses plant uptake of  $\text{NO}_3^-$ <sup>147,201,202</sup> (see also supplementary references [38] and [56–59] for the online version of the paper). A further difficulty arises from the mobility of  $\text{Cl}^-$  in soils, which intensifies profile leaching of  $\text{Ca}^{2+}$  as a counterion<sup>203–205</sup>.

Producers have long been led to believe that KCl fertilization serves an essential role, not only for sustaining crop yield but more importantly, for ensuring a high-quality product that will maximize economic return. To ascertain the credibility of the latter claim, a thorough survey was undertaken of peer-reviewed and university publications that provide the most reliable source of information regarding the agronomic effects of KCl. The findings, summarized in Table 5 for more than 1000 field experiments, altogether contradict the prevailing belief in the value of this fertilizer for improving crop quality, since the frequency of positive responses was only about 8%. On the contrary, the qualitative effect of KCl was negative in 57% of the trials surveyed. In some of these trials, crop quality was reduced despite a significant yield increase<sup>159,160</sup>.

One of the better known consequences of KCl fertilization, reported in Table 5 for studies with corn<sup>153,201,212,216</sup>, wheat<sup>221</sup> and sorghum (*Sorghum bicolor* L. Moench)<sup>137</sup>, arises from the antagonistic effect of  $\text{Cl}^-$  on  $\text{NO}_3^-$  uptake that reduces lodging or stalk rot when susceptible cereal varieties are grown on a soil with high N-supplying power and/or with heavy inputs of fertilizer N, but at the expense of promoting  $\text{NO}_3^-$  loss through leaching or denitrification. The use of KCl can also have a beneficial effect by increasing the fiber strength (micro-naire) of cotton (*Gossypium hirsutum* L.) grown on soils inherently limited in K reserves<sup>222–224,226</sup>, which would be expected considering the lack of a dense rooting system or residue K inputs.

Other qualitative benefits are often claimed for KCl fertilization of grain, fiber, oilseed or sugar crops, but these are difficult to reconcile with the listings in Table 5. This fertilizer, for example, has usually been ineffective for reducing disease severity in barley (*Hordeum vulgare* L.), wheat, soybean or cotton, and even with a positive effect, there was no significant yield increase<sup>202,210,219,225</sup> except where root rot was associated with a high content of  $\text{NO}_3^-$  but not  $\text{K}^+$  or  $\text{Cl}^-$ <sup>147</sup> or when a susceptible variety was grown on an infertile sand<sup>207</sup>. There was likewise little evidence that KCl enhances sucrose content in sugar crops or oil, protein or fiber content or composition. Instead, these constituents were more likely to be adversely affected, as reported by Fintel and Quicke<sup>214</sup> for corn protein that declined in niacin and tryptophan. Such a decline has serious implications for human nutrition in the developing world, where grain is the staple food source.

Tuber crops are no less important to human nutrition, and particularly potato (*Solanum tuberosum* L.) that has a much higher K requirement than grain crops. In many parts of the world, KCl fertilization is a normal practice for potato production; however, there is a hidden cost from lowering starch content, which in turn reduces specific gravity. These effects, clearly documented in Table 5, have adverse consequences for human health such as obesity and cardiovascular disease, arising from greater oil retention in processed products such as potato chips and french fries. The anion supplied by KCl intensifies the decline in starch or dry matter content and specific gravity<sup>163,238,241–244</sup>, and becomes a toxicological concern by enhancing the mobility and plant uptake of soil Cd<sup>239,240,247</sup>. The latter problem has also been reported for cereal crops<sup>208,220</sup>, and may thus be of broader interest for contamination of the food chain, particularly in view of recent clinical evidence linking breast cancer to dietary Cd exposure<sup>248</sup>.

Forage crops remove large amounts of K because their aboveground biomass is repeatedly harvested, and intensive usage of fertilizer KCl is widely promoted to not only sustain productivity, but more importantly, to ensure high forage quality that is critical to animal nutrition. Unfortunately, Table 5 provides no evidence that KCl is of any qualitative benefit to forage crops; rather, the effect was invariably negative, often involving a low content of Ca and/or Mg<sup>159–161,229,230</sup> that predisposes livestock to milk fever<sup>249,250</sup> or grass tetany<sup>229,251</sup>. To prevent these disorders while improving forage quality, Cherney et al.<sup>252</sup> have recommended that the use of fertilizer K or manure be avoided on dairy farms in the northern USA, unless K deficiency is detected by plant analysis.

Elevated K supplies have long been recognized to have an antagonistic impact on the bioavailability of Ca and Mg, with adverse consequences for crop yield and quality. For example, McCalla<sup>253</sup> found that raising the K:Ca ratio in culture studies led to a progressive decrease in the growth of legume bacteria and in the nodulation of alfalfa and soybean roots. This imbalance would normally be ameliorated by liming, but even a neutral Ca salt can be utilized successfully to enhance soybean nodulation on an acidic soil<sup>254</sup>. There are broader ramifications from the antagonistic effect of K on the Ca content of food crops, because low dietary Ca intake has been linked to several human diseases, including osteoporosis, rickets and colon cancer<sup>255–259</sup>.

The problems associated with KCl usage have been thoroughly documented for arid and semi-arid regions by Krauss and Saurat<sup>260</sup>, and arise in part from the presence of a bioactive anion that has detrimental consequences for crop yield and quality. Some of these consequences can be avoided by applying  $\text{K}_2\text{SO}_4$  instead of KCl. The benefits of this strategy for increasing crop yield and/or quality have been documented in numerous studies with potato<sup>133,163,168,261–265</sup> and to a lesser extent

**Table 5.** Condensed version of a survey of peer-reviewed and university publications concerning the effect of KCl fertilization on the quality of selected food, feed and fiber crops.<sup>1</sup>

Crop(s) <sup>2</sup>	Study location(s)	Study period <sup>3</sup>	Site-years studied <sup>4</sup>	Soil type <sup>5</sup>	Parameter of K response	Net effect on crop quality	Reference	
<i>Grain crops</i>								
Barley	Alberta	1989–1998	115	NR	Root rot infestation	None	206	
	Australia	2003	1	s	Powdery mildew severity	Positive	207	
	Manitoba	1990–1992	6	fsl, cl	Cd content	Negative	208	
	North Dakota	1964–1967	13	sl-sicl	Grain protein content	None	209	
		1983	5	l	Root rot induced by high N	Positive	202	
		1984	6	l	Root rot induced by high N	Positive	147	
Barley, wheat	Saskatchewan	1987–1989	14	l-c	Root rot	Positive	210	
Corn	Illinois	1985–1986	10	sil	Leaf Ca and Mg content	Negative	211	
	New Jersey	1994–1995	2	sl	Stalk rot induced by high N	Positive	212	
	New York	1956	1	NR	Stalk rot induced by high N	Positive	201	
	North Carolina	1982–1983	10	ls	Ca and Mg content	Negative	213	
	South Africa	1957–1959	1	NR	Niacin and tryptophan content	Negative	214	
	Tennessee	1951	1	fsl	Lodging induced by high N	Positive	153	
		1957	10	l	Ca and Mg content	Negative	215	
	Wisconsin	1962	1	sil	Lodging induced by high N	Positive	216	
Oat	South Dakota	1986–1987	15	NR	Crown rust incidence	None	152	
					Lodging	Variable		
Sorghum	Kansas	1995–1996	4	sil	Lodging induced by high N	Positive	137	
Soybean	Delaware	1974–1975	40	ls, sil	Gray seed mold, purple seed stain	None	125	
	Georgia	1981	30	s	Cl <sup>-</sup> toxicity	Negative	131	
	Iowa	1995–2001	25	l-cl	Seed oil and protein content	None	217	
	North Carolina	1943	3	fsl	Seed protein content	Negative	146	
	Virginia	1974–1975	2	cl	Nodulation	Positive	158	
	Wisconsin	1927	1	sl	Nodulation	Negative	218	
Wheat	Nepal	2000–2002	4	l	Spot blotch severity	Positive	219	
	North Dakota	1997	124	NR	Cd content	Negative	220	
	Pakistan	1980–1981	3	cl	Grain content of crude protein	Positive	186	
	Pakistan	1956–1957	5	NR	Lodging induced by high N	Positive	221	
<i>Fiber crops</i>								
Cotton	Alabama	1960–1961	2	sl	Micronaire	Positive	222	
	Brazil	2001–2003	3	cl	Micronaire	Positive	223	
	California	1985–1987	4	sl	Micronaire	Positive	224	
	Mississippi	1986–1988	3	fsl	Verticillium wilt severity, nematode infestation	Positive	225	
						Micronaire	None	
			1991–1992	16	fsl	Micronaire	Positive	226
		1993–1994	8	fsl	Lint percentage	Positive	141	
		1995–1997	11	fsl	Micronaire	None	143	
		1999–2001	27	fsl	Nematode infestation	Negative	227	
	Turkey	1999–2000	2	c	Micronaire	None	188	

