Eco Agri-Minerals

Potassium Chloride Fertilizer

Massive study reveals vast problems caused by over application

Attached is a recently published research paper (Khan et al., 2013) using data collected for over a quarter of a century from thousands of fields in the Midwest and supported by an exhaustive literature review (280 citations) and rigorous statistical analysis of the data. Khan and his colleagues points out that despite enormous soil reserves of potassium minerals, potassium chloride (KCl) fertilization has long been promoted as building up the exchangeable potassium (K) of soils to insure against yield and quality loss. To their surprise, they found that KCl fertilization intended to build up soil K;

- reduces bioavailability of soil calcium (Ca^{2+}) and magnesium (Mg^{2+})
- has a detrimental effect on grain and forage quality
- had little or no effect on yield
- several studies showed a decrease in yields as KCl application increased
- K values for soils NOT fertilized with KCl went up over a 51 year period
- compacts soils
- collapses high energy smectite clays into non-swelling illite clays, thus reducing water holding capacity and CEC
- depresses nitrogen uptake
- inhibits nitrification by soil bacteria
- has a negative impact on soil microbiological activity
- is not accessible to deep rooted plants that get enough K from subsoils
- an increase in cadmium (Cd) uptake in potatoes
- soil testing for K has little or no value in predicting fertilizer requirements

The current methods of soil analysis for potassium provide wildly varying and extremely unreliable results that depend on; soil moisture content, the time of the year the sample was pulled (especially right after harvest), temperature of the soil, and whether the lab air dries the sample or not. The soil analytical study was performed by pulling samples every two weeks from various soils over a 14 year period, following the same protocol and experimental design, using the same laboratory analytical method, and all the samples were pulled by the same investigator.

Coupling invalid soil testing results with all the other draw backs listed above, and the almost universal agronomic advice to build K as if it were a bank account, has lead to extreme over application of KCl. In turn, chloride anions (Cl^-) have accumulated to levels toxic to legumes and a concomitant increase in the bioavailability of toxic metals that accumulate in potatoes and cereal grains. In light of the fact that recent clinical studies link cadmium intake to an increased risk of breast cancer, means that the foods we eat—bread, potatoes, potato chips, French fries and beer are toxicologically linked to overuse of KCl in our food system.

The authors point out that deep rooted plants can access the enormous reserves of potassium in subsoils, which was encouraged from the early 1900's but abandoned in the 1960's with the introduction of highly soluble potassium chloride into the world fertilizer market. As biological farming methods encourage underground biological activity that usually result in better root mass, the Khan et al., 2013 may go down in history as a landmark study, like many other studies before it, that lend more support to the principles of biological agriculture.

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

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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[1–3].

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[4]. According to this philosophy, a major rationale for K fertilization is to maintain soil reserves without regard to the economic importance of yield response[5–7] or the overwhelming abundance of mineral K in most arable soils and subsoils, especially those dominated by 2:1 minerals[8–12]. 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[8,9]. 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[13]. 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[14–16], 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[10,17–21] (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[6,7].

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[22], 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[23]. 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^{-1}. Of the six plots sampled by Khan[22] 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^{-1} as NH_4NO_3 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 ($NH_4C_2H_3O_2$)-extraction technique described by Knudsen et al.[24], 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^{-1}, 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^{-1}.

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 $NH_4C_2H_3O_2$ extraction to determine exchangeable K, six successive digestions were performed to liberate non-exchangeable K with boiling 1 M HNO_3[24]. 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 $LiBO_2 \cdot 8H_2O$ in a Pt crucible[25].

The fused sample was dissolved in 0.04 M HNO_3 and analyzed by atomic emission spectroscopy using a Perkin Elmer Model 3110 spectrometer (Perkin Elmer, Norwalk, CT) and an air-C_2H_2 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^{-1} 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[26]. Further details concerning the Morrow Plots and their management can be found in Khan et al.[27].

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^{-1}), test values were multiplied by the corresponding bulk density, obtained from direct measurements in 2005, or by using pedotransfer functions to estimate 1955 values. A more detailed description is available in Khan et al.[27].

