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Potassium fertilization: paradox or K management dilemma?

B. Bar-Yosef[1], H. Magen[2]*, A.E. Johnston[3] and E.A. Kirkby[4]

[1]The Katif Research Center for Coastal Deserts, Sedot Negev, Israel.
[2]The International Potash Institute, Horgen, Switzerland.
[3]Rothamsted Research, Harpenden, AL5 2JQ, UK.
[4]Faculty of Biological Sciences, University of Leeds, LS2 9JT, UK.
*Corresponding author: h.magen@ipipotash.org

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Abstract

In 2014, Khan et al. presented evidence that soil exchangeable K (Exch-K) increases over time without addition of potassium (K) to the soil despite the removal of K in crops on a soil rich in montmorillonite and illite. The authors term this behavior 'The potassium paradox'. From their review of the literature, the authors also report a lack of crop response to potassium chloride (KCl) fertilization. Close evaluation of these findings reveals that their observations can be interpreted and predicted using current knowledge of K in soil chemistry and its uptake by plants, and there is no paradox in K behavior in the soil–plant system. There is also no evidence of a detrimental effect of KCl on crop yield or quality. Their conclusion that the widely used Exch-K soil test is inadequate for managing K fertilization is discussed and some possible modifications to improve its performance are included. We believe that measurement of Exch-K is an essential and valuable tool and its use should be continued, along with improvements in recommending K fertilizer application.

Key words: exchangeable potassium, capacity/intensity, chloride, potassium fertilizer recommendations, non-exchangeable potassium

Background

In 2012, Mueller et al.[1] reported in *Nature* a global study of fertilizer and irrigation needs to close yield gaps for the three most important world cereals—maize, wheat and rice—in relation to an approximate doubling in human food requirements by 2050. Their findings showed that in 73% of the underachieving areas worldwide, yield gaps could be closed with acceptable yields obtained (a 29% global increase), solely by focusing on the nutrient inputs. The required increases in nitrogen (N), phosphorus (P) and potassium (K) application relative to baseline global consumption were evaluated as 18, 16 and 35%, respectively. In light of this work, the required increases in nutrient supply in low-yield regions on the one hand, and the current trend of reducing fertilizer use in high yielding regions on the other, the study by Khan et al.[2] is timely. Although the authors indicate a need for a reassessment of our ability to manage potash fertilization using existing K soil tests, their reports of little response to K fertilization on many soils and the adverse effects of potassium chloride (KCl), the most commonly used K fertilizer, on crop yield and quality must be questioned.

The main concerns raised by Khan et al.[2] are twofold. First, they argue that soil exchangeable K (Exch-K), the main K soil test for predicting crop requirement, is inadequate to evaluate soil K availability. They support this claim from the analysis of soils from the long-term 'Morrow Plots' experiment at the University of Illinois sampled in 1955 and 2005. After 51 years, the Exch-K in the K-unfertilized plots exceeded that of the initial value, and the K uptake in low soil K plots exceeded the K uptake predicted by Exch-K tests. A 4-year field study further showed that Exch-K estimation was dependent on the water content of the analyzed soil samples (field moisture versus air dryness). Second, they conclude that KCl fertilization is unlikely to increase crop yield and, moreover, that it is predominantly detrimental to the quality of major food and fiber crops. The authors support this claim on the basis that only in about 24% of the approximately 300 published papers they reviewed was there a beneficial effect of KCl supply on crop yield, and only in 8% was there an improved crop quality. This commentary evaluates the authors' assessments, statements and conclusions.

Data Evaluation and Discussion

Evaluating the suitability of Exch-K for estimating soil K supply to plants

The authors reconfirm the known effects of soil moisture content and seasonality on Exch-K test values (Figs. 1 and 2[2]). As the Exch-K test involves a strict protocol of sampling (soil depth and timing) and preparing for analysis (soil moisture content and sieve size), the importance of the above factors in determining Exch-K is low as long as sampling and preparation follow prescribed instructions.

The data in Fig. 1 in Khan et al.[2] indicate an increase in Exch-K over a 4-year period (1986–1990) in a silty clay loam soil, with montmorillonite and illite as major clays, without K addition and despite crop uptake. Such a result could be predicted from the studies by Galadima and Silvertooth[3], Jalali and Zarabi[4], and Ghiri et al.[5], which showed that in arid soils, the rate of release of fixed K to the soil solution is 12–75 μmol K kg^{-1} soil d^{-1}, depending on the soil type and the length of extraction. This value can be compared with a rate of release of 20 μmol K kg soil^{-1} d^{-1} for a crop absorbing 200 kg K ha^{-1} in 100 days from the 0 to 20 cm soil layer. The fact that the quantity of fixed K in the 0–20 cm soil layer ranges from 5 to 27 t ha^{-1}, depending on soil minerals and climate[6] and annual intake is about 0.2 ton (t) ha^{-1}, proves that in many cases K released from fixation sites may cause an increase in soil Exch-K over several years.