									The potassium paradox
Crop	Location	Year	n	Soil	Parameter	Effect	Page		
<i>Forage crops</i>									
Alfalfa	Wisconsin	1970–1972	3	sil	Ca and Mg content	Negative	159		
		1970–1972	3	sil	Cl <sup>-</sup> toxicity	Negative	198		
		1972–1973	2	sil	Ca and Mg content	Negative	160		
		1998–2001	11	ls-sil	Ca and Mg content	Negative	228		
Mixed grass-clover	Australia	1966–1971	4	NR	Incidence of grass tetany	Negative	229		
Red clover	Wisconsin	1974	1	sil	Ca and Mg content	Negative	161		
Sorghum × sudangrass	New York	2002–2003	2	sil	Ca and Mg and crude protein content, milk production	Negative	230		
Subterranean clover-ryegrass	Australia	1968–1973	27	s-l	Mg content	Negative	231		
Tall fescue	West Virginia	1971–1975	32	sicl	Ca and Mg content	Negative	232		
<i>Oilseed crops</i>									
Peanut	Alabama	1973–1986	39	ls-sl	Kernel grade	None	110		
Rape	Australia	1993–2003	53	ps	Seed oil content	None	233		
	India	1969–1970	1	sl	Seed protein and oil content	Negative	176		
Safflower	Bangladesh	1973–1974	1	scl	Seed protein content	Negative	172		
					Seed oil content	Positive			
Sunflower	Minnesota, North Dakota	NR	22	fsl-sic	Cd content	Negative	234		
<i>Sugar crops</i>									
Sugarbeet	England	1959–1962	42	NR	Sucrose content, juice purity	None	235		
Sugarcane	Brazil	2006	1	scl	Sucrose content	None	236		
	Florida	1970–1972	2	m	Sucrose content	None	237		
		1978	1	m	Sucrose content	Negative	127		
	India	1989–1992	3	sl	Sucrose yield	Positive	180		
<i>Tuber crops</i>									
Potato	Australia	1982–1984	30	NR	Specific gravity	Negative	238		
		1992–1993	6	sl-c	Cd content	Negative	239		
		1991–1992	5	s-l	Cd content	Negative	240		
		1989–1999	33	s-c	Dry matter content	Negative	241		
	Idaho	1970–1976	4	ls	Specific gravity	Negative	242		
		NR	4	gl	Specific gravity	Negative	133		
	India	2001–2002	4	sl	Dry matter content, specific gravity, chip color	Negative	182		
		2000–2001	4	sl	Tuber weight	Positive	183		
	Ireland	1961–1966	27	NR	Dry matter content	Negative	243		
	Macedonia	1995–1996	2	NR	Starch content	None	168		
	Maine	1955–1958	56	NR	Specific gravity	Negative	244		
	Sweden	1964–1967	68	sl-l	Dry matter content	Negative	245		
	Utah	1988–1989	2	sil	Specific gravity	Negative	156		
	Wisconsin	1992–1995	11	ls-sil	Specific gravity	Negative	163		
Sweet potato	Louisiana	1968–1975	13	sil	Dry matter and protein content, firmness	Negative	246		

<sup>1</sup> A complete listing of all studies surveyed can be found in Table S5 for the online version of the paper.

<sup>2</sup> Latin names for crops not included in Table 4: ryegrass, *Lolium perenne* L. and *Lolium rigidum* Gaudin; subterranean clover, *Trifolium subterranean* L.

<sup>3</sup> NR, not reported.

<sup>4</sup> Values take into account number of genotypes studied.

<sup>5</sup> Abbreviations: c (clay), cl (clay loam), fs (fine sand), fsl (fine sandy loam), gl (gravelly loam), l (loam), lfs (loamy fine sand), ls (loamy sand), m (muck), p (peat), ps (predominately sandy), s (sand), scl (sandy clay loam), sic (silty clay), sicl (silty clay loam), sil (silt loam), sl (sandy loam). NR, not reported.

with several other crops, including alfalfa<sup>160</sup>, soybean<sup>266</sup> and wheat<sup>186,267</sup>.

Tables 4 and 5 (see also Tables S4 and S5 for the online version of the paper) provide little agronomic justification for the buildup-maintenance philosophy that for several decades has intensified the input of fertilizer K, often in conjunction with direct or indirect subsidies at considerable public expense<sup>268,269</sup> (see also supplemental references [60–62] for the online version of the paper). The result has been massive KCl consumption, which for Illinois has surpassed 21 Tg since 1950, equivalent on average to approximately 2200 kg ha<sup>-1</sup><sup>270–272</sup>. A cumulative effect on soil physical and chemical properties would be expected, since K is prone to interlayer fixation that collapses 2:1 clay minerals and converts an active, swelling smectite to an inactive, non-swelling illite<sup>26,273</sup>. The stabilizing value of KCl has long been recognized in the construction of impervious pavement and foundations<sup>274–277</sup>. Unfortunately, the agronomic consequences include a loss of CEC<sup>71,77,278–280</sup> and lower water-holding capacity, which is not conducive to crop growth and productivity.

## Conclusions

Since the onset of industrialized agriculture more than half a century ago, the view has been inculcated that intensive inputs of fertilizer K are indispensable for maximizing crop yield and quality and for the long-term maintenance of soil productivity. This view cannot be reconciled with the considerable volume of scientific evidence presented herein, encompassing soil testing for plant-available K and the consequences of KCl fertilization for agricultural productivity, food safety and soil degradation.

If fertilizer K usage is to be profitable in a production setting, current recommendations will no longer suffice that rely on soil testing for exchangeable K. As a more viable alternative, producers should periodically carry out their own strip trials, for comparing yield with and without upward and downward K rate adjustment. Initially, a 3-year period would be appropriate for repeating these trials, but a longer interval could safely be employed with cash-grain cropping that limits K removal. To avoid the adverse consequences of Cl<sup>-</sup>, K<sub>2</sub>SO<sub>4</sub> would be preferred as a fertilizer source.

**Acknowledgements.** This study was performed with partial funding under TIPAN Project 391-0488, and with additional funding through the <sup>15</sup>N Analysis Service and Projects ILLU-875-316 and ILLU-875-375, Illinois Agricultural Experiment Station. We thank Dr T.R. Peck (now deceased) for directing a thesis project by the senior author to quantify soil K dynamics in relation to fertility evaluation and fertilizer recommendations, and for preserving and archiving soil samples collected from the Morrow Plots. Appreciation is also expressed to the numerous scientists whose work is cited in Tables 2, 4 and 5; to all

responsible for cropping the Morrow Plots since 1876; and to library personnel at the University of Illinois who assisted in obtaining many references cited. Finally, we acknowledge Dr C.G. Hopkins for recognizing a century ago the importance of profile K reserves for sustaining crop K nutrition.

## References

- Howard, A. 1947. *The Soil and Health. A Study of Organic Agriculture*. Devin-Adair, New York.
- Snow, J.S. 2009. *Misunderstanding Soil Ecosystems*. MA thesis, Tufts University, Boston, MA. Available at Web site <http://www.tufts.edu/water/pdf/Thesis/JSnowThesis.pdf> (verified November 27, 2012).
- Visser, J. 2010. *Down to Earth*. PhD thesis, Wageningen University, Wageningen, The Netherlands. Available at Web site <http://edepot.wur.nl/135448> (verified November 27, 2012).
- Truog, E. 1938. Putting soil science to work. *Journal of the American Society of Agronomy* 30:973–985.
- Liebhart, W.C. and Cotnoir, L. 1979. Potassium fertilizer recommendations and changes in potassium soil test values as influenced by additions of potassium. *Communications in Soil Science and Plant Analysis* 10:831–840.
- Olson, R.A., Anderson, F.N., Frank, K.D., Grabouski, P.H., Rehm, G.W., and Shapiro, C.A. 1987. Soil testing interpretations: Sufficiency vs. build-up and maintenance. In J.R. Brown (ed.). *Soil Testing: Sampling, Correlation, Calibration, and Interpretation*. Soil Science Society of America, Madison, WI. p. 41–52.
- Thomas, G.W. 1989. The soil bank account and the farmer's bank account. *Journal of Production Agriculture* 2:122–124.
- Hopkins, C.G. and Aumer, J.P. 1915. Potassium from the Soil. Illinois Agricultural Experiment Station Bulletin 182. University of Illinois, Urbana, IL.
- Blair, A.W. 1919. Utilizing soil potash by means of intermediary crops. *Proceedings of the Society for Promotion of Agricultural Science* 39:69–74.
- Reitemeier, R.F. 1951. Soil potassium. *Advances in Agronomy* 3:113–164.
- Srinivasa Rao, C., Rupa, T.R., Rao, A.S., and Bansal, S.K. 2001. Subsoil potassium availability in twenty-two benchmark soil series of India. *Communications in Soil Science and Plant Analysis* 32:863–876.
- Bradfield, R. 1946. Where are the new discoveries in soil science leading? I. The physical chemistry of soil-plant relationships. *Soil Science Society of America Proceedings* 11:3–8.
- Bray, R.H. 1944. Soil-plant relations I. The quantitative relation of exchangeable potassium to crop yields and to crop response to potash additions. *Soil Science* 58:305–324.
- Bear, F.E. and Toth, S.J. 1948. Influence of calcium on availability of other soil cations. *Soil Science* 65:69–74.
- Eckert, D.J. 1987. Soil test interpretations: Basic cation saturation ratios and sufficiency levels. In J.R. Brown (ed.). *Soil Testing: Sampling, Correlation, Calibration, and Interpretation*. Soil Science Society of America, Madison, WI. p. 53–64.
- Kopittke, P.M. and Menzies, N.W. 2007. A review of the use of the basic cation saturation ratio and the 'ideal' soil. *Soil Science Society of America Journal* 71:259–265.