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[28] 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^{-1}) or by corn (4.2 kg Mg^{-1}), soybean (18.0 kg Mg^{-1}) and oats (5.2 kg Mg^{-1}) harvested for grain. The yield records used were expressed as dry tons $acre^{-1}$ for alfalfa, or as bushels $acre^{-1}$ at a market-standard moisture content of 155 g kg^{-1} (15.5%) for corn (56 lb $bushel^{-1}$), 130 g kg^{-1} (13%) for soybean (60 lb $bushel^{-1}$) and 140 g kg^{-1} (14%) for oats (32 lb $bushel^{-1}$). 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^{-1} for continuous corn, 310 kg K ha^{-1} for the corn–oats rotation, and 256 kg K ha^{-1} 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[29–32], and a K concentration of 13.5 (corn) or 15 (oats) kg Mg^{-1} of dry matter[33].

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^{-1} assuming a bulk density of 1.47 Mg m^{-3}, 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[28] and/or stover[33].

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^+ fixation that promotes interlayer collapse of 2:1 clay minerals, and by the inhibitory effects of KCl on biological N_2 fixation and nitrification.

Statistical analyses

Seasonality and linear trend analysis of the 4-year time series of air-dried test levels of exchangeable K ($kg\,ha^{-1}$) was evaluated statistically as described by Lovell[34]. 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[35], such that the 2005 data provided a variance estimate for the standard error of mean values obtained as a five-core composite in 1955[27]. The step-down Bonferroni adjustment of *P* values[36] was performed with PROC MULTEST in SAS[35] for multiple comparison tests to evaluate net changes in exchangeable K between 1955 and 2005.

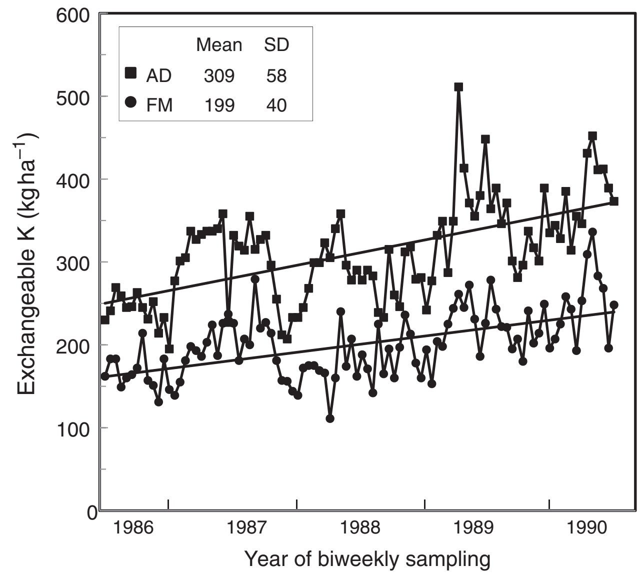

Figure 1. Biweekly changes in exchangeable K for field-moist (FM) and air-dried (AD) samples (0–18 cm) collected on 96 dates between March 13, 1986 and March 15, 1990, from a Drummer soil under a corn (*Zea mays* L.)–soybean (*Glycine max* L. Merr.) rotation. No fertilizer P or K had been applied since 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.

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[13]. 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[37,38] (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[18,21] (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[39].

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.

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[40,41] (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 nonexchangeable 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

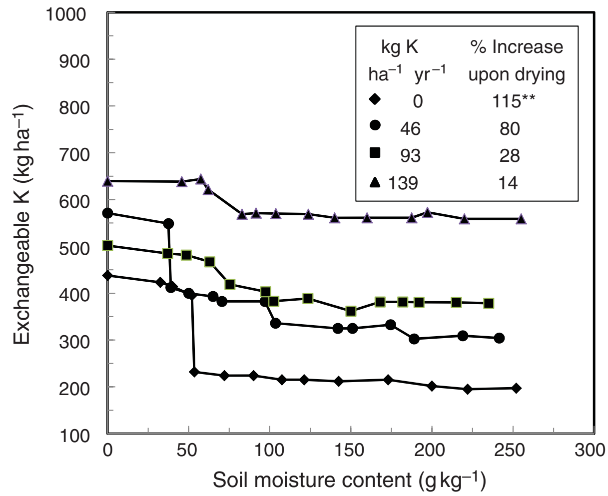

Figure 2. Potassium release curves for a Drummer soil cropped to a corn (*Zea mays* L.)–soybean (*Glycine max* L. Merr.) rotation, with or without annual application of 46–139 kg K ha^{-1} as KCl. Field-moist samples (0–18 cm) were air dried to approximately 40 g kg^{-1} in a forced-air oven at 40°C, 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[28,42].

