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# Editorial

Dear readers,

In our 'fertilizer world', judicious use of nutrients drives it all: farm management is driven by profit and hence farmers strive to apply less nutrients and still obtain improved yields. From another perspective, environmental stewardship (mostly at the national level) emphasizes and enforces regulations to limit nitrogen (N) and phosphorous (P) inputs.

However, the reality is changing and this brings in new challenges. The tools to manage judicious use of nutrients are now more available than ever before: control release fertilizers and N inhibitors exist in a variety of forms and products, which enable better nutrient use efficiency. In terms of monitoring nutrient application and efficiency, precision agriculture provides highly sensitive instruments to provide various diagnostics. As a result, we are seeing an improvement in agronomic science.

In this *e-ifc* edition, we feature a paper from China that could help in improving the use of N and K ("Effect of Combined K and N Application on K Use Efficiency and Balance in Rice-Rice Cropping Systems in the Hilly Regions of Hunan Province, China"; by Lu *et al.*). We also look at "Long-Term Potassium Administration/Deprivation Cycles on Tropical Oxisol: Effects on Soil Fertility and Soybean Performance" by Firmano *et al.*, which provides insights into the long-term K management of the unfertile Cerrado soils in Brazil. These are just two examples of the type of work being carried out to improve nutrient use efficiency.

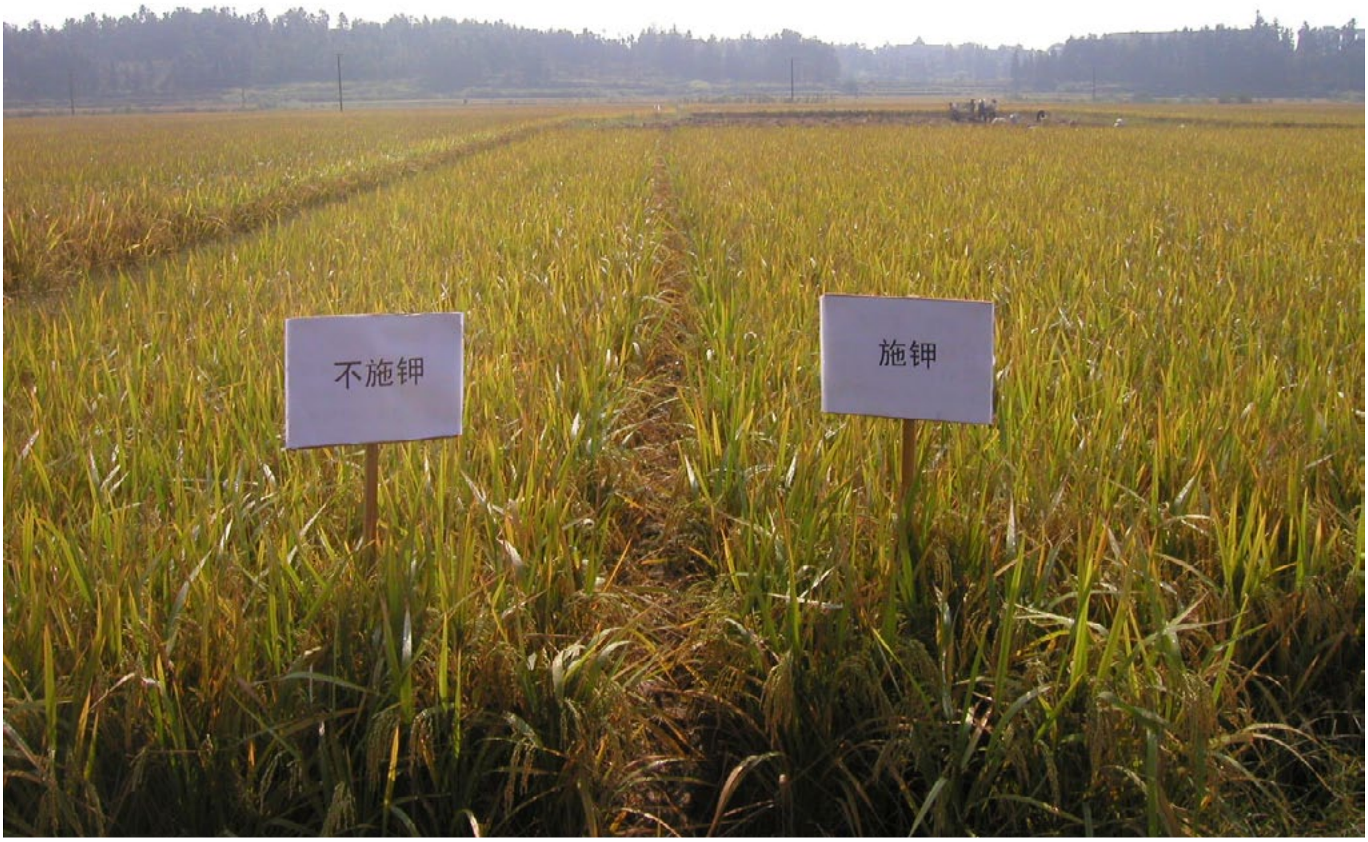
We also encourage you to read a report on the 1st IPI International Polyhalite Symposium which was held in October 2017 in Sanya, Hainan Province, China.

I wish you an enjoyable read.

**Hillel Magen**
**Director**

**Photo cover page:** Potash application in tomato crop in Andhra Pradesh, India. Photo courtesy of Potash for Life, India.

# Research Findings




Rice experiments on paddy soils of the hilly region of Hunan Province, China. Photo by authors.

## Effect of Combined K and N Application on K Use Efficiency and Balance in Rice-Rice Cropping Systems in the Hilly Regions of Hunan Province, China

Lu, Y.H.[(1)(2)], Y.L. Liao[(1)(2)], X. Zhou[(1)(3)], J. Nie[(1)(2)*], J. Xie[(1)(2)], and Z.P. Yang[(1)(2)]

### Abstract

A field experiment under a double-rice cropping system was carried out to study the effects of altered basal potassium (K) application rates (0, 105, and 150 kg $K_2O$ ha$^{-1}$) using two nitrogen (N) rates (150 and 195 kg N ha$^{-1}$) on rice yield, K uptake, fertilizer use efficiency, agronomic efficiency, soil K balance, and economic balance. The experiment was carried out on two types of paddy soil in the hilly regions of Hunan Province, China. The early crop yield increased slightly in response to the first increase in K rate, however, further yield increase was obtained only at the higher N rate. A similar response pattern was observed for the late crop on the red-yellow soil but not on the yellow soil, where the increase in N rate did not raise the rice yield. Potassium utilization rate was generally low, and it declined with increasing K rates. Potassium agronomic efficiency did not exceed 7 kg

[(1)]Soil and Fertilizer Institute of Hunan Province, Changsha 410125, China
[(2)]Scientific Observing and Experimental Station of Arable Land Conservation (Hunan), Ministry of Agriculture, Changsha, China
[(3)]College of Resources and Environment, Hunan Agricultural University, Changsha, China
*Corresponding author: Jun Nie (1224470488@qq.com)

grain $kg^{-1}$ $K_2O$, it declined with increasing K rates but rose in response to an increase in N. Soil soluble K at harvest increased with K rates, however, no significant change was observed in soil exchangeable K. Economic analyses show that the combination of higher K and N rates was the most profitable choice for the early crop, while medium K and lower N rates were the best combination for the late crop. Altogether, these results show that K nutrition is still a focal problem of rice-rice production on paddy soils. They also indicate that the maintenance of soil K balance during the cropping season is the most critical challenge. One recommendation is to examine an alternative approach of splitting the K application rate along the season, to minimize K seepage. In addition, fertilizer management should be adjusted to local soil characteristics, and a suitable balance among soil macro- and microelements must be preserved.

## Introduction

Hunan Province is located in the tropical region of Central Asia. Its climate is characterized as humid monsoon with abundant sunshine, heat and rainfall. The hilly region, comprising 29% of the total province area (Yang, 1989), is the main food production hub in Hunan Province. It possesses superior natural conditions for rice cultivation, usually as a double season crop grown on paddy soils.

Paddy soils are defined through their production environment; typically irrigated and rain-fed lowland rice-cropping systems. Paddy soils make up the largest anthropogenic wetlands on earth. They may originate from any type of soil in pedological terms, but are highly modified by anthropogenic activities. The formation of these Anthrosols is induced by tilling wet soil (puddling), and the flooding and drainage regime associated with the development of a plough pan and specific redoximorphic features. Redox potential oscillations due to paddy management control, microbial community structure and function, and thus short-term biogeochemical processes (Kögel-Knabner *et al.*, 2010).

The increasing intensification of rice production in the region – involving improved varieties, high crop indices and yields, greater use of inorganic (mainly nitrogen [N] and phosphorus [P]) and organic fertilizers, and the growing tendency to remove straw for fuel, forage or just for the convenience of land cultivation – has put significant pressure on the potassium (K) resources of local paddy soils (Yadav, 1998; Wihardjaka *et al.*, 1999). During the last 30 years, farmland soil fertility has been significantly degraded; imbalanced mineral nutrition under intensified rice production, augmented by high temperatures and intense precipitation regimes have led to severe soil K depletion. Therefore, most rice-rice production systems experience a negative K balance (Dai *et al.*, 2000). Local farmers' practices still focus on heavy N application and tend to ignore crop K requirements, which leads to poor crop performance. Therefore, demonstrating the importance of K fertilization to obtain reasonable rice yields is still necessary, particularly in the rice-rice production system (Yadav, 1998).

In the present study, the effect of K application on yields and soil K status was examined in the hilly areas of Hunan Province using two N application levels in order to provide a scientific basis for a rational N and K management on paddy soils.

## Materials and Methods

### Experimental site and basic soil traits

The experiments were conducted in Changsha and Hengshan Counties, Hunan Province.

Changsha County is characterized by red-yellow paddy soils developed from a quaternary red soil, while Hengshan County has yellow paddy soils developed from plate shale. Soil characteristics are shown in Table 1.

### Experiment design

The experiment was conducted in 2012 and was comprised of successive early and late rice. There were six treatments: $N_1K_0$, $N_1K_1$, $N_1K_2$, $N_1K_3$, $N_2K_0$, and $N_2K_3$, as detailed in Table 2.

Most of the N fertilizer was applied at pre-planting for both the early (70%) and the late (60%) rice crops, and the rest was applied


**Map. 1.** Changsha and Hengshan Counties, Hunan Province, China. *Source:* https://en.wikipedia.org/wiki/Xinning_County,_Hunan.

**Table 1.** The physical and chemical properties of the two paddy soils in the experiment.

| Paddy soil type | pH | Organic matter | Total N | Alkaline N | Available P | Total K | Soluble K | Exchangeable K |
|---|---|---|---|---|---|---|---|---|
| | *water* | ---------------*g kg⁻¹*--------------- | | -------------*mg kg⁻¹*------------- | | *g kg⁻¹* | --------------*mg kg⁻¹*------------- | |
| Red-yellow | 5.3 | 32.9 | 12.5 | 298.1 | 6.4 | 9.2 | 54.2 | 103.5 |
| Yellow | 5.8 | 38.3 | 13.4 | 191.2 | 4.9 | 9.9 | 74.3 | 94.4 |

**Table 2.** A detailed description of fertilizer treatments.

| Treatment | Early rice | | | Late rice | | |
|---|---|---|---|---|---|---|
| | N | K | P | N | K | P |
| | Urea | KCl | $P_2O_5$ | Urea | KCl | $P_2O_5$ |
| | *kg ha⁻¹* | *kg $K_2O$ ha⁻¹* | ---------*kg ha⁻¹*--------- | | *kg $K_2O$ ha⁻¹* | *kg ha⁻¹* |
| $N_1K_0$ | 150 | 0 | 75 | 180 | 0 | 45 |
| $N_1K_1$ | 150 | 105 | 75 | 180 | 136.5 | 45 |
| $N_1K_2$ | 150 | 150 | 75 | 180 | 195 | 45 |
| $N_1K_3$ | 150 | 195 | 75 | 180 | 253.5 | 45 |
| $N_2K_0$ | 195 | 0 | 75 | 234 | 0 | 45 |
| $N_2K_3$ | 195 | 195 | 75 | 234 | 253.5 | 45 |

at tillering. Phosphorus and K fertilizers were applied at pre-planting.