- 17 Bray, R.H. and DeTurk, E.E. 1938. The release of potassium from non-replaceable forms in Illinois soils. *Soil Science Society of America Proceedings* 3:101–106.
- 18 Luebs, R.E., Stanford, G., and Scott, A.D. 1956. Relation of available potassium to soil moisture. *Soil Science Society of America Proceedings* 20:45–50.
- 19 Martin, H.W. and Sparks, D.L. 1985. On the behavior of nonexchangeable potassium in soils. *Communications in Soil Science and Plant Analysis* 16:133–162.
- 20 Mengel, K. and Uhlenbecker, K. 1993. Determination of available interlayer potassium and its uptake by ryegrass. *Soil Science Society of America Journal* 57:761–766.
- 21 Skogley, E.O. 1994. Reinventing soil testing for the future. In J.L. Havlin and J.S. Jacobsen (eds). *Soil Testing: Prospects for Improving Nutrient Recommendations*. Soil Science Society of America Special Publication 40. Soil Science Society of America, Madison, WI. p. 187–201.
- 22 Khan, S.A. 1991. Soil K level in relation to K treatment, season of year and soil moisture level. PhD thesis, University of Illinois, Urbana, IL.
- 23 Wascher, H.L., Alexander, J.D., Ray, B.W., Beavers, A.H., and Odell, R.T. 1960. Characteristics of Soils Associated with Glacial Till in Northeastern Illinois. *Illinois Agricultural Experiment Station Bulletin* 665. University of Illinois, Urbana, IL.
- 24 Knudsen, D., Peterson, G.A., and Pratt, P.F. 1982. Lithium, sodium, and potassium. In A.L. Page, R.H. Miller, and D.R. Keeney (eds). *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*. Agronomy Monograph 9. 2nd ed. American Society of Agronomy and Soil Science Society of America, Madison, WI. p. 225–246.
- 25 Suhr, N.H. and Ingamells, C.O. 1966. Solution technique for analysis of silicates. *Analytical Chemistry* 38:730–734.
- 26 Velde, B. and Peck, T. 2002. Clay mineral changes in the Morrow experimental plots, University of Illinois. *Clays and Clay Minerals* 50:364–370.
- 27 Khan, S.A., Mulvaney, R.L., Ellsworth, T.R., and Boast, C.W. 2007. The myth of nitrogen fertilization for soil carbon sequestration. *Journal of Environmental Quality* 36:1821–1832.
- 28 Fernández, F.G. and Hoef, R.G. 2009. Managing soil pH and crop nutrients. In E. Nafziger (ed.) *Illinois Agronomy Handbook*. 24th ed. University of Illinois, Urbana, IL. p. 91–112.
- 29 Leask, W.C. and Daynard, T.B. 1973. Dry matter yield, *in vitro* digestibility, percent protein, and moisture of corn stover following grain maturity. *Canadian Journal of Plant Science* 53:515–522.
- 30 Kiniry, J.R., Williams, J.R., Vanderlip, R.L., Atwood, J.D., Reicosky, D.C., Mulliken, J., Cox, W.J., Mascagni, H.J. Jr, Hollinger, S.E., and Wiebold, W.J. 1997. Evaluation of two maize models for nine U.S. locations. *Agronomy Journal* 89:421–426.
- 31 Prince, S.D., Haskett, J., Steininger, M., Strand, H., and Wright, R. 2001. Net primary production of U.S. Midwest croplands from agricultural harvest yield data. *Ecological Applications* 11:1194–1205.
- 32 Tollenaar, M., Ahmadzadeh, A., and Lee, E.A. 2004. Physiological basis of heterosis for grain yield in maize. *Crop Science* 44:2086–2094.
- 33 Mengel, K. 2007. Potassium. In A.V. Barker and D.J. Pilbeam (eds). *Handbook of Plant Nutrition*. Taylor & Francis, Boca Raton, FL. p. 91–120.
- 34 Lovell, M.C. 2012. Seasonal adjustment of economic time series and multiple regression analysis. *Journal of the American Statistical Association* 58:993–1010.
- 35 SAS Institute. 2013. SAS Onlinedoc 9.1.3. SAS Institute, Cary, NC. Available at Web site <http://support.sas.com/onlinedoc/913/docMainpage.jsp> (verified March 21, 2013).
- 36 Hochberg, Y. 1988. A sharper Bonferroni procedure for multiple tests of significance. *Biometrika* 75:800–802.
- 37 Attoe, O.J. 1946. Potassium fixation and release in soils occurring under moist and drying conditions. *Soil Science Society of America Proceedings* 11:145–149.
- 38 Hanway, J.J., Barber, S.A., Bray, R.H., Caldwell, A.C., Fried, M., Kurtz, L.T., Lawton, K., Pesek, J.T., Pretty, K., Reed, M., and Smith, F.W. 1962. North Central Regional Potassium Studies III. Field Studies with Corn. *Iowa Agricultural Experiment Station Research Bulletin* 503. Iowa State University, Ames, IA.
- 39 Hoskinson, R.L., Hess, J.R., and Alessi, R.S. 1999. Temporal changes in the spatial variability of soil nutrients. In J.V. Stafford (ed.). *Precision Agriculture '99. Part 1*. Academic Press, Sheffield, England. p. 61–70.
- 40 Blakemore, M. 1966. Seasonal changes in the amounts of phosphorus and potassium dissolved from soils by dilute calcium chloride solutions. *Journal of Agricultural Science, Cambridge* 66:139–146.
- 41 Childs, F.D. and Jencks, E.M. 1967. Effect of time and depth of sampling upon soil test results. *Agronomy Journal* 59:537–540.
- 42 International Plant Nutrition Institute. 2009. Soil Fertility Shifts in Eastern Canada and the Northeastern USA. International Plant Nutrition Institute, Norcross, GA. Available at Web site <http://nane.ipni.net/articles/NANE0047-EN> (verified May 25, 2012).
- 43 Fixen, P.E. 2006. Soil test levels in North America. *Better Crops* 90(1):4–7. Available at Web site [http://www.ipni.net/publication/bettercrops.nsf/0/1403E75A034B3F3A8525798000771851/\\$FILE/Better%20Crops%202006-1%20\(lo%20res\).pdf](http://www.ipni.net/publication/bettercrops.nsf/0/1403E75A034B3F3A8525798000771851/$FILE/Better%20Crops%202006-1%20(lo%20res).pdf) (verified August 13, 2012).
- 44 Cope, J.T. Jr 1970. Response of Cotton, Corn, Bermudagrass to Rates of N, P, and K. *Alabama Agricultural Experiment Station Circular* 181. Auburn University, Auburn, AL.
- 45 Cope, J.T. Jr 1981. Effects of 50 years of fertilization with phosphorus and potassium on soil test levels and yields at six locations. *Soil Science Society of America Journal* 45:342–347.
- 46 Cope, J.T. Jr 1984. Long-Term Fertility Experiments on Cotton, Corn, Soybeans, Sorghum, and Peanuts, 1929–1982. *Alabama Agricultural Experiment Station Bulletin* 561. Auburn University, Auburn, AL.
- 47 Mainz, M.A. 1987. Potassium rate study. In Report of Research Results, Northwestern Illinois Agricultural Research and Demonstration Center. University of Illinois, Urbana, IL. p. 45–48.
- 48 Ebelhar, S.A. and Varsa, E.C. 1999. Tillage and potassium placement effects on potassium use efficiency in a corn–soybean rotation. In R.G. Hoef (ed.). 1999 Illinois Fertilizer Conference Proceedings. University of Illinois,

- Urbana, IL. p. 161–180. Available at Web site <http://frec.ifca.com/1999/report13/index.htm> (verified August 9, 2012).
- 49 Li, R.-G. and Barber, S.A. 1988. Effect of phosphorus and potassium fertilizer on crop response and soil fertility in a long-term experiment. *Fertilizer Research* 15:123–136.
  - 50 Mallarino, A.P., Webb, J.R., and Blackmer, A.M. 1991. Soil test values and grain yields during 14 years of potassium fertilization of corn and soybean. *Journal of Production Agriculture* 4:562–566.
  - 51 Mallarino, A.P., Webb, J.R., and Blackmer, A.M. 1991. Corn and soybean yields during 11 years of phosphorus and potassium fertilization on a high-testing soil. *Journal of Production Agriculture* 4:312–317.
  - 52 Vitosh, M.L., Lucas, R.E., and Silva, G.H. 1997. Long-term effects of fertilizer and manure on corn yield, soil carbon, and other soil chemical properties in Michigan. In E.A. Paul, K.A. Paustian, E.T. Elliott and C.V. Cole (eds). *Soil Organic Matter in Temperate Agroecosystems: Long-Term Experiments in North America*. CRC Press, Boca Raton, FL. p. 129–139.
  - 53 Randall, G.W., Evans, S.D., and Iragavarapu, T.K. 1997. Long-term P and K applications. II. Effect on corn and soybean yields and plant P and K concentrations. *Journal of Production Agriculture* 10:572–580.
  - 54 Randall, G.W., Iragavarapu, T.K., and Evans, S.D. 1997. Long-term P and K applications: I. Effect on soil test decline and decline rates and critical soil test levels. *Journal of Production Agriculture* 10:565–571.
  - 55 Brown, J.R., Osburn, D.D., Redhage, D., and Gantzer, C.J. 1995. Multi-crop comparisons on Sanborn Fields, Missouri, USA. In V. Barnett, R. Payne and R. Steiner (eds). *Agricultural Sustainability. Economic, Environmental and Statistical Considerations*. John Wiley, Chichester, England. p. 111–132.
  - 56 Olson, R.A., Frank, K.D., Grabouski, P.H., and Rehm, G.W. 1982. Economic and agronomic impacts of varied philosophies of soil testing. *Agronomy Journal* 74:492–499.
  - 57 Markus, D.K. and Battle, W.R. 1965. Soil and plant responses to long-term fertilization of alfalfa (*Medicago sativa* L.). *Agronomy Journal* 57:613–616.
  - 58 Woodhouse, W.W. Jr 1968. Long-term fertility requirements of coastal bermudagrass. I. Potassium. *Agronomy Journal* 60:508–512.
  - 59 Davis, R.L., Patton, J.J., Teal, R.K., Tang, Y., Humphreys, M.T., Mosali, J., Girma, K., Lawles, J.W., Moges, S.M., Malapati, A., Si, J., Zhang, H., Deng, S., Johnson, G.V., Mullen, R.W., and Raun, W.R. 2003. Nitrogen balance in the Magruder Plots following 109 years in continuous winter wheat. *Journal of Plant Nutrition* 26:1561–1580.
  - 60 Girma, K., Holtz, S.L., Arnall, D.B., Tubaña, B.S., and Raun, W.R. 2007. The Magruder Plots: Untangling the puzzle. *Agronomy Journal* 99:1191–1198.
  - 61 Harper, H.J. 1959. 65 Years of Continuous Wheat. Bulletin B-531. Oklahoma State University, Stillwater, OK.
  - 62 Lutz, J.A. Jr 1973. Potassium supplying power of Groseclose silt loam for corn. *Communications in Soil Science and Plant Analysis* 4:23–30.
  - 63 Zhang, H., Wang, B., and Xu, M. 2008. Effects of inorganic fertilizer inputs on grain yields and soil properties in a long-term wheat-corn cropping system in south China. *Communications in Soil Science and Plant Analysis* 39:1583–1599.
  - 64 Zhang, H.-M., Wang, B.-R., Xu, M.-G., and Fan, T.-L. 2009. Crop yield and soil responses to long-term fertilization on a red soil in southern China. *Pedosphere* 19:199–207.
  - 65 Wang, X., Hoogmoed, W.B., Cai, D., Perdok, U.D., and Oenema, O. 2007. Crop residue, manure and fertilizer in dryland maize under reduced tillage in northern China: II Nutrient balances and soil fertility. *Nutrient Cycling in Agroecosystems* 79:17–34.
  - 66 Wang, X., Cai, D., Hoogmoed, W.B., Perdok, U.D., and Oenema, O. 2007. Crop residue, manure and fertilizer in dryland maize under reduced tillage in northern China: I Grain yields and nutrient use efficiencies. *Nutrient Cycling in Agroecosystems* 79:1–16.
  - 67 Johnston, A.E. and Poulton, P.R. 1977. Yields on the Exhaustion Land and changes in the NPK content of the soils due to cropping and manuring, 1852–1975. In Rothamsted Experimental Station Report for 1976. Part 2. Lawes Agricultural Trust, Harpenden, Herts, England. p. 53–85.
  - 68 Last, P.J., Webb, D.J., Bugg, R.B., Bean, K.M.R., Durrant, M.J., and Jaggard, K.W. 1985. Long-term effects of fertilizers at Broom's Barn, 1965–82. In Rothamsted Experimental Station Report for 1984. Part 2. Lawes Agricultural Trust, Harpenden, Herts, England. p. 231–249.
  - 69 Blake, L., Mercik, S., Koerschens, M., Goulding, K.W.T., Stempen, S., Weigel, A., Poulton, P.R., and Powlson, D.S. 1999. Potassium content in soil, uptake in plants and the potassium balance in three European long-term field experiments. *Plant and Soil* 216:1–14.
  - 70 Dam Kofoed, A. and Nemming, O. 1976. Askov 1894: Fertilizers and manure on sandy and loamy soils. *Annales Agronomiques* 27:583–610.
  - 71 Amberger, A. and Gutser, R. 1976. Effect of long-term potassium fertilization on crops and potassium dynamics of a brown earth (Weißenstephan). *Annales Agronomiques* 27:643–657.
  - 72 Stumpe, H., Garz, J., Johannemann, R., and Buchte, M. 1989. Einfluß der K-Düngung auf den Ertrag und einige Bodeneigenschaften in einem Dauerversuch auf einer Sandlöß-Braunschwarzerde in Halle. *Archiv für Acker- und Pflanzenbau und Bodenkunde* 33:301–310.
  - 73 Brar, B.S. and Pasricha, N.S. 1998. Long-term studies on integrated use of organic and inorganic fertilizers in maize-wheat-cowpea cropping system on alluvial soil of Punjab. In A. Swarup, D. Damodar Reddy, and R.N. Prasad (eds). *Proceedings of a National Workshop on Long-term Soil Fertility Management Integrated Plant Nutrient Supply*. Indian Institute of Soil Science, Bhopal, India. p. 154–168.
  - 74 Sharma, S.P., Sharma, J., and Subehia, S.K. 1998. Long-term effects of chemical fertilizers on crop yields, nutrients uptake and soil environment in western Himalayan soils. In A. Swarup, D. Damodar Reddy, and R.N. Prasad (eds). *Proceedings of a National Workshop on Long-term Soil Fertility Management Integrated Plant Nutrient Supply*. Indian Institute of Soil Science, Bhopal, India. p. 125–138.
  - 75 Lee, R. and Metson, A.J. 1977. Potassium removal from soil by lucerne over three years and the effect of potassium topdressing. *New Zealand Journal of Agricultural Research* 20:185–192.