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^{-1}. 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[43], 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[80]. 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[1]	Fertilizer treatment[2]	Exchangeable K[3]			Cumulative		
		Initial[4]	Final[5]	Net change	K added	K removed	Net K input
		kg ha^{-1}					
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[6]	– 1706
	NPK	218 (4)	327 (26)	109***	1934	2136[7]	– 202
C–O–H	None	217 (6)	382 (18)	165***	0	1088[8]	– 1088
	NPK	217 (6)	332 (27)	115***	3114	2865[9]	249

*** Significant at $\alpha = 0.001$ by the step-down Bonferroni procedure.
[1] 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.
[2] NPK, nitrogen–phosphorus–potassium fertilization using urea (168 [1955–1966] or 224 [since 1967] kg N ha^{-1} yr^{-1} for corn, 28 kg N ha^{-1} yr^{-1} for oats), triple superphosphate (0–96 kg P ha^{-1} yr^{-1}) and KCl (0–186 kg K ha^{-1} yr^{-1}). No amendment was applied before 1955.
[3] Determined by $NH_4C_2H_3O_2$ extraction[24] of air-dried samples.
[4] Mean values reported from triplicate determinations of a single archived five-core composite soil sample (0–15 cm). Standard deviations shown in parentheses.
[5] Mean values reported from triplicate determinations performed on each of three replicate soil samples (0–15 cm). Standard deviations shown in parentheses.
[6] Estimated as 44% by corn, 7% by oats and 49% by soybean.
[7] Estimated as 49% by corn, 3% by oats and 48% by soybean.
[8] Estimated as 54% by corn, 25% by oats and 21% by alfalfa hay.
[9] 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[10,11,20,75,78,81–83] (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[8,9,84]. 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^{-1}, with approximately 3000 kg ha^{-1} 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[19,85–87] (see also supplemental references [22] and [27–30] for the online version of the paper), exhaustive cropping[81,86,88,89] (see supplemental references [8], [15] and [16] for the online version of the paper) and electrodialysis[83,90].

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[91–94] (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.[83] 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[82,95–97], while non-exchangeable K reserves can even be important for growing a shallow-rooted crop such as pineapple on the basaltic Andisols of Hawaii[81].

Soil K reserves are much greater for the profile than the plow layer[12,62,95,97,98] (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[99–101]. This uptake is largely concentrated in the vegetative biomass[33,102], and enriches the surface soil when inorganic K leaches from plant shoots or residues[8,9,81,102–106] (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[1]	Cropping system[2]	Study period	Sampling depth	Exchangeable K[3] Initial	Exchangeable K[3] Final	Exchangeable K[3] Net change	Cumulative K added	Cumulative K removed	Cumulative Net K input	Reference(s)
				cm	kg ha^{-1}						
USA											
Alabama	Ultisols	C–Ct (7)	1954–1969	0–15	113	104	–9	0	332	– 332	44–46
	(fsl$_4$, scl$_2$, sil$_1$)										
					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_w–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_s–W_s	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_w–W_w	1938–2001	0–15	508	414	– 94	0	1219	– 1219	59–61
					464	548	84	1843	1201	584	
Virginia	Ultisols (sil)	C_s–C_s	1966–1971	0–15	224	85	– 139	0	411	– 411	62
					224	124	– 100	336	440	– 104	
China	Inceptisols	W_w–C[4]	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[5]	1856–1974	0–23	313	219	– 94	0	1221	– 1221	67
					313	305	– 8	5040	4294	746	
	Inceptisols (sl)	Sb–W_w–B	1965–1982	0–25	162	132	– 30	0	580	– 580	68
					162	265	102	1992	1160	832	
	Alfisols (sicl)	W_w–W_w	1966–1992	0–23	323	271	– 52	0	675	– 675	69
					1326	1236	– 90	2430	1431	999	