As further evidence, in support of the findings in Fig. 1[2] the authors also cite the results from the Morrow Plots (montmorillonite and illite containing soil) showing that Exch-K increased by more than 50% between 1955 and 2005, particularly in low K treatments, and despite a K removal estimated at 1.4 t K ha^{-1}. In addition to the contribution of fixed-K release, the authors interpret the increase in Exch-K as a consequence of root uptake of K from below 20 cm in the soil profile and its release from plant residues in the top 0–20 cm soil, a mechanism also investigated by others, including Barraclough and Leigh[7] and Singh and Goulding[8]. Considering these facts, the results from the Morrow Plots cannot be regarded as a paradox. Moreover, Nafziger[9] reported that soils sampled frequently in the Morrow Plots (in the continuous corn experiment) between 1967 and 2008 did not show an increase in Exch-K (except for a short time following deep tillage), which raises doubts regarding the long-term K balance estimation in this historic experiment. A similar result of apparent steady Exch-K over time in the Broadbalk experiment in England between the years 1856 and 1987 was reported by Singh and Goulding[8], but not cited in Khan et al.[2].

Bar-Tal et al.[10] studied K transformations in a montmorillonitic silty loam loess soil over one growing season of sweetcorn in a pot experiment. Under zero K fertilization they found that fixed-K contributed to about 35% of the K consumed by plants, and under KCl application of 10 mmol K kg^{-1}soil the K uptake increased and fixation of 12% of the added K was observed. The long-term Exch-K balances were also checked in a montmorillonite–illite clay soil in the permanent plots experiment at Bet Dagan, Israel, over 30 years[11]. The initial (in 1963) cation exchange capacity (CEC) and Exch-K were 380 and 13.7 mmolc kg^{-1} soil (0–20 cm), respectively. In 1993, the Exch-K in the unfertilized plots was 20.9 mmolc kg^{-1}, with no change in CEC, whereas in treatments receiving 30 and 60 g K m^{-2} once every 3 years, the final Exch-K was 19.5 and 14.3 mmolc kg^{-1}, respectively. In 2009, treatments receiving high N, and thus taking up more K, fixed-K was released from soil-illite to furnish the enhanced K consumption[11]. These results, which are not included in the Khan et al.[2] paper, confirm their findings. The uptake of K by the crop exceeded the change in Exch-K plus the applied K, and also there was an increase in Exch-K over time where no K was applied; the results also prove, however, that all the data can be quantitatively interpreted and theoretically explained without recourse to a 'potassium paradox'.

Evaluating the claim that KCl fertilization is unlikely to increase crop yield, impairs yield quality and deteriorates soil productivity

Numerous field experiments with K fertilization are compiled by Khan et al.[2] in Table 4, from which they claim that K fertilization has no positive effect on yield. Unfortunately, those studies that showed no benefit from added K were not evaluated to ensure that the yield limitation was specifically the effect of K, rather than some other factor restricting growth. The most important factors are the level of Exch-K in the soil, lack of water, climate and a deficiency or excess of another mineral nutrient, particularly N. Potassium is required in highest amounts by the plant as an osmoticum to maintain cell turgor and, in this respect, it interacts with N because, by applying N, both cell number and cell size increase and thus also the water content of a crop. The need for K is thus closely dependent on N supply. Additionally, climate, lack of water and disease all affect yield and response to K. Khan et al.[2] did not separately assess till versus no-till, and rain versus irrigated systems, so the agrotechnological factors may have masked the unique effect of K on yield. Consequently, we believe that the authors' statement that K fertilization is detrimental to yield has not been proven. This comment is strengthened by the fact that the authors' database lacks many response studies carried out in regions with semi-arid climates. For example, in a long-term rotation experiment in Australia, Li et al.[12] showed that there was a wheat-yield response to K when Exch-K ranged from 2.5 to 3.4 mmolc kg^{-1} (depending on soil type). A similar result was obtained in two Rothamsted long-term fertilization experiments, where wheat and barley responded by enhanced grain yield to K application of 70 kg K ha^{-1} in starved soils, but not on previously K-enriched plots. The same result was obtained in potatoes[13].

However, despite these reservations, there is still evidence in Table 4[2] showing lack of yield response to KCl. A closer investigation of these data show, however, that all cases can be accounted for by one or more of the following factors: excess available K in soil; rapid K fixation of fertilizer K; and accumulation of K in the surface soil under no-till due to slow K transport down the profile toward the center of the root volume. Cases of reduced yield and quality due to K fertilization most probably resulted from K–Mg and K–Ca antagonism in plant uptake and utilization (in tomato[14] and in forage[15,16]).