Seedlings of the early crop were transplanted in late April, at a row spacing of 13.3 x 20 cm, using the cultivars Zhejiang 7 and Weiyou 402, in Changsha and Hengshan, respectively, and harvested in early July. For the late crop, seedlings of the cultivars, Fengyuan Excellent 272 and Jade Incense 88, were transplanted at 20 x 20 cm spacing in late July in Changsha and Hengshan, respectively, and harvested in mid to late October. Each treatment included four repetitions of 20 $m^2$ in a random block design.

### Sample collection and analyses

Soil samples were collected from the 0-20 cm layer before the experiment ($t_0$), and at the end of each early and late crop cycle. Soil total, soluble, and exchangeable K contents were determined using conventional analytical methods (Lu, 1999). At harvest, grain yield and aboveground biomass were determined. Samples of aboveground plant biomass were weighed, dried, and weighed again, ground to a fine powder and used for determination of K content (Lu, 1999).

### Calculation and statistical analysis

Agricultural performance was evaluated using the following parameters:

*K uptake:* defined as the amount of K absorbed by the aboveground rice biomass (kg $K_2O$ $ha^{-1}$).

*K residue:* calculated as the difference between K uptake and K application rate (kg $K_2O$ $ha^{-1}$).

*K utilization rate:* calculated as: 100 · ($K_{Treatment}$ uptake - $K_0$ uptake)/$K_{Treatment}$ dose (%).

*Agronomic efficiency:* calculated as: ($K_{Treatment}$ grain yield - $K_0$ grain yield)/ $K_{Treatment}$ uptake (kg grain $kg^{-1}$ $K_2O$).

Statistical analyses were carried out using IBM SPSS 21.0 software.

## Results and analysis

### Effects of combined N and K application on rice yields

In both soil types, the highest cumulative grain yields were obtained under the highest combination of N and K application rates (Fig. 1). On the red-yellow soil, in the early crop, the increasing K rates hardly affected the yield under the lower N rate (yield increase ranging from 2.4 to 5.1%), while under the higher N rate, the yield increase was much greater (13.7%) and about 900 kg $ha^{-1}$ more than the control. A similar pattern occurred for the late crop, although yield response to the K application under the lower N rate was more pronounced and ranged from 9.0 to 13.9%. In the late crop, yield response to the aggravated N rate was significant even when no K fertilizer was added, while the higher K rate made no further difference (Fig. 1).

Rice yields on the yellow soil were generally higher than on the red-yellow soil, by 600 kg $ha^{-1}$ per season, on average. Under the lower N rate, yield responded to the first grade of K rate, increasing by 10.3-12.4% and 12.9-17.7%, for the early and the late crop, respectively, but no further significant response could be observed when K rate was increased (Fig. 1). Upgraded N rate had a much smaller and not always significant influence on the yield.

### Effects of combined N and K application on K balance on two paddy soils

The total K uptake of both early and late rice crops increased with the rising K application rates (Table 3). Furthermore, K uptake consistently increased in

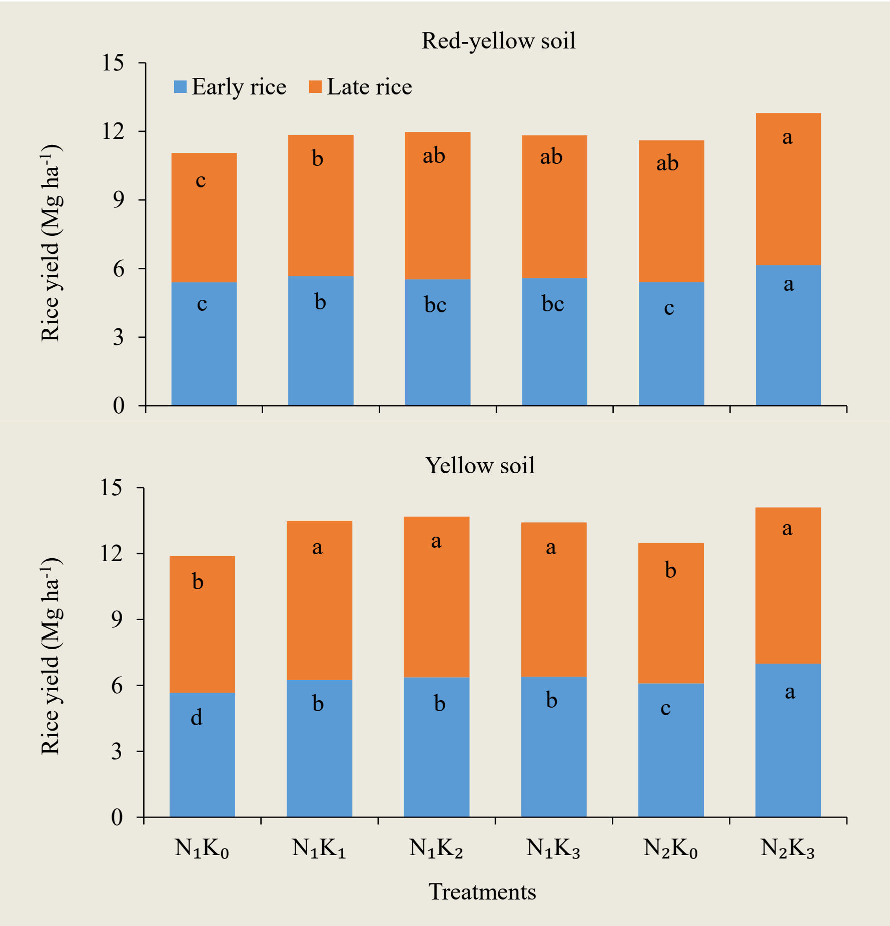



**Fig. 1.** Effect of combined N and K treatments on early and late rice yields on two paddy soil types. Same letters indicate no significant differences at $P < 0.05$.

response to rising N rates. Thus, K uptake was greater in treatments $N_2K_0$ and $N_2K_3$ than in the corresponding $N_1K_0$ and $N_1K_3$ treatments (Table 3).

Potassium uptake occurred under no K application, indicating considerable levels of soil available K, which seemed greater in the yellow than in the red-yellow soil (Table 3). The apparent K residue was negative under the lower K rates, especially for the later crops. Consequently, the K utilization rate was low, particularly in the early crop, ranging from 22 to 32% (Table 3). In the late crop, K utilization rate was considerably higher on the red-yellow soil, where it ranged from 36 to 65%, in comparison to the lower range of 10 to 25% on the yellow soil. The effect of N rate on K utilization rate differed between the early and late crops. While it had insignificant influence in the early crop, increased N rate brought about an increase in K utilization rate in the late crop (Table 3).

Potassium agronomic efficiency (KAE) was significantly higher on the yellow soil, compared with the red-yellow soil (Table 3). Under the lower N rate, KAE declined steeply with the rising K rate.

**Table 3.** K uptake, balance, and agronomic efficiency in double-crop rice grown under combined K and N application on two paddy soils in the hilly region of Hunan Province, China.

| Soil type | Treatment | Early rice | | | | Late rice | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | K uptake | Apparent K residue | K utilization rate | Agronomic efficiency | K uptake | Apparent K residue | K utilization rate | Agronomic efficiency |
| | | *-------kg $K_2O$ $ha^{-1}$-------* | | *%* | *kg grain $kg^{-1}$ $K_2O$* | *-------kg $K_2O$ $ha^{-1}$-------* | | *%* | *kg grain $kg^{-1}$ $K_2O$* |
| Red-yellow | $N_1K_0$ | 87.3 | -87.3 | - | - | 108.2 | -108.2 | - | - |
| | $N_1K_1$ | 120.4 | -15.4 | 31.5 | 2.00 | 197.6 | -61.1 | 65.5 | 3.75 |
| | $N_1K_2$ | 131.1 | 18.9 | 29.2 | 0.67 | 214.0 | -19.0 | 54.3 | 4.04 |
| | $N_1K_3$ | 149.6 | 45.4 | 31.9 | 0.77 | 199.2 | 54.3 | 35.9 | 2.27 |
| | $N_2K_0$ | 113.5 | -113.5 | - | - | 113.6 | -113.6 | - | - |
| | $N_2K_3$ | 161.7 | 33.3 | 24.7 | 2.89 | 259.8 | -6.3 | 57.7 | 1.78 |
| Yellow | $N_1K_0$ | 105.3 | -105.3 | - | - | 175.8 | -175.8 | - | - |
| | $N_1K_1$ | 136.0 | -31.0 | 29.2 | 5.53 | 190.6 | -54.1 | 10.8 | 7.41 |
| | $N_1K_2$ | 139.4 | 10.6 | 22.7 | 4.67 | 201.7 | -6.72 | 13.3 | 5.64 |
| | $N_1K_3$ | 154.3 | 40.7 | 25.1 | 3.75 | 228.0 | 25.5 | 20.6 | 3.16 |
| | $N_2K_0$ | 128.4 | -128.4 | - | - | 181.5 | -181.5 | - | - |
| | $N_2K_3$ | 171.6 | 23.4 | 22.2 | 4.65 | 246.1 | 7.4 | 25.5 | 5.18 |

Excluding the late crop on the red-yellow soil, KAE significantly rose in response to a higher N rate, as indicated by the KAE of $N_2K_3$, which was higher than that of $N_1K_3$ (Table 3).

### Effects of combined N and K application on soil soluble K

Soil soluble K content at the beginning of each crop ($t_0$) was higher than at the harvest of crops which had received the lower K treatments ($K_0$ and $K_1$). Soil soluble K displayed a linear positive response to K application rates and at rates equal to 150 kg $K_2O$ $ha^{-1}$ or above, and it was much greater at harvest than at $t_0$. This response pattern was similar for the two crops, being much clearer at the early crop (Fig. 2). Excluding the case of the late rice crop on the yellow soil, soil soluble K content at harvest was always higher at $N_2K_3$ than at the $N_1K_3$ treatment.

### Effects of combined N and K application on soil exchangeable K

On the red-yellow soil, fertilizer applications had a minor influence on soil exchangeable K (Fig. 3). Even though, at the end of the early crop, increased K rates brought about a recovery of the basal situation. In the late crop, soil exchangeable K declined, and under the lower N rate, the effect of K rates was quite poor. However, under the higher N rate soil exchangeable K recovered and even slightly increased in response to the $K_3$ treatment. On the contrary, soil exchangeable K was highly responsive to K application rates (Fig. 3). At the harvest of the early crop, soil exchangeable K increased by 32% in response to $N_1K_2/K_3$ and reached 125 mg $kg^{-1}$. Here, a higher N rate alone was sufficient for a substantial rise in exchangeable K, which further increased to 130 mg $ha^{-1}$ in response to the $K_3$ treatment. A similar response pattern occurred in the late crop under the lower N rate, nevertheless here, the rise of the exchangeable K in response to the higher N rate was not furthered by the $K_3$ treatment (Fig. 3).