- 76 Agboola, A.A. 1970. Preliminary investigation on the effect of continuous cropping of maize on grain yield and on total nitrogen, available phosphorus and exchangeable potassium on three Nigerian soils. *Nigerian Journal of Science* 4:89–99.
- 77 De Datta, S.K., Gomez, K.A., and Descalsota, J.P. 1988. Changes in yield response to major nutrients and in soil fertility under intensive rice cropping. *Soil Science* 146:350–358.
- 78 Öborn, I., Edwards, A.C., and Hillier, S. 2010. Quantifying uptake rate of potassium from soil in a long-term grass rotation experiment. *Plant and Soil* 335:3–19.
- 79 Tisdale, S.L., Nelson, W.L., and Beaton, J.D. 1985. *Soil Fertility and Fertilizers*. 4th ed. Macmillan Publishing Company, New York, NY.
- 80 Cassman, K.G., Olk, D.C., Brouder, S.M., and Roberts, B. A. 1995. The influence of moisture regime, organic matter, and root eco-physiology on the availability and acquisition of potassium: Implications for tropical lowland rice. In *Potassium in Asia. Balanced Fertilization to Increase and Sustain Agricultural Production*. International Potash Institute, Basel, Switzerland. p. 135–156.
- 81 Abel, F.A.E. and Magistad, O.C. 1935. Conversion of soil potash from the non-replaceable to the replaceable form. *Journal of the American Society of Agronomy* 27:437–445.
- 82 Parker, D.R., Hendricks, G.J., and Sparks, D.L. 1989. Potassium in Atlantic Coastal Plain soils: II. Crop responses and changes in soil potassium under intensive management. *Soil Science Society of America Journal* 53:397–401.
- 83 Mengel, K., Rahmatullah, and Dou, H. 1998. Release of potassium from the silt and sand fraction of loess-derived soils. *Soil Science* 163:805–813.
- 84 Rouse, R.D. and Bertramson, B.R. 1949. Potassium availability in several Indiana soils: Its nature and methods of evaluation. *Soil Science Society of America Proceedings* 14:113–123.
- 85 Wood, L.K. and DeTurk, E.E. 1941. The absorption of potassium in soils in non-replaceable forms. *Soil Science Society of America Proceedings* 5:152–161.
- 86 Oliveira, V., Ludwick, A.E., and Beatty, M.T. 1971. Potassium removed from some southern Brazilian soils by exhaustive cropping and chemical extraction methods. *Soil Science Society of America Proceedings* 35:763–767.
- 87 Ganeshamurthy, A.N. 1983. An estimate of the uptake of subsurface soil potassium by crops in two long-term experiments. *Journal of Agricultural Science, Cambridge* 101:495–497.
- 88 Badraoui, M., Bloom, P.R., and Delmaki, A. 1992. Mobilization of non-exchangeable K by ryegrass in five Moroccan soils with and without mica. *Plant and Soil* 140:55–63.
- 89 Zubillaga, M.M. and Conti, M.E. 1996. Availability of exchangeable and non-exchangeable K in Argentine soils with different mineralogy. *Zeitschrift für Pflanzenernährung und Bodenkunde* 159:149–153.
- 90 Mortland, M.M., Lawton, K., and Uehara, G. 1958. Fixation and release of potassium by some clay minerals. *Soil Science Society of America Proceedings* 21:381–384.
- 91 Hinsinger, P.H., Dufey, J.E., and Jaillard, B. 1991. Biological weathering of micas in the rhizosphere as related to potassium absorption by plant roots. In B.L. McMichael and H. Persson (eds) *Plant Roots and Their Environment*. Elsevier, Amsterdam, The Netherlands. p. 98–105.
- 92 Hoffland, E., Kuyper, T.W., Wallander, H., Plassard, C., Gorbushina, A.A., Haselwandter, K., Holmström, S., Landeweert, R., Lundström, U.S., Rosling, A., Sen, R., Smits, M.M., van Hees, P.A.W., and van Breemen, N. 2004. The role of fungi in weathering. *Frontiers in Ecology and the Environment* 2:258–264.
- 93 van Schöll, L., Kuyper, T.W., Smits, M.M., Landeweert, R., Hoffland, E., and van Breemen, N. 2008. Rock-eating mycorrhizas: Their role in plant nutrition and biogeochemical cycles. *Plant and Soil* 303:35–47.
- 94 Arocena, J.M., Velde, B., and Robertson, S.J. 2012. Weathering of biotite in the presence of arbuscular mycorrhizae in selected agricultural crops. *Applied Clay Science* 64:12–17.
- 95 Yuan, T.L., Zelazny, L.W., and Ratanaprasatporn, A. 1976. Potassium status of selected Paleudults in the Lower Coastal Plain. *Soil Science Society of America Journal* 40:229–233.
- 96 Sparks, D.L., Martens, D.C., and Zelazny, L.W. 1980. Plant uptake and leaching of applied and indigenous potassium in Dohan soils. *Agronomy Journal* 72:551–555.
- 97 Woodruff, J.R. and Parks, C.L. 1980. Topsoil and subsoil potassium calibration with leaf potassium for fertility rating. *Agronomy Journal* 72:392–396.
- 98 Bray, R.H. 1940. The chemical nature of soil potassium in relation to its availability in Illinois soils. PhD thesis, University of Illinois, Urbana, IL.
- 99 Kuhlmann, H., Claassen, N., and Wehrmann, J. 1985. A method for determining the K-uptake from subsoil by plants. *Plant and Soil* 83:449–452.
- 100 Kuhlmann, H. 1990. Importance of the subsoil for the K nutrition of crops. *Plant and Soil* 127:129–136.
- 101 Witter, E. and Johansson, G. 2001. Potassium uptake from the subsoil by green manure crops. *Biological Agriculture and Horticulture* 19:127–141.
- 102 Jouany, C., Colomb, B., and Bosc, M. 1996. Long-term effects of potassium fertilization on yields and fertility status of calcareous soils of south-west France. *European Journal of Agronomy* 5:287–294.
- 103 Grimes, D.W. and Hanway, J.J. 1967. An evaluation of the availability of K in crop residues. *Soil Science Society of America Proceedings* 31:705–706.
- 104 Borisova, N.I., Vasineva, L.V., and Semenov, Y.I. 1984. Use of potassium from straw and green mass of barley, labelled with <sup>40</sup>K, by plants. *Soviet Agricultural Science* 12:28–30.
- 105 Dierolf, T.S. and Yost, R.S. 2000. Stover and potassium management in an upland rice–soybean rotation on an Indonesian Ultisol. *Agronomy Journal* 92:106–114.
- 106 Rosolem, C.A., Calonego, J.C., and Foloni, J.S.S. 2005. Potassium leaching from millet straw as affected by rainfall and potassium rates. *Communications in Soil Science and Plant Analysis* 36:1063–1074.
- 107 Glass, A.D.M. 1983. Regulation of ion transport. *Annual Review of Plant Physiology* 34:311–326.
- 108 Saha, M.N., Chaudhury, J., Saha, A.R., and Ray, P.K. 1998. Effect of intensive cropping and fertilizer use on soil properties and crop yields in a long-term experiment. In A. Swarup, D. Damodar Reddy and R.N. Prasad (eds). *Proceedings of a National Workshop on Long-term Soil Fertility Management Integrated Plant Nutrient Supply*. Indian Institute of Soil Science, Bhopal, India. p. 215–220.