Table 2. (*Cont.*)

Location	Soil order[1]	Cropping system[2]	Study period	Sampling depth	Exchangeable K[3] Initial	Final	Net change	Cumulative K added	K removed	Net K input	Reference(s)
Denmark	Alfisols (s)	W_w–Rcl–B–Gcl	1949–1972	0–20	65	52	−13	0	456	−456	70
					188	172	−15	1584	1584	0	
	Alfisols (sl)	W_w–Rcl–B–Gcl	1949–1972	0–20	98	62	−36	0	696	−696	
					152	122	−30	1584	2160	−576	
Germany	Alfisols (sil)	Rc–Ce–Ce	1914–1975	0–15	158	123	−35	0	4531	−4531	71
					158	131	−27	5127	7039	−1912	
	Mollisols (sl)	Po–P–W_s–Rc–B	1977–1984	0–20	170	179	9	0	568	−568	72
					496	448	−48	1792	1256	536	
India	Inceptisols (ls)	C–W_w–Cp[4]	1971–1996	0–15[6]	8(8)	7(0)	−1(8)	0	3952	−3952	73
					9(6)	9(8)	(2)	2860	5642	−2782	
	Alfisols	C–W_w[4]	1972–1996	0–15	194	148	−46	0	1508	−1508	74
					194	167	−27	2460	2393	67	
New Zealand	Inceptisols	A–A[4]	1971–1974	0–20	216	225	9	0	571	−571	75
					216	394	178	786	758	28	
Nigeria	Alfisols (sc_1, ls_2)	C–C[4] (3)	1966–1968	0–15	381	198	−183	0	197	−197	76
					381	228	−153	168	239	−71	
Philippines	Inceptisols (sic)	Ri–Ri	1968–1986	0–20	521	13(5)	−38(6)	0	578[7]	−578	77
					521	15(6)	−36(5)	950	759[7]	191	
	Vertisols (c)	Ri–Ri	1968–1986	0–20	209	24(9)	4(0)	0	580[7]	−580	
					209	39(3)	18(4)	950	799[7]	151	
	Vertisols (c)	Ri–Ri	1968–1986	0–20	938	57(3)	−36(5)	0	531[7]	−531	
					938	62(6)	−31(2)	950	677[7]	273	
Poland	Alfisols (ls)	Ry–Ry	1963–1995	0–25	107	200	93	0	1254	−1254	69
					320	300	−20	2574	2310	264	
		Po–B–Rcl–W_w–Ry	1963–1995	0–25	113	147	33	0	1584	−1584	
					327	363	37	2574	3069	−495	
Scotland	Spodosols (ls)	Pr–Pr[8]	1969–1998	0–15	72	20	−52	448[9]	1608	−1160	78
					55	24	−31	1969[9]	3158	−1189	

[1] 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), sicl (silty clay loam), sil (silt loam) and sl (sandy loam). Subscripts indicate the number of soils studied with a given texture.

[2] 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_s, 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_s, spring wheat (*Triticum aestivum* L.); W_w, winter wheat (*Triticum aestivum* L.). Values in parentheses indicate the number of separate trials summarized.

[3] Parentheses indicate digital uncertainty in estimating data reported in figures.

[4] All crops were grown annually.

[5] Prior to 1901, the cropping system was W_w–W_w (1856–1875) or Po–Po (1876–1901).

[6] Assumed as the depth for sampling surface soil.

[7] Rice grain was assumed to contain 0.04 g K kg^{-1} at a moisture content of 140 g kg^{-1} [79].

[8] 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.