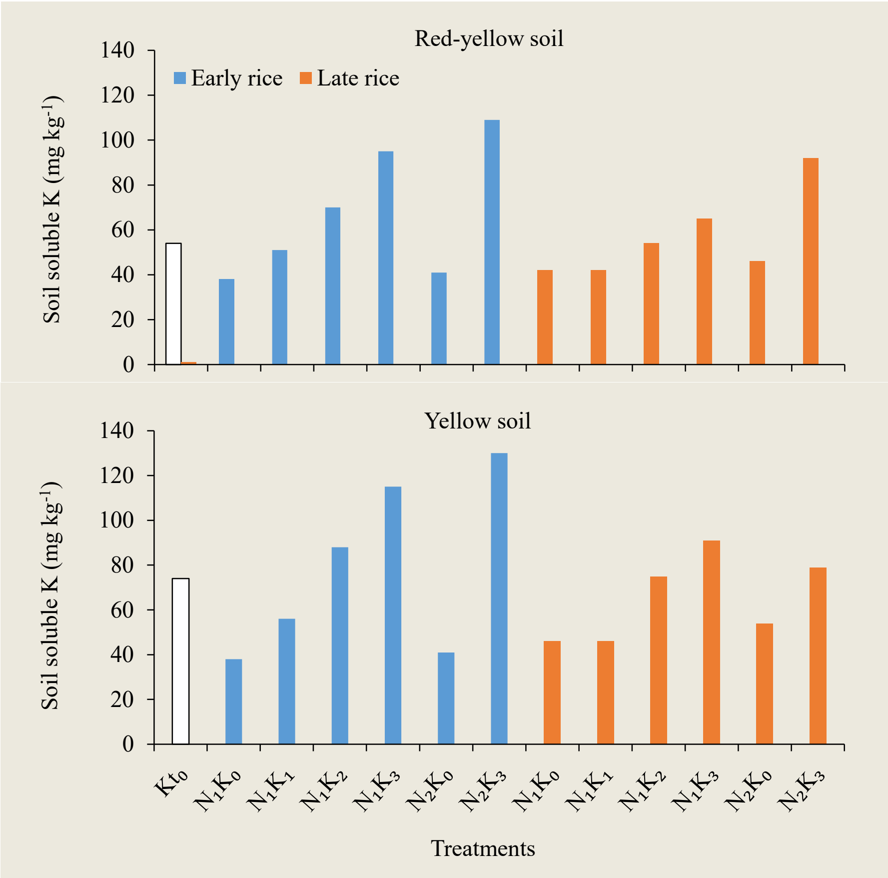



**Fig. 2.** Effects of combined N and K application on soil soluble K contents in two paddy soils in the hilly region of Hunan Province, China. Empty, blue, and orange bars represent soluble K contents at the beginning of the experiment (K $t_0$), after the early, and after the late rice crops, respectively.

### Economic considerations

Two principal parameters were used to evaluate the economic aspect of the examined fertilization practices: 1) the revenue:investment ratio (RIR); and, 2) the net increase in profit. RIR must be greater than 1, otherwise the farmer loses money. When this term is fulfilled, the profitability of each practice is compared to the alternative practices.

In the early crop on the red-yellow soil, RIR was < 1 and the net profit was negative whenever N was applied at the lower rate ($N_1$). Under those circumstances, $N_2K_3$ was the sole profitable treatment (Table 4). However, in the late crop on the same soil, the situation was different; here, a lower fertilizer combination, $N_1K_2$, yielded the highest profit. In this case, the highest yield or revenue did not necessarily indicate the highest profit.

Revenues were significantly higher on the yellow soil, especially for the late crop (Table 4). The net increase in profit was positive and RIR greater than 1 among all treatments. In the early crop, the highest net increase in profit was obtained for treatment $N_2K_3$, whereas $N_1K_1$ was the best treatment of the late crop.

## Discussion

Potassium is an important nutrient element required to achieve high and stable rice yields (Xie *et al.*, 2000; Singh *et al.*, 2002). A large number of studies have shown that K application in paddy soils can significantly increase rice yields (Liao *et al.*, 2008; Yang *et al.*, 2008). The

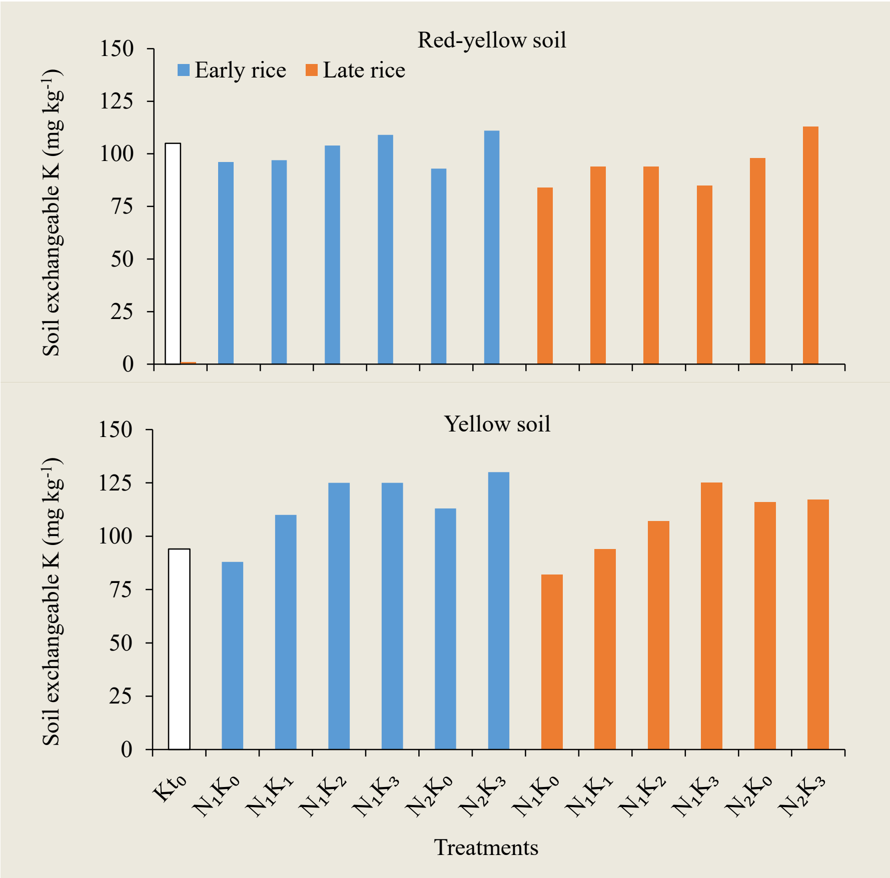



**Fig. 3.** Effects of combined N and K application on soil exchangeable K contents in two paddy soils in the hilly region of Hunan Province, China. Empty, blue, and orange bars represent exchangeable K contents at the beginning of the experiment (K $t_0$), after the early, and after the late rice crops, respectively.

present results may offer a more careful approach to K application regimes, ensuring they are suitable for the rice-rice system, and take into account differences between paddy soils and the interaction between N and K in this system.

Rice yields were consistently higher in response to the basic K application rate (105 kg $K_2O$ ha$^{-1}$), compared to the non-fertilized control ($N_1K_0$). However, as long as the N rate remained at the lower level (150 kg ha$^{-1}$), raising the K rate to 150 or 195 kg ha$^{-1}$ resulted in no further increase in yield (Fig. 1). However, an increase of the N rate to 195 kg ha$^{-1}$, accompanied with the highest K rate (195 kg $K_2O$ ha$^{-1}$), gave rise to a significant yield elevation in most cases. These results raise some questions regarding the nutrient limiting rice growth and yield at each condition. Apparently, under the lower N rate, crop K demands are fulfilled by the basic K application rate and further K input might be wasted. At this point, additional N supply allows further crop development, reestablishing crop K demand.

The positive influence of the interaction between N and K on crop growth and development is well documented (Doberman, 2007; Buresh *et al.*, 2010; Wang *et al.*, 2011). The approach of 'high N with high K' may increase rice yield, as occurred for the early crop, nevertheless it might also lead to a significant waste of nutrients, as occurred in the late crop, with the obvious economic as well as environmental consequences. Optimizing nutrient application would, however, require a better understanding of the applied nutrient fate in the soil and the estimated nutrient use efficiency.

Total soil K is roughly comprised of three fractions: soluble, exchangeable, and mineral K (Zörb *et al.*, 2014). The soluble K fraction is comprised of $K^+$ ions and is the one most available to plant roots. Exchangeable K represents the interphase between the liquid and solid phases of the soil. The $K^+$ ions are adsorbed to the negatively charged surface of the soil particles, but can be quite rapidly released to the soluble fraction. Thus, exchangeable K acts as a reserve for soil available K, and the quantity stored is largely dependent on the cation exchange capacity (CEC) of local soil particles. The mineral K fraction is considered as a long-term reserve, which usually does not take part in the immediate soil K balance. Most K fertilizers enrich the soil with soluble K, which might be allocated between the liquid and the exchangeable fractions according to the chemical balance between the two at the temporary soil moisture content. Paddy soils display a unique type of rhizosphere, interchanging between wet and dry field conditions, when soils are continuously flooded during most of the rice-growing season and then drained during the non-cropping season (Yang, 1989; Doberman *et al.*, 1996; Kögel-Knabner *et al.*, 2010). In addition to the significant consequences of this pattern on soil structural, and chemical (Yang *et al.*, 2004; Magahud *et al.*, 2015) and microbial characteristics (Dong *et al.*, 2014), soil K balance is especially affected (Doberman *et al.*, 1996; Xie *et al.*, 2000). Under flooding conditions, K fertilizer supplied at the beginning of the cropping season is predestined to four possible termini: soluble K; exchangeable K; crop uptake; and, seepage away from the field. In the early crop presented, the soluble K at harvest increased on both soil types with the rising K application rate, while the exchangeable K increased considerably only on the yellow soil (Fig. 2 and 3). Early crop K utilization rates were relatively

**Table 4.** Economic evaluation of combined N and K application on double rice cropping system in two paddy soils in the hilly region of Hunan Province, China.

| Soil type | Treatment | Early rice | | | | | Late rice | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Revenue | Revenue increase | Fertilizer cost | Net increase in profit | RIR | Revenue | Revenue increase | Fertilizer cost | Net increase in profit | RIR |
| | | *Yuan ha$^{-1}$* | | | | | *Yuan ha$^{-1}$* | | | | |
| Red-yellow | $N_1K_0$ | 14,893 | - | 1,308 | - | - | 16,196 | - | 1,255 | - | - |
| | $N_1K_1$ | 15,666 | 773 | 2,115 | -34 | 0.96 | 17,661 | 1,464 | 2,210 | 509 | 1.53 |
| | $N_1K_2$ | 15,257 | 364 | 2,358 | -686 | 0.35 | 18,447 | 2,251 | 2,620 | **886** | 1.65 |
| | $N_1K_3$ | 15,439 | 546 | 2,673 | -819 | 0.40 | 17,841 | 1,645 | 3,029 | -130 | 0.93 |
| | $N_2K_0$ | 14,937 | - | 1,543 | - | - | 17,732 | - | 1,536 | - | - |
| | $N_2K_3$ | 16,988 | 2,051 | 2,908 | **686** | 1.50 | 19,019 | 1,287 | 3,311 | -488 | 0.73 |
| Yellow | $N_1K_0$ | 15,630 | - | 1,308 | - | - | 17,783 | - | 1,255 | - | - |
| | $N_1K_1$ | 17,233 | 1,604 | 2,115 | 797 | 1.99 | 20,675 | 2,891 | 2,210 | **1,936** | 3.03 |
| | $N_1K_2$ | 17,562 | 1,932 | 2,358 | 882 | 1.84 | 20,929 | 3,146 | 2,620 | 1,781 | 2.30 |
| | $N_1K_3$ | 17,647 | 2,018 | 2,673 | 653 | 1.48 | 20,077 | 2,294 | 3,029 | 519 | 1.29 |
| | $N_2K_0$ | 16,803 | - | 1,543 | - | - | 18,275 | - | 1,536 | - | - |
| | $N_2K_3$ | 19,303 | 2,501 | 2,908 | **1,136** | 1.83 | 20,315 | 2,039 | 3,311 | 265 | 1.15 |

*Note:* Rice prices used for calculations were: early rice - 2.76 yuan kg$^{-1}$; late rice - 2.86 yuan kg$^{-1}$; fertilizer prices: N - 5.22 yuan kg$^{-1}$ urea; $P_2O_5$ - 7.00 yuan kg$^{-1}$; $K_2O$ - 7.00 yuan kg$^{-1}$.

poor, at less than 35% in both soil types. Although significantly higher on the yellow soil, K agronomic efficiency of the early crop was generally low (Table 3), compared to published reports on paddy soils (Doberman *et al*., 1998; Ali *et al*., 2005; Buresh *et al*., 2010). This pattern was principally similar for the late crop, although K utilization rates were much higher for the red-yellow soil, and K agronomic efficiency was higher for the yellow soil (Table 3). These results suggest that large proportions of applied K were lost to seepage.