- 109 Walker, M.E., Flowers, R.A., Henning, R.J., Keisling, T.C., and Mullinix, B.G. 1979. Response of early bunch peanuts to calcium and potassium fertilization. *Peanut Science* 6:119–123.
- 110 Hartzog, D.L. and Adams, J.F. 1988. Relationship between soil-test P and K and yield response of runner peanuts to fertilizer. *Communications in Soil Science and Plant Analysis* 19:1645–1653.
- 111 Roberts, S. and Beaton, J.D. 1988. Potato Use of Phosphorus and Potassium in Sandy Soils. Research Bulletin XB1004. Washington State University, Pullman, WA.
- 112 Davenport, J.R. and Bentley, E.M. 2001. Does potassium fertilizer form, source, and time of application influence potato yield and quality in the Columbia Basin? *American Journal of Potato Research* 78:311–318.
- 113 Bailey, L.D. 1983. Effects of potassium fertilizer and fall harvests on alfalfa grown on the eastern Canadian prairies. *Canadian Journal of Soil Science* 63:211–219.
- 114 Rowberry, R.G. and Ketcheson, J.W. 1978. Sources of potassium in potato fertilizer and times of application. *Canadian Journal of Plant Science* 58:779–782.
- 115 Terman, G.L. 1977. Yields and nutrient accumulation by determinate soybeans, as affected by applied nutrients. *Agronomy Journal* 69:234–238.
- 116 Burmester, C.H. and Adams, F. 1983. Fertilizer requirements for new plantings of tall fescue and white clover on two low-fertility Ultisols. *Agronomy Journal* 75:936–940.
- 117 Laughlin, W.M., Martin, P.F., and Smith, G.R. 1973. Potassium rate and source influences on yield and composition of bromegrass forage. *Agronomy Journal* 65:85–87.
- 118 Bhangoo, M.S. and Albritton, D.J. 1972. Effect of fertilizer nitrogen, phosphorus, and potassium on yield and nutrient content of Lee soybeans. *Agronomy Journal* 64:743–746.
- 119 Maples, R. and Keogh, J.L. 1974. Fertilization of Cotton with Potassium, Magnesium, and Sulfur on Certain Delta Soils: Alfisols Formed from Mississippi River Valley Alluvium. Arkansas Agricultural Experiment Station Bulletin 787. University of Arkansas, Fayetteville, AR.
- 120 Rupe, J.C., Widick, J.D., Sabbe, W.E., Robbins, R.T., and Becton, C.B. 2000. Effect of chloride and soybean cultivar on yield and the development of sudden death syndrome, soybean cyst nematode, and southern blight. *Plant Disease* 84:669–674.
- 121 Cassman, K.G., Kerby, T.A., Roberts, B.A., Bryant, D.C., and Brouder, S.M. 1989. Differential response of two cotton cultivars to fertilizer and soil potassium. *Agronomy Journal* 81:870–876.
- 122 Linquist, B.A., Byous, E., Jones, G., Williams, J.F., Six, J., Horwath, W., and van Kessel, C. 2008. Nitrogen and potassium fertility impacts on aggregate sheath spot disease and yields of rice. *Plant Production Science* 11:260–267.
- 123 Barbarick, K.A. 1985. Potassium fertilization of alfalfa grown on a soil high in potassium. *Agronomy Journal* 77:442–445.
- 124 Allinson, D.W., Guillard, K., Rafey, M.M., Grabber, J.H., and Dest, W.M. 1992. Response of reed canarygrass to nitrogen and potassium fertilization. *Journal of Production Agriculture* 5:595–601.
- 125 Svec, L.V., Andrews, A.K., and Crittenden, H.W. 1976. Soybean (*Glycine max* (L.) Merr.) yield and disease incidence with potassium fertilization. *Communications in Soil Science and Plant Analysis* 7:727–741.
- 126 Sartain, J.B., Forbes, R.B., and Usherwood, N.R. 1979. Yield response of soybeans to P and K fertilization as correlated with soil extractable and tissue nutritional levels. *Communications in Soil Science and Plant Analysis* 10:1219–1232.
- 127 Elwali, A.M.O. and Gascho, G.J. 1983. Sugarcane response to P, K, and DRIS corrective treatments on Florida Histosols. *Agronomy Journal* 75:79–83.
- 128 Obreza, T.A. and Rhoads, F.M. 1988. Irrigated corn response to soil-test indices and fertilizer nitrogen, phosphorus, potassium, and magnesium. *Soil Science Society of America Journal* 52:701–706.
- 129 Welch, L.F., Adams, W.E., and Carmon, J.L. 1963. Yield response surfaces, isoquants, and economic fertilizer optima for coastal bermudagrass. *Agronomy Journal* 55:63–67.
- 130 Walker, M.E., Morris, H.D., and Carter, R.L. 1974. The Effect of Rate and Method of Application of N, P, and K on Yield, Quality and Chemical Composition of Spanish and Runner Peanuts. Georgia Agricultural Experiment Station Research Bulletin 152. University of Georgia, Athens, GA.
- 131 Parker, M.B., Gascho, G.J., and Gaines, T.P. 1983. Chloride toxicity of soybeans grown on Atlantic Coast Flatwoods soils. *Agronomy Journal* 75:439–443.
- 132 Walker, M.E., Gaines, T.P., and Parker, M.B. 1989. Potassium, magnesium, and irrigation effects on peanuts grown on two soils. *Communications in Soil Science and Plant Analysis* 20:1011–1032.
- 133 McDole, R.E., Stallknecht, G.F., Dwelle, R.B., and Pavek, J.J. 1978. Response of four potato varieties to potassium fertilization in a seed growing area of eastern Idaho. *American Potato Journal* 55:495–504.
- 134 Welch, L.F., Johnson, P.E., McKibben, G.E., Boone, L.V., and Pendleton, J.W. 1966. Relative efficiency of broadcast versus banded potassium for corn. *Agronomy Journal* 58:618–621.
- 135 Stivers, R.K. and Ohlrogge, A.J. 1952. Influence of phosphorus and potassium fertilization of two soil types on alfalfa yield, stand, and content of these elements. *Agronomy Journal* 44:618–621.
- 136 Hanway, J.J., Barber, S.A., Bray, R.H., Caldwell, A.C., Engelbert, L.E., Fox, R.L., Fried, M., Hovland, D., Ketcheson, J.W., Laughlin, W.M., Lawton, K., Lipps, R.C., Olson, R.A., Pesek, J.T., Pretty, K., Smith, F.W., and Stickney, E.M. 1961. North Central Regional Potassium Studies. I. Field Studies with Alfalfa. Iowa Agricultural Experiment Station Research Bulletin 494. Iowa State University, Ames, IA.
- 137 Sweeney, D.W., Moyer, J.L., Jardine, D.J., and Whitney, D.A. 2011. Nitrogen, phosphorus, and potassium effects on grain sorghum production and stalk rot following alfalfa and birdsfoot trefoil. *Journal of Plant Nutrition* 34:1330–1340.
- 138 Templeton, W.C. Jr and Taylor, T.H. 1966. Yield response of a tall fescue-white clover sward to fertilization with nitrogen, phosphorus, and potassium. *Agronomy Journal* 58:319–322.
- 139 Gascho, G.J., Davis, J.F., Fogg, R.A., and Frakes, M.G. 1969. The effects of potassium carriers and levels of potassium and nitrogen fertilization on the yield and