[9] 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.[1]

Year	Exchangeable K[2]	Non-exchangeable K recovered in six successive extractions[3]							Total K[4]
		Ext. 1	Ext. 2	Ext. 3	Ext. 4	Ext. 5	Ext. 6	Ext. 1–6	
	$kg\,ha^{-1}$								
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)

[1] 160–180 $kg\,N\,ha^{-1}$ 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.
[2] Determined by extraction with 1 M $NH_4C_2H_3O_2$ (pH 7)[24] after air drying at 40°C.
[3] Determined after extraction of exchangeable K, by boiling with 1 M HNO_3[24].
[4] Determined by fusion with $LiBO_2{\cdot}8H_2O$, followed by dissolution in 1 M HNO_3[25]. 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^+ than for Ca^{2+} or Mg^{2+} 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[33,107]. 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[59,60,71,77,108] (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[109–112], 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[38,144,148,192], soybean[120,125,131,175], wheat (*Triticum aestivum* L.)[186], sugarbeet (*Beta vulgaris* L.)[139], sugarcane (*Saccharum officinarum* L.)[127], alfalfa[145], peanut (*Arachis hypogaea* L.)[109,191], rape (*Brassica napus* L.)[176] and cowpea (*Vigna unguiculata* L.)[166]. In several of these studies, the loss of yield was intensified by increasing the rate of KCl application[38,109,120,125,175,192], and in some cases the higher rate transformed significant yield gain to loss[127,186].

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[193–195] and microbial processes[196,197]. 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.[1]

Location	Soil order[2]	Exchangeable K[3]	K applied (as KCl)	Site-years studied[4]	Cropping system[5]	Yield without fertilizer K[6]	Yield response to K[7] Lowest	Highest	Reference
		$kg\,ha^{-1}$	$kg\,ha^{-1}\,yr^{-1}$			$Mg\,ha^{-1}$	-----------%-----------		
North America									
Canada									
Manitoba	Mollisols (scl)	50–310 (15)	0–200	15	A[9]	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[9]–S	2.6	27* (75)	44* (150)	115
	Ultisols (fsl, sil)	25–42[8](20)	0–112	6	Tf, Wc[9]	3.6	25^{ns} (28)	46* (112)	116
Alaska	Inceptisols (sil)	256	0–186	2	Sbg[9]	3.2	−15^{ns} (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^{ns} (587)	120
California	Mollisols (sl)	65[8]	0–480	3	Ct	2.(4)	11** (120)	31*** (480)	121
	Alfisols (l)	67[8] (20)	0–100	3	Ri[9]	7.(8)	5* (63)	7* (100)	122
Colorado	Mollisols (cl)	335[8] (15)	0–750	16	A[9]	52.7	6* (375, 750)	6* (375, 750)	123
Connecticut	Inceptisols (fsl)	121[7]	0–448	6	Rc[9]	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[8] (15)	0–200	1	S–Vg	4.0	6^{ns} (50)	15* (200)	126
	Histosols	43 (30)	0–560	1	Sc[9]	97.2	−4** (560)	6** (280)	127
	Ultisols (lfs)	17–150[8] (15)	0–418	2	C–(S or Ar[9])	9.5	19* (209)	21* (418)	128
Georgia	Ultisols (sl)	NR	0–188	3	Bg[9]	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^{ns} (121)	109
	Ultisols (s)	NR	0–186	30	S	1.7	−30* (186)	−30* (186)	131
	Entisols (ls)	10[8] (25)	0–56	3	C–Pn	3.5	47* (56)	47* (56)	132
Idaho	Mollisols (gl)	92–112[8] (20)	0–415	5	A[9]–Po	24.8	20* (415)	21* (208)	133
Illinois	Alfisols (sil)	60–86 (15)	0–224	2	Sg–C	4.1	2^{ns} (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^{ns} (28)	7* (56)	
Indiana	Alfisols (fs)	51[8] (18)	0–372	3	A[9]	3.7	32** (93)	54** (372)	135
	Alfisols (sil)	74[8] (18)	0–372	2	A[9]	5.1	15* (93)	21* (372)	
Iowa	Mollisols (sl-sil)	141–491 (15)	0–335	9	A[9]	4.3	1^{ns} (74, 112)	12* (335)	136
	Alfisols (sil)	62–190 (15)	0–140	5	A[9]–C	5.7	10* (28)	16* (112)	38
Kansas	Alfisols (sil)	45–108[8] (15)	0–140	6	(A[9] or Bt[9])–Sr	6.(0)	10* (70, 140)	10* (70, 140)	137
Kentucky	Ultisols (sil)	NR	0–372	3	Tf/Wc[9]	5.1	0^{ns} (372)	7* (140)	138
Michigan	Alfisols (sl, l)	77–242 (15)	0–335	7	A, Rcl, Sbg[9]	4.1	8^{ns} (19)	33* (335)	136
	Alfisols (l)	NR	93–186	1	Sb	50.7[10]	−6* (186)	−6* (186)	139
Minnesota	Alfisols (sil)	102–142 (15)	0–140	2	A[9]–C	5.2	10^{ns} (28)	25* (140)	38
	Entisols (fs)	122 (15)	0–140	1	A[9]–C	3.9	−18* (140)	3^{ns} (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[9]–C	4.6	16* (28)	37** (140)	