There is no doubt that significant rates of K application are a must for rice-rice cropping systems on paddy soils. The severe soil K deficiency caused by long-term non-application of K fertilizer in southern paddy soil has become one of the main limiting factors of high-yielding rice production (Xie and Zhou, 1995; Li *et al*., 1998). In recent years, soil fertility monitoring results revealed that soil available K content in southern paddy soil regions showed a decreasing trend, with an annual decline rate ranging from 0.58 to 3.32 mg K kg$^{-1}$ year$^{-1}$ (Xie and Zhou, 1995). At present fertilization levels, in spite of the prevailing 'balanced NPK approach', K status is generally in deficit, and in some areas the deficit is serious (Liao *et al*., 2007; Liao *et al*., 2009; Wang *et al*., 2010). In order to restore and maintain soil K fertility, soil K balance must be closely monitored. It is generally believed that the lower the soil K status, the more obvious the effect of K application is, and the higher the K utilization rate is (Wang, 2010). In the present study, however, yield response was highest for the lower K application rate but it did not increase further with rising K rates, unless N rate was also raised (Fig. 1). This, together with the evidence of significant K waste to seepage, highlights the need for significant improvement of K fertilization management.

Custom basal K application provides a short opportunity for K uptake by the crop, because plants are small, their root system has not fully developed yet, and soil soluble K is diminishing rapidly due to seepage. Alternatively, K application doses should be split during the cropping season, thus broadening the crop's opportunity windows for K uptake. Also, rice K demand changes according to biomass and stage of development; maximum rice yields were obtained where K had been applied from 25 to 50 days after planting (Ali *et al*., 2005). Potassium application regimes should therefore be adjusted to local soil characteristics, as shown previously (Zheng *et al*., 1989; Dai *et al*., 2000; Doberman, 2007; Buresh *et al*., 2010; Wang *et al*., 2010; He *et al*., 2015; Shivanna and Sheelarani. 2015), and demonstrated in the present study. Differences between cultivars in the rate of K uptake must also be considered (Fageria, 2015). While designing a new fertilization approach, a careful balance must be kept between K and the other macro- and microelements (Li *et al*., 1998; Doberman, 2007; Wang *et al*., 2011).


Experimental sites. Photos by authors.

Economic evaluations in the present study show that a farmer's maximum profit from the early rice crop is obtained with high N and K application rates, while a lower N and K combination was sufficient for the late crop (Table 4). Nevertheless, the suggested alteration in K application regime is expected to change K utilization rate, K agronomic efficiency, and consequently the farmer's inputs and revenue. Hence, the economic aspect should be reconsidered after the new approach is established.

### Acknowledgement

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**The paper "Effect of Combined K and N Application on K Use Efficiency and Balance in Rice-Rice Cropping Systems in the Hilly Regions of Hunan Province, China" also appears on the IPI website at:**

**Regional activities/China**

# Research Findings

Potassium deficiency symptoms in upper soybean leaves. Photo by R.F. Firmano.

## Long-Term Potassium Administration/Deprivation Cycles on Tropical Oxisol: Effects on Soil Fertility and Soybean Performance

**Firmano, R.F.[1]*, A. de Oliveira Jr.[2], C. Castro[2], F. Vale[3], and L.R.F. Alleoni[1]**

### Abstract

Highly weathered soils in the humid tropics generally present low potassium (K) mineral reserves. When K fertilization is restricted, exchangeable K forms tend to run out quickly, hampering crop yield. Furthermore, in the long-term, soil mineral reserves may be affected. A field experiment carried out from 1983 to 2016 at Londrina (Paraná state), evaluated the effect of potassium chloride (KCl) fertilizer rates (0, 40, 80, 120, 160 and 200 kg $K_2O$ $ha^{-1}$ $year^{-1}$) on soybean yield under long cycles of K application (1983-1988; 1995-2008) and K deprivation (1988-1994; 2008-2014). In October 2015, each plot was divided into two, and K fertilizer was reapplied to one half, whilst the second half remained K deprived. The objectives of the present study were to explore soybean nutrition under long-term withheld K

[1]Department of Soil Science, University of São Paulo, ESALQ, Piracicaba, SP, Brazil
[2]Brazilian Agricultural Research Corporation, National Soybean Center, Londrina, PR, Brazil
[3]IPI Coordinator for Latin America, International Potash Institute (IPI), Zug, Switzerland
*Corresponding author: ruanff@usp.br

fertilization to study the dynamics of K forms in the soil, and to identify an optimum K fertilization rate that would also maintain K reserves in a highly weathered soil. Soil exchangeable K contents (evaluated using the Mehlich-1 and the ion exchange resin methods) corresponded highly with previous K application rates, whilst non-exchangeable K and soil total K were much less affected by treatments.

Soybean responded dramatically to exchangeable K levels at the lower K range and according to Mehlich-1 and the ion exchange resin method, was saturated already above 70 and 110 mg kg$^{-1}$, respectively. This K residue level was stored in the soil 8 years after an application rate of 120 kg $K_2O$ ha$^{-1}$ and, with no additional fertilizer, was sufficient to support 90% of the maximum yield obtained from the plots where K had been reapplied.

The results indicate that the role of non-exchangeable and structural K forms has been underestimated. Also, a large proportion of the applied K reaches and is stored in the structural K forms, where it remains accessible to plant roots in the long-term. In conclusion, a K application range of 80-120 kg $K_2O$ ha$^{-1}$ is expected to support reasonable growth, development, and yield of soybean on humid tropical Oxisols, whilst preserving future soil fertility. Lower rates would allow sufficient yields in the short-term, but soil fertility might decline with time. Higher application rates would be partially wasted and could even lead to a reduction in yields.

*Keywords: Glycine max* L.; highly weathered soil; Mehlich-1; non-exchangeable K.

## Introduction

Brazil is the fourth largest potassium (K) fertilizer consumer in the world, importing 90-95% of its annually rising demand. Potassium fertilizer demand increased by 10% from 2015 to 2016, translating to 700,000 tonnes of potassium oxide ($K_2O$). Highly weathered soils typically contain 300-2,000 mg K kg$^{-1}$ (Silva *et al.*, 2000), a relatively low mineral reserve in comparison to temperate climate soils in Brazil, which may have up to 30,000 mg kg$^{-1}$. Interestingly, though born from a poor-K parent rock material and developed under humid tropical conditions, highly weathered soils may encompass mineral K sources sufficient to support crop nutrition. Indeed, species cultivated on soils rich with ferric and aluminum oxides with prevalent kaolinite and quartz, and under restricted K fertilization, often display deficiency symptoms and low tissue K contents (Lalitha and Dhakshinamoorthy, 2014; Darunsontaya *et al.* 2010). Still, high crop yields have frequently been reported over the years in spite of the humid tropical climate and soils originating from basaltic rocks, and even without K fertilization (Adamo *et al.*, 2016; Qiu *et al.*, 2014).

In Brazil, plant available soil K is measured using acidic solutions, such as with the Mehlich-1 or the ion-exchange resin methods. Nevertheless, the exchangeable phase is not the sole K source for plant nutrition (Rosolem *et al.*, 2012). For instance, soybean (*Glycine max* L.) crops exhibit a very rapid response to small changes at the lower range of exchangeable K content in the soil, however, this response diminishes at the higher range (Fig. 1). Crop response to K application is also quite often negligible, even on highly weathered acidic soils of the humid tropics and subtropics (Rosolem *et al.*, 2001). Such a phenomenon has been attributed to K reserves ingrained in the mineral soil fraction, mainly in ditrigonal positions in the phyllosilicate structure, or edge and fracture positions of these minerals in intermediate stages of weathering (Sharpley and Smith, 1988).

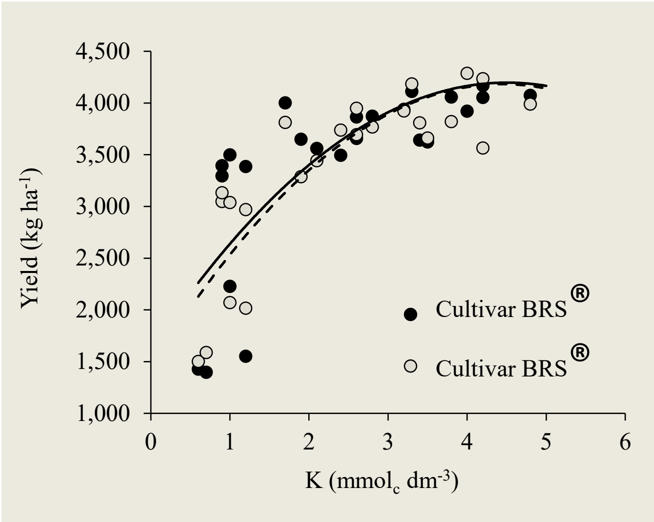


**Fig. 1.** Soybeans cultivar yields as a function of exchangeable K contents (Mehlich-1) in soil. Oliveira Jr. *et al.*, 2013.

Potassium deficiency symptoms often occur in plants grown on soils where the exchangeable K forms have gradually been exhausted overtime, and not adequately replenished via fertilization. In this scenario, the estimated K losses from agricultural systems may have serious economic consequences. Modern and high-yielding soybean cultivars occupy 33.9 million ha in Brazil (Brazilian Supply Company, 2017) and demand higher K inputs than traditional cultivars. The absence of such levels can lead to the exhaustion of soil exchangeable K forms, whereas the impact on other soil K reserves is unclear. The objectives of the present study were to explore soybean nutrition under long-term withheld K fertilization to study the dynamics of K forms in the soil, and to identify an optimum K fertilization rate that would also maintain K reserves in a highly weathered soil.

## Materials and methods

### Study area

A long-term field experiment started in 1983 in a region of basaltic spills where the vegetation is classified as semi-deciduous seasonal forest. The region (51° 10' W and 23° 11' S, 590 m above sea level) is located in the Paraná State Basin (Fig. 2). The northern part of the 3rd plateau in Paraná State, Brazil, is characterized as a Cfa Köppen type climate (subtropical humid), with rains throughout all seasons (1,800 mm annually) and possible droughts in the winter. The soil is a Rhodic Hapludox (Soil Survey Staff, 2010). The chemical attributes and textural characterization (Mehlich, 1953; Raij, 1998) of soil samples collected in July 2015, are listed in Table 1.

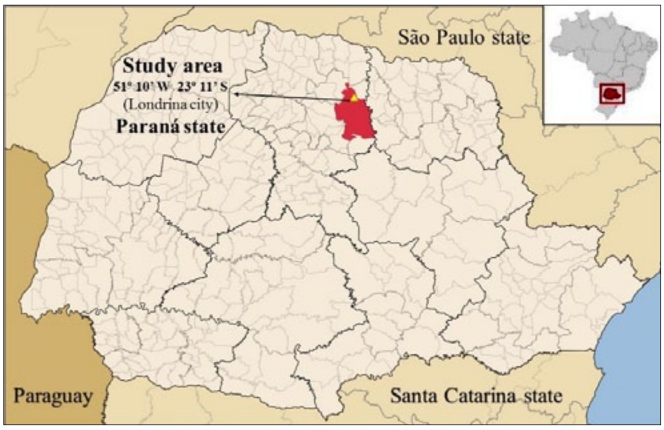


**Fig. 2.** Location map of the study area.

The experiment aimed to evaluate the long-term effects of restricted and unrestricted K fertilization cycles on soil K forms and on grain yields. The experiment design consisted of randomized complete blocks arranged in 24 plots (40 m², 8 x 5 m), with four replicates and six treatments, consisting of one control and five K rates (40, 80, 120, 160 and 200 kg $K_2O$ ha$^{-1}$ year$^{-1}$) applied as KCl (60% $K_2O$).

Potassium applications took place from 1983 to 1988 and again from 1995 to 2008, but not from 1989 to 1994 or 2008 to 2014. During the rounds of application, K was applied annually for the summer crops, with 40 kg $K_2O$ ha$^{-1}$ year$^{-1}$ applied at sowing, and the remaining amounts as a side dressing. In October 2015, the plots were divided in two to receive new treatments: one half would be reapplied with K fertilizer and the other half would continue not to receive K - for the eighth consecutive year (2015-2016).