- quality of sugar beets. *Journal of the American Society of Sugar Beet Technologists* 15:298–305.
- 140 Grissom, P. and Spurgeon, W.I. 1961. Fertility Practices for Cotton and Corn in the Yazoo-Mississippi Delta. Mississippi State University Agricultural Experiment Station Bulletin 614. Mississippi State University, State College, MS.
- 141 Pettigrew, W.T. 1999. Potassium deficiency increases specific leaf weights and leaf glucose levels in field-grown cotton. *Agronomy Journal* 91:962–968.
- 142 Adeli, A. and Varco, J.J. 2002. Potassium management effects on cotton yield, nutrition, and soil potassium level. *Communications in Soil Science and Plant Analysis* 25:2229–2242.
- 143 Pettigrew, W.T. 2003. Relationships between insufficient potassium and crop maturity in cotton. *Agronomy Journal* 95:1323–1329.
- 144 Wortmann, C.S., Dobermann, A.R., Ferguson, R.B., Hergert, G.W., Shapiro, C.A., Tarkalson, D.D., and Walters, D.T. 2009. High-yielding corn response to applied phosphorus, potassium, and sulfur in Nebraska. *Agronomy Journal* 101:546–555.
- 145 Malm, N.R. 1972. Fertilization of Established Alfalfa with Nitrogen and Potassium. New Mexico Agricultural Experiment Station Research Report 240. New Mexico State University, Las Cruces, NM.
- 146 Nelson, W.L., Burkhart, L., and Colwell, W.E. 1945. Fruit development, seed quality, chemical composition, and yield of soybeans as affected by potassium and magnesium. *Soil Science Society of America Proceedings* 10:224–229.
- 147 Goos, R.J., Johnson, B.E., and Holmes, B.M. 1987. Effect of potassium chloride fertilization on two barley cultivars differing in common root rot reaction. *Canadian Journal of Plant Science* 67:395–401.
- 148 Lueking, M.A., Johnson, J.W., and Himes, F.L. 1983. Effects of increasing the rates of potassium and nitrapyrin on nitrogen uptake by corn. *Agronomy Journal* 75:247–249.
- 149 Hudak, C., Stehouwer, R., and Johnson, J. 1989. An evaluation of K rate, placement and tillage systems for soybeans. *Journal of Fertilizer Issues* 6:25–31.
- 150 Robinson, R.R., Rhykerd, C.L., and Gross, C.F. 1962. Potassium uptake by orchardgrass as affected by time, frequency and rate of potassium fertilization. *Agronomy Journal* 54:351–353.
- 151 Alva, A.K. 1985. A comparison of fertilizer recommendations by soil testing program and alfalfa yield response in soils of two associations. *Communications in Soil Science and Plant Analysis* 16:213–228.
- 152 Gaspar, P.E., Reeves, D.L., Schumacher, T.E., and Fixen, P.E. 1994. Oat cultivar response to potassium chloride on soils testing high in potassium. *Agronomy Journal* 86:255–258.
- 153 Wittels, H. and Seatz, L.F. 1953. Effect of potash fertilization on yield, stalk breakage and mineral composition of corn. *Soil Science Society of America Proceedings* 17:369–371.
- 154 Clement-Bailey, J. and Gwathmey, C.O. 2007. Potassium effects on partitioning, yield, and earliness of contrasting cotton cultivars. *Agronomy Journal* 99:1130–1136.
- 155 Nelson, L.R., Keisling, T.C., and Rouquette, F.M. Jr 1983. Potassium rates and sources for coastal bermudagrass. *Soil Science Society of America Journal* 47:963–966.
- 156 Westermann, D.T., Tindall, T.A., James, D.W., and Hurst, R.L. 1994. Nitrogen and potassium fertilization of potatoes: Yield and specific gravity. *American Potato Journal* 71:417–431.
- 157 Camper, H.M. and Lutz, J.A. Jr 1977. Plowsole placement of fertilizer for soybeans and response to tillage of plowsole. *Agronomy Journal* 69:701–704.
- 158 Jones, G.D., Lutz, J.A. Jr, and Smith, T.J. 1977. Effects of phosphorus and potassium on soybean nodules and seed yield. *Agronomy Journal* 69:1003–1006.
- 159 Smith, D. 1975. Effects of potassium topdressing a low fertility silt loam soil on alfalfa herbage yields and composition and on soil K values. *Agronomy Journal* 67:60–64.
- 160 Rominger, R.S., Smith, D., and Peterson, L.A. 1976. Yield and chemical composition of alfalfa as influenced by high rates of K topdressed as KCl and K<sub>2</sub>SO<sub>4</sub>. *Agronomy Journal* 68:573–577.
- 161 Smith, D. and Smith, R.R. 1977. Responses of red clover to increasing rates of topdressed potassium fertilizer. *Agronomy Journal* 69:45–48.
- 162 Smith, D. and Powell, R.D. 1979. Yield of alfalfa as influenced by levels of P and K fertilization. *Communications in Soil Science and Plant Analysis* 10:531–543.
- 163 Panique, E., Kelling, K.A., Schulte, E.E., Hero, D.E., Stevenson, W.R., and James, R.V. 1997. Potassium rate and source effects on potato yield, quality, and disease interaction. *American Potato Journal* 74:379–398.
- 164 Fageria, N.K., Wright, R.J., Baligar, V.C., and Carvalho, J.R.P. 1990. Upland rice response to potassium fertilization on a Brazilian Oxisol. *Fertilizer Research* 21:141–147.
- 165 Rosolem, C.A. and Nakagawa, J. 2001. Residual and annual potassic fertilization for soybeans. *Nutrient Cycling in Agroecosystems* 59:143–149.
- 166 Cox, F.R. and Uribe, E. 1992. Management and dynamics of potassium in a humid tropical Ultisol under a rice-cowpea rotation. *Agronomy Journal* 84:655–660.
- 167 Casanova, E. 2000. Phosphorus and potassium fertilization and mineral nutrition of soybean. *Interciencia* 25:92–95.
- 168 Jekić, M., Trpeski, V., and Raimi, N. 1998. The effect of KCl and K<sub>2</sub>SO<sub>4</sub> in NPK fertilizers on yield, quality and economical earning by production of potato on alluvium of the Vardar. *Macedonian Agricultural Review* 45:11–15.
- 169 Gaydou, E.M. and Arrivets, J. 1983. Effects of phosphorus, potassium, dolomite, and nitrogen fertilization on the quality of soybean. Yields, proteins, and lipids. *Journal of Agricultural and Food Chemistry* 31:765–769.
- 170 Lombin, G. and Mustafa, S. 1981. Potassium response of cotton on some Inceptisols and Oxisols of northern Nigeria. *Agronomy Journal* 73:724–729.
- 171 Lombin, G. and Singh, L. 1986. Fertilizer responses of groundnuts (*Arachis hypogae* L.) under continuous intensive cultivation in the Nigerian savannah. *Fertilizer Research* 10:43–58.
- 172 Rahman, M.A., Chakravarty, D., Shahidullah, M., and Hossain, M.T. 1978. Studies on the effect of nitrogen phosphorus and potassium on the growth, yield and nutrient contents of safflower (*Carthamus tinctorius* L.). *Bangladesh Journal of Scientific and Industrial Research* 13:32–39.

- 173 Chowdhury, M.K.A. and Rahman, M.H. 1990. Potash requirement of sugarcane in Gangetic River flood plain soils of Bangladesh. *Journal of the Indian Society of Soil Science* 38:688–691.
- 174 Bokhtiar, S.M., Karim, A.J.M.S., Hossain, K.M., Hossain, T., and Egashira, K. 2001. Response of radish to varying levels of irrigation water and fertilizer potassium on clay terrace soil of Bangladesh. *Communications in Soil Science and Plant Analysis* 32:2979–2991.
- 175 Hymowitz, T., Jethmalani, S.C., Tiwari, K.L., and Walker, W.M. 1971. Effect of inoculum, variety, nitrogen, phosphorus, and potassium on yield, protein and oil content of soybeans at Jabalpur, M. P. India. *Communications in Soil Science and Plant Analysis* 2:283–292.
- 176 Gupta, B.R., Pathak, R.K., Bhan, S., and Singh, A. 1972. Effect of NPK on yield, nutrient uptake and quality of toria (*Brassica campestris* Var. Toria T.9). *Indian Journal of Agronomy* 17:88–91.
- 177 Stilwell, T.C., Sekhon, G.S., and Arscott, T.G. 1975. Response to potassium fertilization of three Punjab soils. *Indian Journal of Agricultural Science* 45:149–151.
- 178 Grewal, J.S. and Singh, S.N. 1980. Effect of potassium nutrition on frost damage and yield of potato plants on alluvial soils of the Punjab (India). *Plant and Soil* 57:105–110.
- 179 Mehta, S.C., Singh, N., Mittal, S.B., and Singh, M. 1991. Response of paddy and wheat to nitrogen and potassium fertilization. *Crop Research* 4:84–89.
- 180 Subramanian, K.S. 1994. Influence of soil and foliar application of potassium on growth, nutrient utilization, yield and quality of sugarcane (*Saccharum officinarum* L.). *New Botanist* 21:13–20.
- 181 Singh, K.N. and Sharma, D.P. 2001. Response of wheat to nitrogen and potassium in saline soils. *Experimental Agriculture* 37:417–427.
- 182 Kumar, P., Pandey, S.K., Singh, S.V., Rawal, S., and Kumar, D. 2004. Effect of potassium fertilization on processing grade tuber yield and quality parameters in potato (*Solanum tuberosum*). *Indian Journal of Agricultural Science* 74:177–179.
- 183 Moinuddin, Singh, K., Bansal, S.K., and Pasricha, N.S. 2004. Influence of graded levels of potassium fertilizer on growth, yield, and economic parameters of potato. *Journal of Plant Nutrition* 27:239–259.
- 184 Gunarto, L., Yahya, M., Supadmo, H., and Buntan, A. 1985. Response of corn to NPK fertilization grown in a latosol in South Sulawesi, Indonesia. *Communications in Soil Science and Plant Analysis* 16:1179–1188.
- 185 Hanolo, W. and Pulung, M.A. 1994. Effect of P and K fertilizers on growth and yield of pea. *Acta Horticulturae* 369:335–339.
- 186 Bakhsh, A., Khattak, J.K., and Bhatti, A.U. 1986. Comparative effect of potassium chloride and potassium sulfate on the yield and protein content of wheat in three different rotations. *Plant and Soil* 96:273–277.
- 187 Khan, Q., Himayatullah, M.N., Khan, N., and Shah, Z. 1994. Effect of various levels of potassium on wheat crop. *Sarhad Journal of Agriculture* 10:337–343.
- 188 Gormus, O. 2002. Effects of rate and time of potassium application on cotton yield and quality in Turkey. *Journal of Agronomy and Crop Science* 188:382–388.
- 189 Nguyen, H., Schoenau, J.J., Nguyen, D., Van Rees, K., and Boehm, M. 2002. Effects of long-term nitrogen, phosphorus, and potassium fertilization on cassava yield and plant nutrient composition in North Vietnam. *Journal of Plant Nutrition* 25:425–442.
- 190 Brennan, R.F. and Bolland, M.D.A. 2007. Influence of potassium and nitrogen fertiliser on yield, oil and protein concentration of canola (*Brassica napus* L.) grain harvested in south-western Australia. *Australian Journal of Experimental Agriculture* 47:976–983.
- 191 Hall, A.M. 1975. Effect of phosphorus, potassium, and calcium on peanuts at Mauke (Cook Islands). *New Zealand Journal of Experimental Agriculture* 3:117–120.
- 192 Rehm, G.W., Sorensen, R.C., and Wiese, R.A. 1981. Application of phosphorus, potassium, and zinc to corn grown for grain or silage: Early growth and yield. *Soil Science Society of America Journal* 45:523–528.
- 193 Hoeft, R.G., Walsh, L.M., and Liegel, E.A. 1975. Effect of seed-placed fertilizer on the emergence (germination) of soybeans (*Glycine max* L.) and snapbeans (*Phaseolus vulgaris* L.). *Communications in Soil Science and Plant Analysis* 6:655–664.
- 194 Mascarenhas, H.A.A., Hiroce, R., and Braga, N.R. 1976. Cloreto de potassio para a soja. *Bragantia* 35:CXXV–CXXVII.
- 195 Sangoi, L., Ernani, P.R., Bianchet, P., Vargas, V.P., and Picoli, G.J. 2009. Efeito de doses de cloreto de potássio sobre a germinação e o crescimento inicial do milho, em solos com texturas contrastantes. *Revista Brasileira de Milho e Sorgo* 8:187–197.
- 196 Curtin, D., Steppuhn, H., Campbell, C.A., and Biederbeck, V.O. 1999. Carbon and nitrogen mineralization in soil treated with chloride and phosphate salts. *Canadian Journal of Soil Science* 79:427–429.
- 197 Roseberg, R.J., Christensen, N.W., and Jackson, T.L. 1986. Chloride, soil solution osmotic potential, and soil pH effects on nitrification. *Soil Science Society of America Journal* 50:941–945.
- 198 Smith, D. and Peterson, L.A. 1975. Chlorine concentrations in alfalfa herbage and soil with KCl topdressing of a low fertility silt loam soil. *Communications in Soil Science and Plant Analysis* 6:521–533.
- 199 Hahn, B.E., Olson, F.R., and Roberts, J.L. 1942. Influence of potassium chloride on nitrification in Bedford silt loam. *Soil Science* 54:113–121.
- 200 Golden, D.C., Sivasubramaniam, S., Sandanam, S., and Wijedasa, M.A. 1984. Inhibitory effects of commercial potassium chloride on the nitrification rates of added ammonium sulphate in an acid red yellow podzolic soil. *Tea Quarterly* 53:43–46.
- 201 Younts, S.E. and Musgrave, R.B. 1958. Chemical composition, nutrient absorption, and stalk rot incidence of corn as affected by chloride in potassium fertilizer. *Agronomy Journal* 50:426–429.
- 202 Timm, C.A., Goos, R.J., Johnson, B.E., Sobolik, F.J., and Stack, R.W. 1986. Effect of potassium fertilizers on malting barley infected with common root rot. *Agronomy Journal* 78:197–200.
- 203 Johnston, A.E., Goulding, K.W.T., and Mercer, E. 1993. Potassium leaching from a sandy loam soil. *Potash Review* 12(4):1–16.
- 204 Askegaard, M. and Eriksen, J. 2000. Potassium retention and leaching in an organic crop rotation on loamy sand as