Mississippi	Entisols (sil)	NR	0–112	2	C–Ct	1.3	17* (37)	31* (112)	140
	Inceptisols (fsl)	289–465 (15)	0–112	8	Ct	1.0	9* (112)	9* (112)	141
	Entisols (si)	115[8] (15)	0–204	2	Ct	1.2	7* (68)	13* (204)	142
	Inceptisols (fsl)	138–159[8] (15)	0–112	11	Ct	1.1	5* (112)	5* (112)	143
Nebraska	Entisols$_1$, Mollisols$_{15}$	91–609[8] (20)	0–40	16	C–S	14.4	– 3* (40)	– 3* (40)	144
New Mexico	Entisols (fsl)	NR	0–56	3	A[9]	16.6	– 2* (56)	– 2* (56)	145
North Carolina	Ultisols (fsl)	12[8]	0–112	3	C–S	0.35	131* (11)	342* (112)	146
North Dakota	Mollisols (l)	570–940	0–99	4	B	2.7	1^{ns} (24)	4* (99)	147
Ohio	Mollisols (sicl)	NR	0–360	2	C	9.2	– 20*** (90)	– 19*** (360)	148
	Alfisols (sil)	190	0–74	6	C–S	3.0	1^{ns} (37)	7* (74)	149
Pennsylvania	Alfisols (sicl)	32 (15)	0–112	6	Og[9]	4.0	21* (56)	29* (112)	150
	Alfisols$_4$ (sil), Ultisols$_2$ (sil)	61–140 (15)	0–525	16	A[9]	2.(8)	66* (175)	72* (350)	151
South Dakota	Mollisols	> 391	0–71	20	O	2.5	3* (35, 71)	3* (35, 71)	152
Tennessee	Mollisols (fsl)	NR	0–186	1	C	5.0	– 2^{ns} (149)	18* (19)	153
	Alfisols (sil)	198–444 (15)	56–112	6	Ct	1.8[10]	5* (112)	5* (112)	154
Texas	Ultisols (fs, fsl)	NR	0–278	6	Bg[9]	10.3	24* (139, 278)	24* (139, 278)	155
Utah	Mollisols (sil)	59–77[8] (30)	0–224	2	Po	37.4	15* (224)	15* (224)	156
Virginia	Ultisols (sl)	55 (15)	0–372	6	S	1.8	25* (372)	25* (372)	157
	Ultisols (cl)	66–121	0–112	2	S	1.6	85* (28)	139* (112)	158
Wisconsin	Mollisols (sil)	142 (15)	0–1120	3	A[9]	6.5	22* (56)	53* (672)	159
	Alfisols (sil)	124 (15)	0–1792	2	A[9]	8.3	11^{ns} (1344)	32* (448)	160
	Mollisols (sil)	167 (15)	0–896	1	A[9]	6.2	14* (896)	22* (448)	161
	Mollisols (sil)	142 (15)	0–672	2	A[9]	5.8	34* (224)	37* (672)	162
	Entisols (ls)	72–90[8]	0–372	4	Po	34.8	17* (93)	25* (280)	163
South America									
Brazil	Oxisols	46[8]	0–168	9	Ri–Ri	1.1	9* (42)	19** (126)	164
	Oxisols (ls)	20–52[8] (20)	0–199	2	S	1.(5)	65* (33)	111* (133)	165
Peru	Ultisols	55[8] (15)	0–120	6	Ri–Cp[9]	2.1	4^{ns} (20)	22* (80)	166
		55[8] (15)	0–120	4	Ri–Cp[9]	0.8	– 24* (20)	25* (120)	
Venezuela	Oxisols (scl)	38[8]	0–135	2	S	1.0	8^{ns} (9)	173* (108)	167
Europe									
Macedonia	Entisols	83[8] (20)	0–100	2	Po	33.3	13** (100)	13** (100)	168
Africa									
Madagascar	Oxisols (sl)	55[8] (20)	0–75	5	S	0.5	278** (25)	422** (50, 75)	169
Nigeria	Oxisols (ls-sl)	31–817[8] (15)	0–75	9	Ct	1.9	35* (25)	42* (75)	170
	Alfisols, Ultisols (ls)	39–78[8] (15)	0–40	20	Gn	1.4	24* (20)	31* (40)	171
	Inceptisols (ls)	20–66[8] (15)	0–40	20	Gn	1.1	20* (20)	22* (40)	
Asia									
Bangladesh	Inceptisols (scl)	20[8]	28–37	1	Sa	1.3[10]	8* (37)	8* (37)	172
	Entisols (scl)	78–86[8] (30)	0–180	2	Sc[9]	74.8	6* (45, 135)	9* (70, 90)	173
	Inceptisols (sicl)	133[8] (20)	66–133	1	Ra[9]	24.0[10]	8* (100)	12* (133)	174
India	Vertisols	NR	9–150	2	S	3.1[10]	– 7* (37)	– 3* (19)	175
	Inceptisols (sl)	223	0–33	1	R[9]	1.1	– 20* (33)	– 20* (33)	176
	Alfisols, Inceptisols	22–60[8] (15)	0–156	6	W_w[9]	4.(8)	3^{ns} (156)	6** (104)	177
	Inceptisols (s-sl)	56–158[8]	0–84	28	Po[9]	12.1	15* (42)	22* (84)	178
	Inceptisols (ls, sil)	NR	0–66	4	Ri[9]	5.3	6* (33)	11* (66)	179
				4	W_w[9]	3.0	12* (33)	24* (66)	