**Table 1.** Soil chemical and textural attributes.

| Soil layer | pH | Calcium | Magnesium | $K_1$ | $K_2$ | Aluminum | $H^+$+Al |
|---|---|---|---|---|---|---|---|
| *m* | *0.01 CaCl₂* | | | *cmol$_c$ kg$^{-1}$* | | | |
| 0.0-0.2 | 4.4 | 2.4 | 1.3 | 0.12 | 0.15 | 0.9 | 6.6 |
| 0.2-0.4 | 4.3 | 1.9 | 1.1 | 0.09 | 0.13 | 0.9 | 6.7 |
| | OC | Phosphorus | CEC | V | Clay | Silt | Sand |
| | *g kg$^{-3}$* | *mg kg$^{-3}$* | *cmol$_c$ kg$^{-1}$* | *%* | | *g kg$^{-1}$* | |
| 0.0-0.2 | 16 | 31 | 10.4 | 37 | 715 | 229 | 56 |
| 0.2-0.4 | 8 | 18 | 10.7 | 32 | 712 | 228 | 60 |

*Note:* OC = Organic carbon ($K_2Cr_2O_7$); Ca, Mg and Al (KCl 1 mol L$^{-1}$); P and $K_1$ (Mehlich-1); $K_2$ (ion exchange resin); $H^+$+Al = (SMP - Schoemaker-McLean-Pratt buffer solution); CEC = cation exchange capacity; V represents the percentage of saturation by basic character cations ($Ca^{2+}$, $Mg^{2+}$ and $K^+$) in relation to the CEC of the soil, which is obtained by the sum of these cations with $H^+$ and $Al^{3+}$.

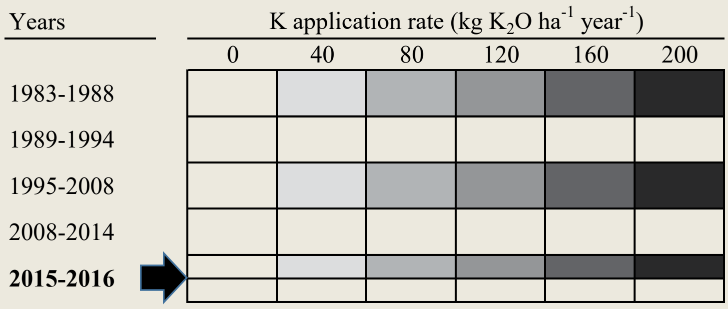


**Fig. 3.** A schematic description of the multi-annual K application (1983-1988; 1995-2008) and deprivation (1988-1994; 2008-2014) cycles. Soil and crop examinations took place during 2015-2016 (black arrow), when each plot was divided into two for new treatments: K reapplication vs. K deprived control.

The area was predominantly cultivated with soybean in the summer and with wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), sunflower (*Helianthus annuus* L.) or black oat (*Avena strigosa* L.) in winter. Yield and plant nutritional status assessments were made for soybean, which is the only species cultivated every year in the area, and the one with the highest amount of K per unit mass in its tissues. Seeding, pesticide application, weeding and harvesting were done mechanically.

### Soil sampling and preparation

Composite soil samples derived from five subsamples, randomly collected in each experimental unit from 0.0-0.2 and 0.2-0.4 m deep, were collected in July 2015 - before the K reapplication - and in December 2015 - two months after the K reapplication. The samples were dried (50°C) and sieved (2 mm mesh). Native soil samples near the experiment were also collected from the same soil depths as mentioned above to compare the effect of cultivation and treatments on soil chemical and mineralogical attributes.

**K forms**

The exchangeable soil K was extracted separately using two different methods: Mehlich-1 solution (Mehlich, 1953), and the ion exchange resin (van Raij, 1998).

The non-exchangeable K phase was extracted using boiling nitric acid ($HNO_3$) (Knudsen *et al.*, 1986; Pratt, 1997). Since K availability varied as per the previously applied K rates, concentrations of 0.25, 0.5, 2.0, and 4.0 mol $L^{-1}$ were used in addition to the reference concentration - 1 mol $L^{-1}$ $HNO_3$, thus calibrating the $HNO_3$ technique to the low K range expected under extended periods of withheld K. Non-exchangeable K contents were calculated based on the difference between the total K contents obtained by the $HNO_3$ extraction, and the exchangeable K contents obtained by the Mehlich-1 or the ion exchange resin methods.

For total K determination, 5 g of soil samples were digested by the EPA 3052 method (USEPA, 1996), in the presence of 2 ml of HCl, 9 ml of $HNO_3$ and 3 ml of HF (hydro-fluoric acid). Moist digestion was carried out in a microwave oven under the following conditions: 5.5 min of heating to, and then maintenance at 180°C under 2 MPa pressure for 9.5 min, and 10 min of cooling to room temperature. The extract was filtered on quantitative filter paper and transferred to 100 ml flasks. The K contents were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES).

**Mineralogical analyses**

Powdered and parallel-oriented soil fraction samples, separated according to Gee and Or (2002), were evaluated by X-ray diffraction (XRD) in order to characterize the soil mineralogy. Analyses were performed on a computer-controlled X-ray diffractometer using a copper tube graphite monochromator. The velocity of the goniometer was 0.02º2θ $s^{-1}$, with a range of 3 to 90º2θ.

**Plant sampling and preparation**

At the full bloom stage (R2) of the soybean, with a relatively high rate of K absorption (Zobiole *et al.*, 2012), trifolia diagnostic leaves (third from the apex of the plant and without petiole) were collected randomly from each subplot. Mechanical harvesting was performed at full soybean maturity (R8), and 6 m of the three central lines of each subplot (9 $m^2$) were sampled. All plant tissues were dried at 50°C, milled, and sieved in 35 sieves (mesh size 0.5 mm). The fresh and dry aerial parts were taken to calculate the biomass produced in each subplot.

**K contents in leaves**

The plant tissue (0.25 g per sample) was digested in 6 ml of $HNO_3$ (65% v/v $HNO_3$) and 2 ml of hydrogen peroxide ($H_2O_2$). The nutrient content was determined using ICP-AES. Moist digestion was carried out in a microwave oven under the following conditions: 10 min of heating to, and then maintenance at 170°C for 15 min under 2 MPa pressure, and cooling for 20 min to room temperature.

**Yield**

Yield was determined based on the grain mass per sampled plot (9 $m^2$), adjusted to 13% water content, and converted into kg $ha^{-1}$.

**Statistical analyses**

Regression analyses were carried out to determine K rates of the subplots with and without K reapplication. The data on soil chemical attributes and K forms underwent analysis of variance and Tukey's comparison (5%). Simple linear correlations were applied to verify the presence of significant correlations between the K contents extracted from the soil, by different methods, with the soybean yield attributes and K contents in plant organs.

**Results**

XRD examination revealed that the clay mineralogy of the experimental site is composed of kaolinite (d: 0.725, 0.444, 0.356, 0.234, 0.169, 0.149 nm); hematite (d: 0.296, 0.250, 0.220, 0.183, 0.163, 0.145 nm); gibbsite (d: 0.483 nm); quartz (0.334 nm); maghemite (0.293 nm) as the dominant minerals (Firmano, 2017). No differences could be observed between selected treatments, in spite of the significant contrast in their K application regime.

Soil sampling took place at the end of the eighth year, in which K application was readministered, or not, following seven years of K deprivation. Generally, all soil samples displayed low total K contents, ranging from 500 to 700 mg $kg^{-1}$ soil, with only minor differences between the two soil layers (0-0.2 and 0.2-0.4 m. The highest total K content was found after the 80 kg $K_2O$ $ha^{-1}$ rate had been reapplied, followed by the content of the native forest soil. The unfertilized control had the lowest total K content. Interestingly, the highest K reapplication rate ($+K_{160}$) displayed a relatively low K content, equivalent to that of its non-fertilized control ($-K_{160}$).

The sand soil fraction had the lowest total K contents, ranging from 193 to 168 mg $kg^{-1}$. It contributed less than 2.5% of the total soil K - less than its relative portion in the soil texture (Table 1). The silt fraction displayed the highest total K contents, ranging from 775 to 900 mg $kg^{-1}$ soil, with no remarkable differences between treatments (Fig. 4). The clay fraction exhibited lower total K contents, from 450 mg $kg^{-1}$ at the control up to 680 mg $kg^{-1}$ at the $+K_{80}$ treatment. Nevertheless, since clay is the dominant fraction (>71%) in the soil texture, it contributed 62-71% of the soil's K reserve. Furthermore, changes occurring in the clay fraction determined the total and available soil K status. Cultivation seemed to not have much influence on the mean total K distribution in soil fractions, which was 65, 33, and 2% for the clay, silt, and sand fractions, respectively vs. 61, 36, and 3% for the same fractions in the native forest (Fig. 4).

In contrast, total soil K contents were significantly affected by interactions between cultivation and the various nutrition treatments (Figs. 5 and 6). On average, total K contents were quite similar in the experimental area and the native forest - 781 and 803 mg kg$^{-1}$, respectively, however, content was significantly lower under K rates below or equal to 80 kg $K_2O$ ha$^{-1}$, and particularly under no K fertilization. On the other hand, rates equal to or greater than 120 kg $K_2O$ ha$^{-1}$ meant that K reserves were maintained in the soil over time (Fig. 5).

Non-exchangeable K content was lowest in plots that had received the lowest K doses throughout the 33 years of the experiment. However, it increased linearly from 40 to 60 mg kg$^{-1}$ soil depending on prior K application rates. After seven years of deprivation, the effect of K reapplication on the non-exchangeable K contents was marginal, irrespective of dosage (Fig. 5). The non-exchangeable K content was however significantly dependent on the $HNO_3$ concentration used for sample extraction, as well as on the method used to determine the exchangeable K contents – Mehlich-1 or ion exchange resin. In the cases where total soil K was higher than 800 mg kg$^{-1}$, the lower $HNO_3$ concentrations (0.25-0.5 mol L$^{-1}$) were sufficient to yield most of the non-exchangeable K fraction. However, below this threshold, more rigorous concentrations were needed (Fig. 5). Furthermore, where the non-exchangeable K fraction was calculated using the resin-determined exchangeable K, non-exchangeable K forms of the relatively K-poor soils were detectable solely using the higher $HNO_3$ concentration range.

Following seven years of K deprivation, in July 2015, the soil exchangeable K contents followed the pattern of past K doses, especially where doses had been higher than 80 kg $K_2O$ ha$^{-1}$