The possibility of yield reduction due to soil structure deterioration as a consequence of KCl application, as suggested by Khan et al.[2], can be disproved by the studies of Chen et al.[17] and Levy and Torrento[18]. Chen et al.[17] demonstrated that increasing the contribution of Exch-K to the CEC [Exch-K percentage (EPP)] in clayey soils up to ~20% had a negligible effect on clay dispersion and aggregate stability, the major factors involved in hydraulic conductivity reduction. A significant reduction in hydraulic conductivity (>50%) did not occur until the EPP approached 50–70%[17] a value greatly in excess of that of (EPP<10%) found in most cultivated soils. Thus there is virtually no possibility that KCl application adversely affects soil structure.

Khan et al.[2] have attributed adverse effects of KCl fertilizer on yield to chloride (Cl) toxicity in the plant and increased salinity in the root zone, but with scant evidence in support of this statement. Their suggestion to replace KCl by potassium sulfate (K_2SO_4) would be expensive due to the difference in the unit price of K in these two fertilizers. Additionally, there could be problems in rain-fed agriculture as, under such conditions, KCl is the only source of Cl for plants. Chloride, as an essential plant nutrient, is required by crops in the range of 4–8 kg Cl ha^{-1} and is particularly important at sites distant from the sea[16]. Indeed, the most well-documented example of agricultural Cl deficiency is in the wheat-growing regions of the Great Plains of the USA[19]. The global increase of irrigated crops (currently estimated at 24% of the total cultivated land[20]) will no doubt increase the use of fertigation. Potassium sulfate cannot be added via the water because of the low calcium sulfate ($CaSO_4$, gypsum) solubility, whereas KCl has no practical solubility constraints and is therefore more suitable for K fertigation.

Required improvements for measuring soil K availability

The results presented by Khan et al.[2] show no evidence of a ‘potassium paradox’ but rather draw attention to the need for an understanding of the chemistry of soil K and soil–plant K interaction in relation to K fertilization. This could involve defining soil K in terms of intensity and capacity factors[21,22], as well as taking into account the transport of K in the soil, which mainly takes place by diffusion and which generally constitutes the limiting step in the acquisition of K by crop plants[23]. This approach avoids the uncertainties associated with the Exch-K test, and improves K management decisions by considering those effects that determine K uptake by the crop, namely: growth conditions, soil water content, K–Ca exchange, K transfer between soil K pools, root distribution in soil and clay content and mineralogy. Such an approach is incorporated into the dynamic soil-crop-K model of Greenwood and Karpinets[24,25] successfully field-tested in predicting K fertilizer requirements of ten different vegetable crops to increasing rates of K application. Unfortunately, however, this approach requires the determination of too many parameters for its regular use by extension services or private consultants. A simpler approach would involve defining K needs by both capacity and intensity factors. This could be achieved by relating K extracted by 0.01 M $CaCl_2$ soil extract (which is another important K availability soil test, particularly in calcareous soils; the intensity factor) with the K extracted by 1 M ammonium acetate (the capacity factor). Another approach is to relate plant uptake with Exch-K. Leigh and Johnston[26] showed that for cereals, the concentration of K in tissue water remained essentially constant throughout growth at about 200 mmol kg^{-1} tissue water in soil well supplied with K but only 50 mmol kg^{-1} tissue water in K-deficient soils. Thus it is possible to assess whether soil K supply is adequate based on the concentration of K in the tissue water.

Whatever tool is used to manage the plant-available K status, the principles of environmental sustainability prohibit mining soil K below the critical level required to achieve optimum crop yields now and in the future. This requires replacing the K removed in a crop by an amount at least equal to that removed by the crop, so that the critical level of plant-available K is maintained[27–30]. The amount of K applied may exceed that removed in the crop where leaching or fixation occur, or may be less than that removed in harvested crops where large amounts of structural K are released annually from soil minerals. In both these cases, regular soil sampling and analysis for Exch-K every 3–5 years will ensure that the critical level is being maintained. On deep soils where crops have an appreciable amount of root in the subsoil, it may be necessary to sample the 0–20 and 20–40 cm soil layers separately. In the case of cereal crops, as much as 50% of the roots may be present in the subsoil[7] and K taken up from the deeper soil layers can also be cycled within the soil profile[31].

Conclusions

There is no paradox in the behavior of K in soil. Khan et al.[2] generalize as to the lack of suitability of Exch-K as a soil test from their findings from one particular soil, high in non-exchangeable reserves of K. In many soils, the Exch-K soil test is the simplest, but it is generally recognized that the response of the crop to Exch-K and applied K fertilizer can be affected by many factors, e.g., climate, water deficit and limiting nutrient supply other than K. The reliability of the Exch-K soil test may be increased by sampling not only the 0–20 cm but also the 20–40 cm soil layer because K is acquired from both. The claim that zero or negative yield response to KCl application is widespread has not been substantiated, and in cases where it was correctly observed it was most probably due to the result of excess K application, K immobilization in the soil, and K–Mg and K–Ca antagonisms in the soil and in plant uptake and utilization. Until an easily operated computerized capacity/intensity-based system for K management in soil is developed, the Exch-K soil test will remain the best tool for recommending K fertilization.

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