Table 4. (*Cont.*)

Location	Soil order[2]	Exchangeable K[3]	K applied (as KCl)	Site-years studied[4]	Cropping system[5]	Yield without fertilizer K[6]	Yield response to K[7]		Reference
							Lowest	Highest	
	Alfisols (sl)	125	0–156	3	Sc[9]	103.6	11* (125)	19* (188)	180
	Aridisols (sl)	160 (15)	0–75	3	W_w[9]	4.7	10* (50)	14* (75)	181
	Inceptisols (sl)	138	0–166	4	Po[9]	28.4	17* (42)	38* (166)	182
	Inceptisols (sl)	75[8]	62–187	8	Po[9]	21.3[10]	17* (124)	21* (187)	183
Indonesia	Oxisols	51[8]	0–75	1	C	0.5	400* (25)	600* (75)	184
	Oxisols	NR	0–105	1	P	0.2	1^{ns} (26)	11* (105)	185
	Ultisols (c)	55[8] (12)	23–83	6	Cp–Ri–S[9]	6.3[10]	37* (83)	37* (83)	105
Pakistan	Aridisols (cl)	135[8] (15)	0–148	1	Ri–W_w[9]	2.5	– 14^{ns} (111)	23* (37)	186
		160[8] (15)	0–148	1	F–W_w[9]	2.1	– 12* (148)	16* (37)	
	Aridisols (sicl)	125[8] (25)	0–199	1	W_w[9]	3.6	11^{ns} (33)	29** (133–199)	187
Turkey	Vertisols (c)	560–750[8]	0–199	2	Ct	2.6	12* (66)	27* (133)	188
Vietnam	Ultisols	8[8] (20)	0–133	9	Cs	2.8	454* (33)	546* (133)	189
Australasia									
Australia	Alfisols$_4$, Entisols$_5$, Inceptisols$_1$ (s)	19–37[8] (10)	0–60	10	Cn	1.(2)	25* (15)	51* (60)	190
Mauke	Ultisols (cl)	NR	0–132	1	Pn	1.2	– 16* (132)	– 16* (132)	191

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

[1] A complete listing of all studies surveyed can be found in Table S4, for the online version of the paper.