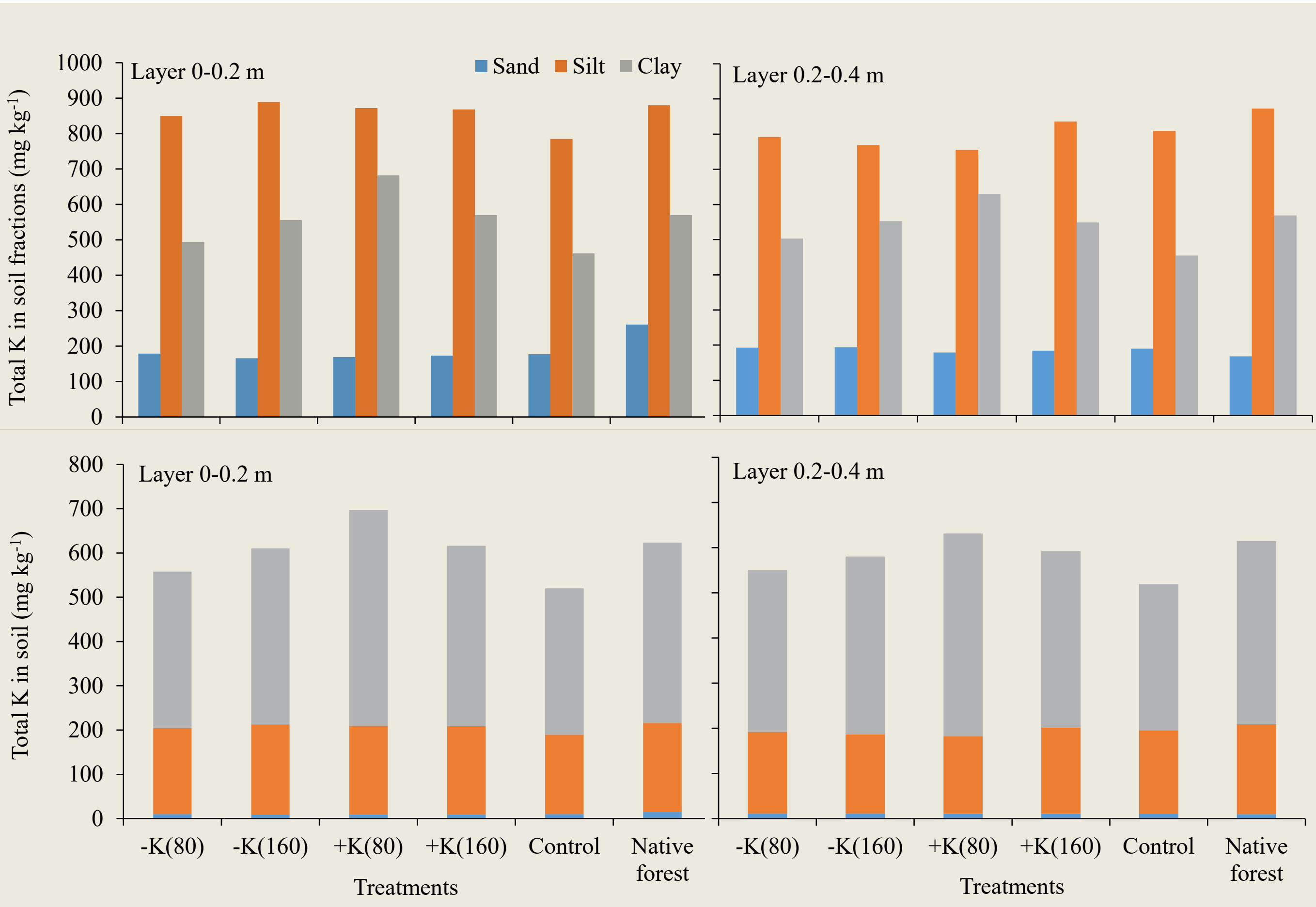


**Fig. 4.** Total K content in soil fractions from representative samples taken from plots in 2016 following 7 years of K deprivation (-K) and K reapplication carried out in the eighth year at two rates - 80 and 160 kg $K_2O$ ha$^{-1}$. The control sample from a nearby non-cultivated native forest never received K application.

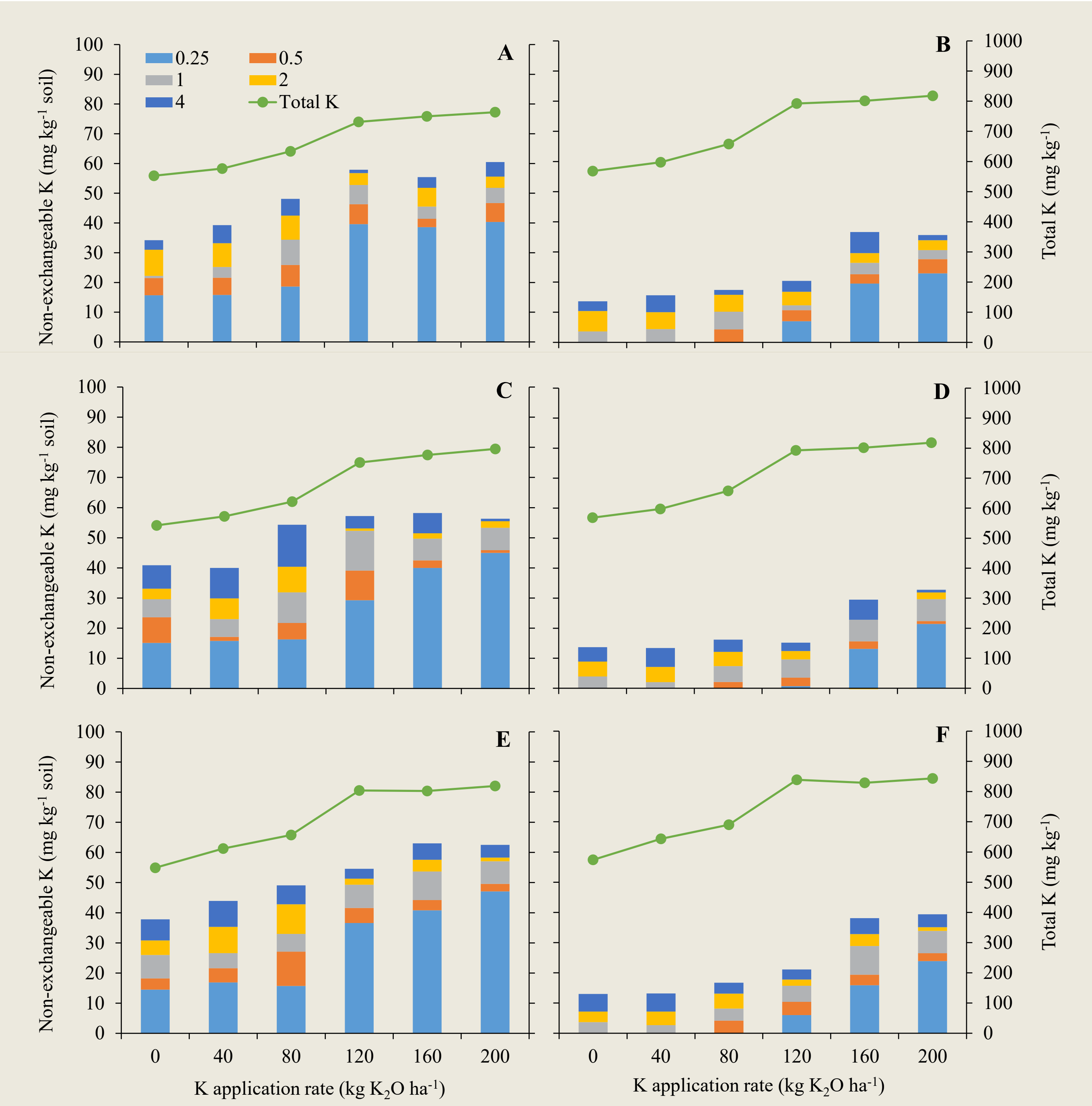


**Fig. 5.** Total (extracted using $HNO_3$ + HF) and non-exchangeable soil K (extracted with five concentrations of $HNO_3$: 0.25; 0.5; 1; 2; and 4 mol $L^{-1}$) following seven years of K deprivation and as a function of past and reapplied K rates: A and B - the last year of K deprivation in July 2015; C and D - shortly after reapplication in Dec 2015 of the eight years; E and F - after reapplication at the end of eight years in 2016. Non-exchangeable K contents were calculated by subtracting exchangeable K, extracted using either Mehlich-1 (A, C, E) or ion exchange resin (B, D, F), from the total K contents.

year$^{-1}$ (Fig. 6). Where K deprivation continued for half of the plots, this situation remained the same 6 months later in December 2015. Nonetheless, $K_2O$ reapplication to the other half of the plots brought about a significant increase in exchangeable K contents, which was proportional to the dose applied (Fig. 6). Although the response pattern of the exchangeable K levels to the reapplied nutrient was similar for the two extraction methods, the ion exchange resin technique obtained consistently higher levels.

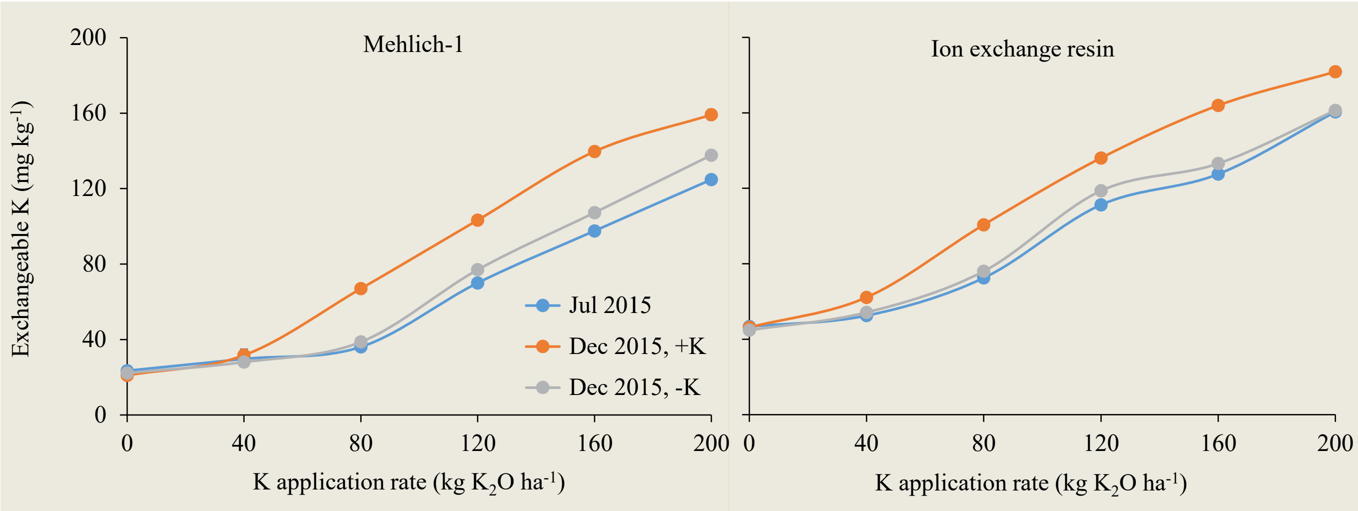


**Fig. 6.** Mean values of exchangeable K, extracted using the Mehlich-1 or the ion exchange resin method, to measure the effects of residual K before nutrient reapplication (July 2015), and soon after K had been reapplied (+K) or not (-K), (Dec 2015).

The difference varied from 22 to 42 mg kg$^{-1}$ soil, being smaller but significant at the smaller K doses (0-80 kg $K_2O$ ha$^{-1}$), where the resin's results were 2-fold greater.

Soybean yield was highly responsive to very slight changes in the lower range of soil exchangeable K (Fig. 7A and B). Maximum grain yields were obtained at the low range of 60-80 mg kg$^{-1}$ of soil exchangeable K - determined using the Mehlich-1 method. Any further increase in exchangeable K failed to produce higher yields. A similar pattern, but at a significantly higher range of exchangeable K (above 100 mg kg$^{-1}$) was observed where the ion exchange resin method was employed. The yields obtained under the reapplied K treatment at the lower doses of 40 and 80 kg ha$^{-1}$ were significantly higher, by 25 and 12.5%, respectively, than the corresponding non-fertilized control. At this responsive range, the difference in K availability between the reapplied and control treatments surged dramatically by 25-30 mg kg$^{-1}$ (Fig. 6). At the higher application rates, the difference in yields was much smaller, ranging from 5-7.5 mg kg$^{-1}$ (Fig. 7A and B), in spite of the consistently higher soil K availability (Fig. 6).

A similar but more gradual response pattern was observed for leaf K content (Fig. 7C and D). Here, saturation was reached above soil exchangeable K contents of 120 mg kg$^{-1}$ at the reapplied K treatments, as compared to above 100 mg kg$^{-1}$ for the corresponding control samples (Mehlich-1). Again, the ion exchange resin method gave rise to a similar response pattern but at higher ranges of exchangeable K. Leaf K contents were 40% greater in plants grown with 80 kg $K_2O$ ha$^{-1}$ reapplied K, as compared to the corresponding control. The differences at the other K application rates were much smaller or none (Fig. 7C and D). Also, K reapplication significantly enhanced soybean grain size and quality, particularly at a dose range of 40-120 kg $K_2O$ ha$^{-1}$ (Fig. 8).