- affected by contrasting potassium budgets. *Soil Use and Management* 16:200–205.
- 205 Brye, K.R. and Norman, J.M. 2004. Land-use effects on anion-associated cation leaching in response to above-normal precipitation. *Acta Hydrochimica et Hydrobiologica* 32:235–248.
- 206 Karamanos, R.E., Harapiak, J.T., and Flore, N.A. 2003. Application of seed-row potash to barley (*Hordeum vulgare* L.) grown on soils with high “available” potassium levels. *Canadian Journal of Plant Science* 83:291–303.
- 207 Brennan, R.F. and Jayasena, K.W. 2007. Increasing applications of potassium fertiliser to barley crops grown on deficient sandy soils increased grain yields while decreasing some foliar diseases. *Australian Journal of Agricultural Research* 58:680–689.
- 208 Grant, C.A., Bailey, L.D., and Therrien, M.C. 1996. The effect of N, P and KCl fertilizers on grain yield and Cd concentration of malting barley. *Fertilizer Research* 45:153–161.
- 209 Zubriski, J.C., Vasey, E.H., and Norum, E.B. 1970. Influence of nitrogen and potassium fertilizers and date of seeding on yield and quality of malting barley. *Agronomy Journal* 62:216–219.
- 210 Tinline, R.D., Ukrainetz, H., and Spurr, D.T. 1993. Effect of fertilizers and of liming acid soil on common root rot in wheat, and of chloride on the disease in wheat and barley. *Canadian Journal of Plant Pathology* 15:65–73.
- 211 Walker, W.M. and Raines, G.A. 1988. Effect of corn cultivar, phosphorus and potassium on yield and chemical composition. *Journal of Plant Nutrition* 11:1715–1726.
- 212 Heckman, J.R. 1998. Corn stalk rot suppression and grain yield response to chloride. *Journal of Plant Nutrition* 21:149–155.
- 213 Ebelhar, S.A., Kamprath, E.J., and Moll, R.H. 1987. Effects of nitrogen and potassium on growth and cation composition of corn genotypes differing in average ear number. *Agronomy Journal* 79:875–881.
- 214 Fintel, R.G.H. von and Quicke, G.V. 1962. Soil fertilization and the protein, zein, essential amino acid and niacin content of maize grain. *South African Journal of Agricultural Science* 5:165–175.
- 215 Boswell, F.C. and Parks, W.L. 1957. The effect of soil potassium levels on yield, lodging, and mineral composition of corn. *Soil Science Society of America Proceedings* 21:301–305.
- 216 Liebhardt, W.C. and Murdock, J.T. 1965. Effect of potassium on morphology and lodging of corn. *Agronomy Journal* 57:325–328.
- 217 Haq, M.U. and Mallarino, A.P. 2005. Response of soybean grain oil and protein concentrations to foliar and soil fertilization. *Agronomy Journal* 97:910–918.
- 218 Helz, G.E. and Whiting, A.L. 1928. Effects of fertilizer treatment on the formation of nodules on the soybean. *Journal of the American Society of Agronomy* 20:975–981.
- 219 Sharma, P., Duveiller, E., and Sharma, R.C. 2006. Effect of mineral nutrients on spot blotch severity in wheat, and associated increases in grain yield. *Field Crops Research* 95:426–430.
- 220 Norvell, W.A., Wu, J., Hopkins, D.G., and Welch, R.M. 2000. Association of cadmium in durum wheat grain with soil chloride and chelate-extractable soil cadmium. *Soil Science Society of America Journal* 64:2162–2168.
- 221 Wahhab, A. and Ali, R. 1962. Effect of nitrogen, phosphorus and potash on lodging, yield, plant characters and the chemical composition of irrigated wheat. *Pakistan Journal of Scientific Research* 14:8–16.
- 222 Bennett, O.L., Rouse, R.D., Ashley, D.A., and Doss, B.D. 1965. Yield, fiber quality and potassium content of irrigated cotton plants as affected by rates of potassium. *Agronomy Journal* 57:296–299.
- 223 Bernardi, A.C. de C., Oliveira, J.P. de Jr, Leandro, W.M., Mesquita, T.G. da S., Freitas, P.L. de, and Carvalho, M. da C.S. 2009. Doses e formas de aplicação da adubação potássica na rotação soja, milho e algodão em sistema plantio direto. *Pesquisa Agropecuária Tropical* 39:158–167.
- 224 Cassman, K.G., Kerby, T.A., Roberts, B.A., Bryant, D.C., and Higashi, S.L. 1990. Potassium nutrition effects on lint yield and fiber quality of Acala cotton. *Crop Science* 30:672–677.
- 225 Minton, E.B. and Ebelhar, M.W. 1991. Potassium and aldicarb-disulfoton effects on verticillium wilt, yield, and quality of cotton. *Crop Science* 31:209–212.
- 226 Pettigrew, W.T., Heitholt, J.J., and Meredith, W.R. Jr 1996. Genotypic interactions with potassium and nitrogen in cotton of varied maturity. *Agronomy Journal* 88:89–93.
- 227 Pettigrew, W.T., Meredith, W.R. Jr, and Young, L.D. 2005. Potassium fertilization effects on cotton lint yield, yield components, and reniform nematode populations. *Agronomy Journal* 97:1245–1251.
- 228 Peters, J.B., Kelling, K.A., Speth, P.E., and Offer, S.M. 2005. Alfalfa yield and nutrient uptake as affected by pH and applied K. *Communications in Soil Science and Plant Analysis* 36:583–596.
- 229 Rogers, G., Porter, R., Jolley, L.C., and Leaver, D.D. 1977. Management factors and grass tetany in dairy cattle. *Australian Veterinary Journal* 53:523–528.
- 230 Ketterings, Q.M., Godwin, G., Cherney, J.H., and Kilcer, T.F. 2005. Potassium management for brown midrib sorghum × sudangrass as replacement for corn silage in the north-eastern USA. *Journal of Agronomy and Crop Science* 191:41–46.
- 231 Meissner, A.P. and Clarke, A.L. 1977. Response of mown pasture to potassium fertilizer in south-eastern South Australia. *Australian Journal of Experimental Agriculture and Animal Husbandry* 17:765–775.
- 232 Balasko, J.A. 1977. Effects of N, P, and K fertilization on yield and quality of tall fescue forage in winter. *Agronomy Journal* 69:425–428.
- 233 Brennan, R.F. and Bolland, M.D.A. 2006. Soil and tissue tests to predict the potassium requirements of canola in south-western Australia. *Australian Journal of Experimental Agriculture* 46:675–679.
- 234 Li, Y.-M., Chaney, R.L., and Schaefer, A.A. 1994. Effect of soil chloride level on cadmium concentration in sunflower kernels. *Plant and Soil* 167:275–280.
- 235 Tinker, P.B.H. 1965. The effects of nitrogen, potassium and sodium fertilizers on sugar beet. *Journal of Agricultural Science, Cambridge* 65:207–212.
- 236 Otto, R., Vitti, G.C., and de Cerqueira Luz, P.H. 2010. Manejo da adubação potássica na cultura da cana-de-açúcar. *Revista Brasileira de Ciência do Solo* 34:1137–1145.
- 237 Gascho, G.J. and Kidder, G. 1979. Responses to Phosphorus and Potassium and Fertilizer Recommendations for Sugarcane in South Florida.