[2] 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.

[3] Air-dried data reported. Values in parentheses indicate sampling depth in cm. NR, not reported.

[4] Values take into account the number of genotypes studied and/or the use of multiple tillage systems.

[5] 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 hypogoea* 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 bromegrass (*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_w, winter wheat (*Triticum aestivum* L.). Underscoring indicates the crop(s) studied for K response.

[6] 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.

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

[8] Values expressed as $mg\,kg^{-1}$.

[9] Above-ground residues removed.

[10] Yield when the lowest K rate was applied with N or N and P.

Many leguminous crops are sensitive to Cl^- toxicity, including soybean[120,131] and alfalfa[159,160,198], and Cl^- can reduce soil N availability by inhibiting nitrification in soils[195,196,199,200] (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 NO_3^- [147,201,202] (see also supplementary references [38] and [56–59] for the online version of the paper). A further difficulty arises from the mobility of Cl^- in soils, which intensifies profile leaching of Ca^{2+} as a counterion[203–205].

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[159,160].

One of the better known consequences of KCl fertilization, reported in Table 5 for studies with corn[153,201,212,216], wheat[221] and sorghum (*Sorghum bicolor* L. Moench)[137], arises from the antagonistic effect of Cl^- on 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 NO_3^- loss through leaching or denitrification. The use of KCl can also have a beneficial effect by increasing the fiber strength (micronaire) of cotton (*Gossypium hirsutum* L.) grown on soils inherently limited in K reserves[222–224,226], 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[202,210,219,225] except where root rot was associated with a high content of NO_3^- but not K^+ or Cl^-[147] or when a susceptible variety was grown on an infertile sand[207]. 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[214] 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[163,238,241–244], and becomes a toxicological concern by enhancing the mobility and plant uptake of soil Cd[239,240,247]. The latter problem has also been reported for cereal crops[208,220], 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[248].

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[159–161,229,230] that predisposes livestock to milk fever[249,250] or grass tetany[229,251]. To prevent these disorders while improving forage quality, Cherney et al.[252] 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[253] 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[254]. 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[255–259].

The problems associated with KCl usage have been thoroughly documented for arid and semi-arid regions by Krauss and Saurat[260], 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 K_2SO_4 instead of KCl. The benefits of this strategy for increasing crop yield and/or quality have been documented in numerous studies with potato[133,163,168,261–265] 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.[1]

Crop(s)[2]	Study location(s)	Study period[3]	Site-years studied[4]	Soil type[5]	Parameter of K response	Net effect on crop quality	Reference
Grain crops							
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^{-} 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
Fiber crops							
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

Forage crops							
Alfalfa	Wisconsin	1970–1972	3	sil	Ca and Mg content	Negative	159
		1970–1972	3	sil	Cl^- 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
Oilseed crops							
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
Sugar crops							
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
Tuber crops							
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

[1] A complete listing of all studies surveyed can be found in Table S5 for the online version of the paper.
[2] Latin names for crops not included in Table 4: ryegrass, *Lolium perenne* L. and *Lolium rigidum* Gaudin; subterranean clover, *Trifolium subterranean* L.
[3] NR, not reported.
[4] Values take into account number of genotypes studied.
[5] 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[160], soybean[266] and wheat[186,267].

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[268,269] (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 $kg\,ha^{-1}$ [270–272]. 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[26,273]. The stabilizing value of KCl has long been recognized in the construction of impervious pavement and foundations[274–277]. Unfortunately, the agronomic consequences include a loss of CEC[71,77,278–280] 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 indispensible 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^-, K_2SO_4 would be preferred as a fertilizer source.

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