**Photo 1.** K deficiency symptoms in soybean and maize in the northern state of Paraná. Photo by R.F. Firmano.

## Discussion

Soil fertility, in the sense of K availability, can be analyzed by the instantaneous $K^+$ concentration in the soil solution at the roots vicinity. This instantaneous $K^+$

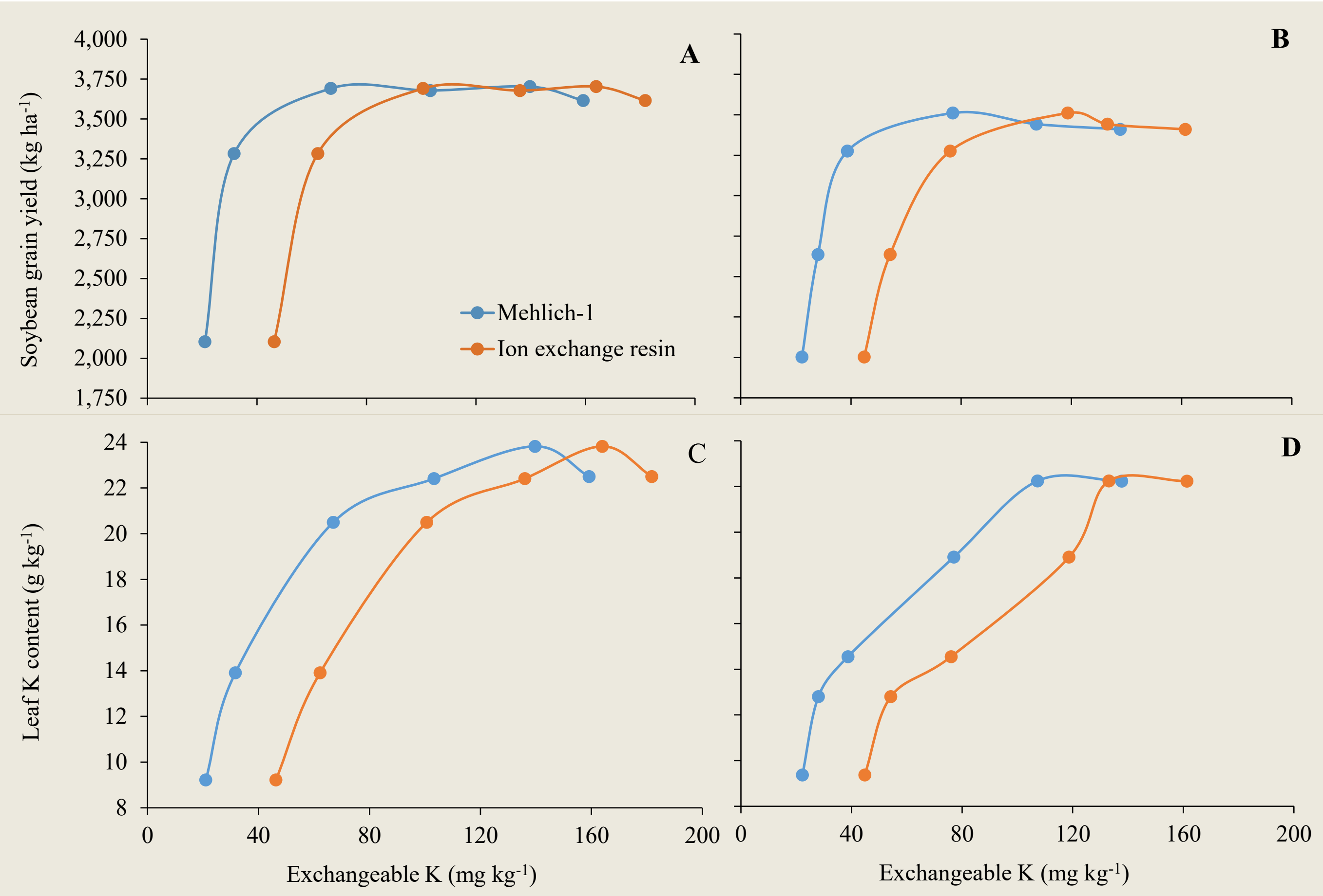


**Fig. 7.** Soybean yield (A, B) and leaf K contents (C, D) as functions of actual levels of soil exchangeable K, determined using the Mehlich-1 or ion exchange resin methods. Measurements took place in 2016, with soybean crops reapplied with 0, 40, 80, 120, 160, and 200 kg $K_2O$ ha$^{-1}$ (A, C) vs. non-fertilized control (B, D) after seven years of K deprivation.

concentration is the momentary outcome of complex relationships and fluxes between the different K forms, soil phases, uptake by plants, fertilizer application regime, and loss due to leaching (Fig. 9).

Under the extensive precipitation characteristic of humid tropic regions, outward K fluxes (leaching) might dominate the system, thus promoting K movement from structural and non-exchangeable forms to the exchangeable fraction, rather than the opposite. However, fluxes replenishing the exchangeable K phase are assumed to be much slower than the outward fluxes (K removal by plants and leaching).

The clay mineral profile at the experimental site was comprised mainly by kaolinite, a 1:1 class mineral with low CEC (cation exchange capacity) values (about 10 meq 100 g$^{-1}$), while 2:1 class clay minerals with substantially higher CEC values were scarce. The significant presence of kaolinite ([$Al_2Si_2O_5(OH)_4$]) was expected, as this phyllosilicate can be found in higher amounts in well-developed soils of the humid tropics (Fontes *et al.*, 2001). Goethite and hematite (α-FeOOH and α-$Fe_2O_3$) are dominant iron oxides in Oxisols (Childs, 1981). The presence of quartz and hematite was expected due to the pedoenvironmental conditions, such as high iron (Fe) content in the parent material, high temperatures, rapid mineralization of organic matter and pH close to neutrality (Schwertmann and Murad, 1983). Gibbsite ([$Al(OH)_3$]), the most representative aluminum hydroxide in tropical humid soils, was also expected (Fontes *et al.*, 2001). Thus, in spite of comprising 72% clay (Table 1), the local clay mineral profile can establish relatively low CEC, insufficient to retain considerable levels of exchangeable K. This was the major reason why the control plants manifested K deficiency symptoms; after 34 years of K deprivation, the exchangeable K phase was almost depleted (Fig. 6) and unable to support even a minimum yield level (Fig. 7).

It may be postulated that the depletion of exchangeable K, under continuous conditions of crop cultivation with insufficient K

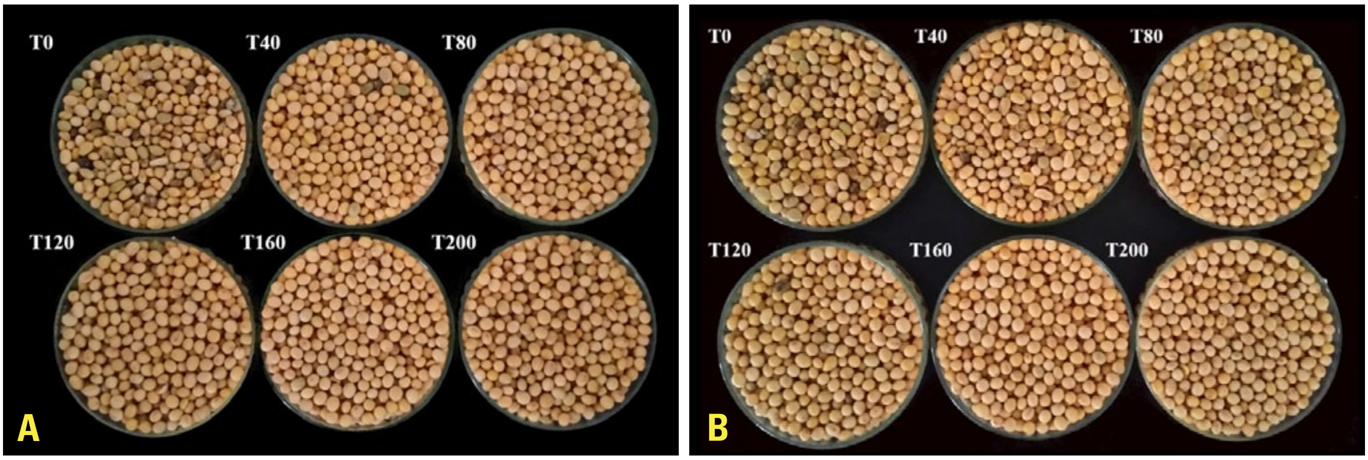


**Fig. 8.** Soybean grain quality for different K reapplication rates (A) vs. control samples with no K reapplication (B), in subplots deprived of K for seven years but demonstrating the residual effects of prior K fertilization.

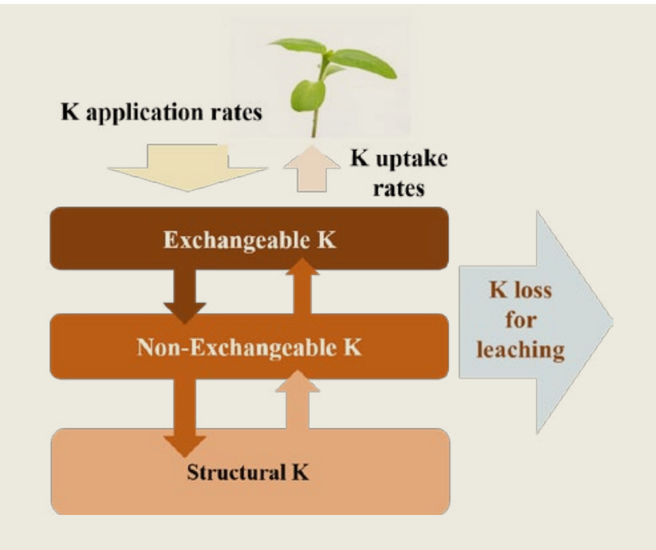


**Fig. 9.** A simplified diagram describing the dynamics among K forms in agricultural systems.

replenishment, accelerated the release of exchangeable, and subsequently non-exchangeable K forms, from the total K reserves. This assumption is partially supported by the degradation of 2:1-type clay minerals, and the very poor crystallinity which did not allow sufficient detectability in the XRD tests. Under accelerated depletion of exchangeable K, the rates of K release from the structural phase of the clay minerals are too high, and hence those structures are loosened and disappear.

Nevertheless, the contribution of the structural K forms to short-cycle nutrient species is low, given the small amounts of K released over time (Figs. 4 and 5). Kaminski *et al.* (2007) observed little participation of structural K from Alfisol under successive crops cultivation. Similar results were obtained for Oxisols (Moterle *et al.*, 2016). Therefore, although comprising the major part of soil K reserves, structural K forms only become bioavailable after more available forms are intensely removed by crops, especially under deprived K fertilization (Csathó, 2002), or due to a direct action of microorganisms and organic acids (Basak and Biswas, 2009).

The reduction in non-exchangeable forms was possibly influenced by the low soluble $K^+$ levels in plots with a history of low K application rates - 80 kg $K_2O$ ha$^{-1}$ or less (Fig. 5). Here, the balance between K input and output was negative; K loss due to leaching and take-up by crops was higher than K application. The continuous $K^+$ depletion disturbed the balance between K forms and to reestablish the cation chemical equilibrium, K was released from non-exchangeable fractions (Simonsson *et al.*, 2007). Plant roots have an active role in this process, excreting both protons and organic acids to their microenvironment (Paola *et al.*, 2016), thus accelerating K release from the non-exchangeable phase (Bortoluzzi *et al.*, 2005; Melo *et al.*, 2005).

Two methods were employed in the present study to quantify the exchangeable K in the soil: Mehlich-1, and the ion exchange resin. The Mehlich-1 mechanism of extracting exchangeable K uses a double acid solution to enrich the soil sample with protons, and exchange them for $K^+$ ions adsorbed to the electronegative surface of mineral or organic colloidal particles (Mehlich, 1953). The ion exchange resin approach challenges the soil particles with a substantially higher CEC, thus competing for cations. Generally, the response patterns to both methods for prior and current K application rates were similar, excluding some deviations at the extremely low and high levels (Fig. 6). This confirms van Raij's (1998) remarks, ascribing similar results to both methods, on tropical soils. However, considerable quantitative differences occurred between the methods, indicating that the ion exchange resin method is more efficient at extracting $K^+$ ions, as it


**Photo 2.** Phenological stages and symptoms of K deficiency in selected time and locations at the experiment site throughout soybean cycle. Photo by R.F. Firmano.

consistently obtained values higher than those of the Mehlich-1 method (Fig. 6). Some of the difficulties of the Mehlich-1 method to accurately extract exchangeable K from relatively poor soils are reflected by the non-exchangeable K results (Fig. 5). The higher levels obtained using Mehlich-1, especially when higher acid concentrations were employed, may again suggest that the ion exchange resin is more efficient at accessing hard-to-get $K^+$ ions. Alternatively, it may be questionable whether that 'hidden' exchangeable K is accessible by plant roots. However, the establishment of a standard and reliable method to quantify the exchangeable K phase in soils has not yet been reached.