- Florida Agricultural Experimental Station Bulletin 809. University of Florida, Gainesville, FL.
- 238 Maier, N.A., Dahlenburg, A.P., and Frensham, A.B. 1986. Potassium nutrition of irrigated potatoes in South Australia. 3. Effect on specific gravity, size and internal bruising of tubers. *Australian Journal of Experimental Agriculture* 26:737–744.
- 239 Sparrow, L.A., Salardini, A.A., and Johnstone, J. 1994. Field studies of cadmium in potatoes (*Solanum tuberosum* L.). III. Response of cv. Russet Burbank to sources of banded potassium. *Australian Journal of Agricultural Research* 45:243–249.
- 240 McLaughlin, M.J., Maier, N.A., Freeman, K., Tiller, K.G., Williams, C.M.J., and Smart, M.K. 1995. Effect of potassic and phosphatic fertilizer type, fertilizer Cd concentration and zinc rate on cadmium uptake by potatoes. *Fertilizer Research* 40:63–70.
- 241 Allison, M.F., Fowler, J.H., and Allen, E.J. 2001. Responses of potato (*Solanum tuberosum*) to potassium fertilizers. *Journal of Agricultural Science, Cambridge* 136:407–426.
- 242 McDole, R.E. 1978. Potassium fertilizer trials with potatoes on coarse-textured soils in southeastern Idaho. *American Potato Journal* 55:161–170.
- 243 Herlihy, M. and Carroll, P.J. 1969. Effects of N, P and K and their interactions on yield, tuber blight and quality of potatoes. *Journal of the Science of Food and Agriculture* 20:513–517.
- 244 Murphy, H.J. and Goven, M.J. 1959. Factors Affecting the Specific Gravity of the White Potato in Maine. *Maine Agricultural Experiment Station Bulletin* 583. University of Maine, Orono, ME.
- 245 Hahlin, M. and Johansson, O. 1973. Fosfor- och kaliumgödsling till matpotatis. *Lantbruks-högskolans meddelande. Serie A. NR 192*. Royal Agricultural College of Sweden, Uppsala, Sweden.
- 246 Constantin, R.J., Jones, L.G., and Hernandez, T.P. 1977. Effects of potassium and phosphorus fertilization on quality of sweet potatoes. *Journal of the American Society of Horticultural Science* 102:779–781.
- 247 McLaughlin, M.J., Palmer, L.T., Tiller, K.G., Beech, T.A., and Smart, M.K. 1994. Increased soil salinity causes elevated cadmium concentrations in field-grown potato tubers. *Journal of Environmental Quality* 23:1013–1018.
- 248 Julin, B., Wolk, A., Bergkvist, L., Bottai, M., and Åkesson, A. 2012. Dietary cadmium exposure and risk of postmenopausal breast cancer: A population-based prospective cohort study. *Cancer Research* 72:1459–1466.
- 249 Goff, J.P. and Horst, R.L. 1997. Effects of addition of potassium or sodium, but not calcium, to prepartum rations on milk fever in dairy cows. *Journal of Dairy Science* 80:176–186.
- 250 Horst, R.L., Goff, J.P., Reinhardt, T.A., and Buxton, D.R. 1997. Strategies for preventing milk fever in dairy cattle. *Journal of Dairy Science* 80:1269–1280.
- 251 Allcroft, R. and Burns, K.N. 1968. Hypomagnesaemia in cattle. *New Zealand Veterinary Journal* 16:109–128.
- 252 Cherney, J.H., Cherney, D.J.R., and Bruulsema, T.W. 1998. Potassium management. In J.H. Cherney and D.J.R. Cherney (eds). *Grass for Dairy Cattle*. CAB International, Wallingford, England. p. 137–160.
- 253 McCalla, T.M. 1937. Behavior of Legume Bacteria (*Rhizobium*) in Relation to Exchangeable Calcium and Hydrogen Ion Concentration of the Colloidal Fraction of the Soil. *Missouri Agricultural Experiment Station Research Bulletin* 256. University of Missouri, Columbia, MO.
- 254 Albrecht, W.A. and Davis, F.L. 1929. Physiological importance of calcium in legume inoculation. *Botanical Gazette* 88:310–321.
- 255 Heaney, R.P. and Barger-Lux, M.J. 1994. Low calcium intake: The culprit in many chronic diseases. *Journal of Dairy Science* 77:1155–1160.
- 256 Wu, K., Willett, W.C., Fuchs, C.S., Colditz, G.A., and Giovannucci, E.L. 2002. Calcium intake and risk of colon cancer in women and men. *Journal of the National Cancer Institute* 94:437–446.
- 257 Newmark, H.L., Heaney, R.P., and Lachance, P.A. 2004. Should calcium and vitamin D be added to the current enrichment program for cereal-grain products? *American Journal of Clinical Nutrition* 80:264–270.
- 258 Nordin, B.E.C. 1997. Calcium and osteoporosis. *Nutrition* 13:664–686.
- 259 Centeno, V., de Barboza, G.D., Marchionatti, A., Rodríguez, V., and de Talamoni, N.T. 2009. Molecular mechanisms triggered by low-calcium diets. *Nutrition Research Reviews* 22:163–174.
- 260 Krauss, A. and Saurat, A. 1989. Potassium sulphate: K fertilizers for arid and semi-arid zones. In *Proceedings of the Workshop on the Role of Potassium in Improving Fertilizer Use Efficiency*. National Fertilizer Development Corporation, Islamabad, Pakistan. p. 171–185.
- 261 Lucas, R.E., Wheeler, E.J., and Davis, J.F. 1954. Effect of potassium carriers and phosphate:potash ratios on the yield and quality of potatoes grown in organic soils. *American Potato Journal* 31:349–352.
- 262 Dickins, J.C., Harrap, F.E.G., and Holmes, M.R.J. 1962. Field experiments comparing the effects of muriate and sulphate of potash on potato yield and quality. *Journal of Agricultural Science, Cambridge* 59:319–326.
- 263 Rowberry, R.G., Sherrell, C.G., and Johnston, G.R. 1963. Influence of rates of fertilizer and sources of potassium on the yield, specific gravity and cooking quality of Katahdin potatoes. *American Potato Journal* 40:177–181.
- 264 Lujan, L. and Smith, O. 1964. Potato quality XXV. Specific gravity and after-cooking darkening of Katahdin potatoes as influenced by fertilizers. *American Potato Journal* 41:274–278.
- 265 Højmark, J.V. 1977. Virkningen af stigende mængde kaliumklorid og kaliumsulfat på kartoffeludbytte, kokekvalitet og farve af chips. *Tidsskrift for Planteavl* 81:68–80.
- 266 Rosolem, C.A., Nakagawa, J., Machado, J.R., and Yamada, T. 1979. Efeitos de modos de aplicação, doses e fontes de potássio na produção da soja. *Revista de Agricultura, Piracicaba* 54:13–19.
- 267 Abd El-Hadi, A.H., Khadr, M.S., El-Kholy, M.H., Zahran, F.A., and Negm, A.Y. 2002. Comparative effect of potassium sulphate and potassium chloride on crop production and soil chemical properties under Egyptian conditions. *Egyptian Journal of Agricultural Research* 80:521–537.



- 268 Bansil, P.C. 2004. Agricultural subsidies. A global view. In B. Dorin and T. Jullien (eds). *Agricultural Incentives in India. Past Trends and Prospective Paths Towards Sustainable Development*. Manohar Publishers, New Delhi, India. p. 39–65.
- 269 Environmental Working Group. 2012. Farm Subsidy Database. Available at Web site <http://farm.ewg.org/> (verified May 25, 2012).
- 270 Brown, W.W. 1950–1963. *Commercial Fertilizer Year Book*. Walter W. Brown, Atlanta, GA.
- 271 Illinois Department of Agriculture. 1964–2010. *Illinois Commercial Fertilizer Tonnage Report*. Illinois Department of Agriculture, Springfield, IL. Available since 2004 at Web site <http://www.agr.state.il.us/programs/fert2/> (verified August 9, 2012).
- 272 United States Department of Agriculture. 2012. USDA National Agricultural Statistics Service. Available at Web site <http://www.nass.usda.gov> (verified May 25, 2012).
- 273 Tributh, H., Boguslawski, E.v., Lieres, A.v., Steffens, D., and Mengel, K. 1987. Effect of potassium removal by crops on transformation of illitic clay minerals. *Soil Science* 143:404–409.
- 274 Frydman, S., Ravina, E., and Ehrenreich, T. 1977. Stabilization of heavy clay with potassium chloride. *Geotechnical Engineering* 8:95–108.
- 275 Abood, T.T., Kasa, A.B., and Chik, Z.B. 2007. Stabilisation of silty clay soil using chloride compounds. *Journal of Engineering Science and Technology* 2:102–110. Available at Web site <http://jestec.taylors.edu.my/Vol%202%20Issue%201%20April%2007/102-110%20Abood.pdf> (verified August 9, 2012).
- 276 Chaitanya G, K.N.K., Prasada Raju, G.V.R., and Ramu, K. 2011. Evaluation studies of expansive soil treated with electrolytes. *International Journal of Engineering Science and Technology* 3:8298–8306. Available at Web site [http://www.idc-online.com/technical\\_references/pdfs/civil\\_engineering/EVALUATION%20STUDIES%20OF%20EXPANSIVE%20SOIL%20TREATED%20WITH%20ELECTROLYTES.pdf](http://www.idc-online.com/technical_references/pdfs/civil_engineering/EVALUATION%20STUDIES%20OF%20EXPANSIVE%20SOIL%20TREATED%20WITH%20ELECTROLYTES.pdf) (verified August 9, 2012).
- 277 Venkara Muthyalu, P., Ramu, K., and Prasada Raju, G.V.R. 2012. Study on performance of chemically stabilized expansive soil. *International Journal of Advances in Engineering and Technology* 2:139–148. Available at Web site <http://www.archives-ijaet.org/media/1516-IJAET0612724.pdf> (verified August 9, 2012).
- 278 Deist, J. and Talibudeen, O. 1967. Ion exchange in soils from the ion pairs K-Ca, K-Rb, and K-Na. *Journal of Soil Science* 18:125–137.
- 279 Palaniappan, S., Peck, T.R., and Beavers, A.H. 1973. Effect of application of high rates of potassium on cation exchange capacity and potassium status of two Illinois soils. *Communications in Soil Science and Plant Analysis* 4:31–40.
- 280 Cassman, K.G., Roberts, B.A., Kerby, T.A., Bryant, D.C., and Higashi, S.L. 1989. Soil potassium balance and cumulative cotton response to annual potassium additions on a vermiculitic soil. *Soil Science Society of America Journal* 53:805–812.