The principal aim of K application regimes is to construct and replenish sufficient levels of available K during crop growth and development, avoiding nutrient shortage as well as saturation. In the present study, the response of soybean plants to relatively small increases in K availability was very sharp, particularly at the lower range of nutrient availability (Fig. 7). Potassium content in leaves upsurged from 9.1 to 25.6 g kg$^{-1}$ and yields reached their maximum levels following a relatively small change in available K. While reapplication at low rates - 40 kg $K_2O$ ha$^{-1}$ - was insufficient to increase nutrient saturation in the exchangeable K phase, plant response was significant. Clover and Mallarino (2013) identified the critical K concentrations for several modern soybean cultivars, below which, yield losses range between 20 to 23 g kg$^{-1}$ K. On the other hand, in the present study, when rates of 160 and 200 kg $K_2O$ ha$^{-1}$ were reapplied, the levels of available K exceeded plant demand and uptake, and even caused a slight yield reduction (Fig. 7).

The most striking finding of the present study is the ability of the soil to preserve considerable levels of fertility over long periods of K deprivation. After 8 years without K fertilization, where prior application rates were equal to or greater than 120 kg $K_2O$ ha$^{-1}$, K exchangeable content was higher than 71 mg kg$^{-1}$ (Mehlich-1) or 112 mg kg$^{-1}$ (ion exchange resin) (Fig. 6). These levels, with no additional K application, produced 90% of the maximum yield obtained from corresponding plots reapplied with K (Fig. 7A and B). Thus, the rapid response phase of soybean to available K occurs at the lower range of soil K contents for soybean grown on Oxisols at K exchangeable levels less than 40 mg dm$^{-3}$ (Mehlich-1), as observed by Rosolem and Nakagawa (2001). Furthermore, in the plots that were not applied with K fertilizer for 34 years, soil exchangeable K content was 22 (Mehlich-1) or 45 (ion exchange resin) mg kg$^{-1}$ (control, Fig. 6), and soybean yield levels reached 2,000 kg ha$^{-1}$ - about 60% of the maximum (Fig. 7). These results provide strong indications that the role of the non-exchangeable and the structural K forms has been underestimated. Moreover, they shed new light on the actual role of K fertilizer application on humid tropic Oxisols; a large proportion of the applied K reaches and is stored in the structural K forms, where it remains accessible to plant roots in the long-term (Fig. 9).

In conclusion, a K application range of 80-120 kg $K_2O$ ha$^{-1}$ is expected to support reasonable growth, development, and yield of soybean on humid tropical Oxisols, whilst preserving future soil fertility. Lower rates would allow sufficient yields in the short-term, but soil fertility might decline over time. Higher application rates will be partially wasted and even lead to a slight reduction in yields.

**Photo 3.** Difference in soybean maturation speed in the subplots that received K (+K) and in those that did not receive K (-K) after the last restriction cycle of the experiment. Photo by R.F. Firmano.

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**The paper "Long-Term Potassium Administration/Deprivation Cycles on Tropical Oxisol: Effects on Soil Fertility and Soybean Performance" also appears on the IPI website at:**

**Regional activities/Latin America**

# Research Findings

Photo by N. Cohen Kadosh. 2017.

## Polyhalite - A Multi-Nutrient Fertilizer Preventing Ca and Mg Deficiencies in Greenhouse Tomatoes under Desalinized Irrigation Water

Sacks, M.[1]*, S. Gantz[1], U. Mezuman[2], L. Peled[2], and P. Imas[3]

### Abstract

Greenhouse tomatoes (*Lycopersicon esculentum* Mill.) represent a highly sophisticated agriculture in which all plant requirements are accurately fulfilled and optimized in order to maximize yields and benefits to farmers. This includes balanced mineral nutrition applied through fertigation. Desalinated irrigation water lacks essential nutrients such as sulfur (S), calcium (Ca) and magnesium (Mg), and the incorporation of these to composite fertilizers used for fertigation is costly and, in some cases, impractical. Excess nitrogen (N) application, which often occurs as a result of organic manure supplementation, might reduce produce quality and is known to have serious ecological consequences. Polyhalite, a new mineral fertilizer consisting of S, potassium (K), Mg and Ca, offers an opportunity for pre-planting soil amendment and provides prolonged availability of these nutrients during the whole season. A case study was conducted to examine the effect of polyhalite

[1]Agricultural Extension Services, Ministry of Agriculture and Rural Development, Bet-Dagan, Israel
[2]ICL Haifa, Israel
[3]Chief Agronomist, ICL Fertilizers, Israel
*Corresponding author: molliesacks@gmail.com

at four levels: 0, 1, 1.5, and 2 Mg $ha^{-1}$, on the performance of on-farm greenhouse tomatoes. Polyhalite prevented Ca and Mg deficiency symptoms that occurred in the control, boosted plant vigor and increased the warm-season's marketable yield by 5-7%. Polyhalite can fully replace all other Ca and Mg liquid fertilizers. It can also provide 33% of the K dose, as well as N-free Mg, thus reducing K-Mg competition and avoiding surplus N nutrition. Given the primality of the present case study and the advantages observed, polyhalite appears as a considerable alternative to other fertilizers. Further research is required in order to combine an optimized polyhalite application with other fertilizer inputs in greenhouse tomatoes.

*Keywords:* Blossom-end rot; excess nitrogen; fertigation; *Lycopersicon esculentum* Mill.; polyhalite; potassium; sulfur.

## Introduction

In recent decades, the trend to produce fresh table tomatoes in greenhouses has steadily increased, resulting in greenhouse tomatoes becoming dominant in many vegetable markets around the world. Greenhouse tomato production has many advantages: it enables out-of-season production, thus extending supplier presence on the market shelves; it provides efficient plant protection, where open-field tomatoes are prone to harmful virus diseases distributed by insects; and productivity can be very high, reaching 18, 35, and even 50 kg $m^{-2}$ $year^{-1}$, in China (Qiu *et al.*, 2013), Israel, and in the Netherlands (FAO, 2014), respectively.

However, these high productivity levels necessitate corresponding fertilizer inputs (Jiang *et al.*, 2015). Thus, the application of high doses of chemical fertilizers, particularly nitrogen (N), is quite common practice among farmers to ensure high yields. For example, the seasonal average N input from chemical fertilizer increased during 1994-2004 in Shouguang, China, from 817 to 1,178 kg N $ha^{-1}$, three to five times more than plant requirements (Song *et al.*, 2012). Consequently, N recovery efficiency in such systems drops to below 15%, indicating that most applied chemical fertilizer is either washed out of the root zone or lost to the atmosphere and groundwater by different pathways (Min *et al.*, 2012).

Soil organic matter is one of the important soil components, and has a significant role in greenhouse vegetable production. It is widely believed that soil quality declines when soil organic carbon (OC) is below 20% (Loveland and Webb, 2003). Intensive use, high temperature and humidity accelerate the mineralization of soil organic matter, reducing soil OC (Grandy and Robertson, 2007). Composted animal manure is widely used for soil amendment. On loose soils, it significantly improves soil structure and water retention and assists the build-up of soil nutrient reserves (Xin *et al.*, 2016). Manure application can restore soil microbial community diversity and improve the rhizosphere microenvironment (Zhen *et al.*, 2014). Furthermore, poultry manure has shown significant ability to decrease parasitic nematode problems (Thoden *et al.*, 2011).

Appropriate irrigation management is essential for maximizing crop yield, fertilizer and water use efficiency for vegetable production. Drip irrigation combined with optimized fertilization can accurately control the timing and amount of irrigation and reduce fertilizer losses (Tanaskovik *et al.*, 2011; Fan *et al.*, 2014). The use of composite liquid fertilizers enables, in most cases, the matching of temporal application to current demands of most mineral nutrients. Nevertheless, reliance on fertigation requires special consideration of the irrigation water quality in terms of electrical conductivity (EC) as a measure of salinity, water pH, and the presence of essential mineral nutrients. In recent years, desalinated sea water has been a primary source for irrigation water in many regions in Israel. This water lacks mineral nutrients, particularly calcium (Ca), magnesium (Mg), and sulfur (S) that are essential for plant growth and development.

Magnesium deficiency impairs plant hormonal balance, interrupting signal transduction and causing sugar accumulation in productive leaves that consequently reduces photosynthesis through a negative feedback inhibition (Gransee and Führs, 2013; Verbruggen and Hermans, 2013). Sulfur (S) is recognized as the fourth major plant nutrient after N, phosphorus (P), and potassium (K) (Khan *et al.*, 2005) and has been associated with high productivity (Zhao *et al.*, 1999; Saito, 2004; Kovar and Grant, 2011). Sulfur is essential for protein synthesis so often interacts with N to significantly enhance crop productivity (Jamal *et al.*, 2010). *Solanaceae* crop species, including sensitive tomato cultivars, may express typical Ca deficiency symptoms such as yellowish leaves and increasing rates of fruit blossom-end rot (BER) (Fig. 1) with a consequent reduction in marketable yields (Gleason and Edmunds, 2005; Ho and White, 2005; Mestre *et al.*, 2012). Due to considerable differences in solubility, interactions with other solutes or high cost, application methods other than fertigation may be considered for Ca, Mg, and S.

Polyhalite, a new mineral fertilizer (Polysulphate™), mined in the UK from deep underground. It contains four important plant nutrients: S ($SO_3$, 48%), K ($K_2O$, 14%), Mg (MgO, 6%), and Ca (CaO, 17%), marketed in powder or granular form. It is suitable for a broad range of crops including open-field and greenhouse vegetables. Polyhalite has a low environmental impact as its production processes involve only mining, grinding, screening and packaging. Polyhalite, as Polysulphate, has been authorized for organic agriculture and is available in an increasing number of countries such as Brazil, Canada, China, France, Germany, Italy, the Netherlands, UK and the USA. Polyhalite gains special importance where Ca, Mg, and S are available at levels lower than the minimum threshold securing normal crop development. The

**Fig. 1.** Blossom-end rot (BER) in tomato - a typical physiological disorder resulting from Ca deficiency. Photo by A. Bustan. 2009.

fertilizer is available to plant roots as it is easily, though steadily, dissolved into the soil solution upon irrigation. Polyhalite provides S in the form of sulphate, which is available to plants without any need for breakdown by microorganisms. However, the fertilizer is not suitable for fertigation, so in this case study it is applied as a pre-planting fertilizer.

Modern intensive agriculture offers farmers a wide range of practices and opportunities to increase production and benefits. Nevertheless, employing this arsenal is often quite complex and requires flexibility/responsiveness to changing circumstances. The optimization of mineral nutrition during the cropping season is particularly sensitive to local soil fertility, fertilizer choice and application regime, as well as irrigation water quality. In the case study presented, the potency of polyhalite applied as a pre-planting fertilizer to prevent typical Ca and Mg deficiencies and to ensure considerable yield and produce quality was examined in the context of farmer's practice in winter season (September to June) greenhouse tomatoes in Israel.

## Materials and methods

The observation was carried out in a farmer's greenhouse on light to medium sandy loam soil (cation exchange capacity [CEC] - 15 meq 100 $g^{-1}$ soil) in Beit-Ezra, located in the coastal plain of Israel. The greenhouse size was 0.8 ha with 0.25 ha used for the trial. The soil was solarized before and during eight weeks after a chemical disinfection (Dichloropropene and Metam sodium, 200 and 400 L $ha^{-1}$, respectively, with 40 mm of irrigated water) took place. A pre-planting organic fertilizer (40 $m^3$ $ha^{-1}$ chicken manure [250 kg $m^{-3}$, 85% dry weight] containing 3.0, 1.4, 2.1, 1.2, 0.3, and 0.3% of N [organic form], P, K, Ca, Mg, and S, respectively) was applied to the entire area to prevent nematodes. Before planting, the soil was irrigated with 70 mm water. Polyhalite fertilizer was spread and embedded along the planting rows according to treatments (Table 1).

Cluster tomato (cv. Ikram, Zeraim Gedera Syngenta, Ltd., grafted on Arnold rootstock) seedlings were planted on 11 Sep 2016, at a density of 22,000 branches $ha^{-1}$. Desalinated water (650 mm during the season, with an $EC_w$ range of 0.35-0.45 dS $m^{-1}$, and with Ca, Mg, and Cl concentrations of 35-40, 1-5, and 45 ppm, respectively) was used for irrigation. Liquid fertilizer Sarit Super 5-2-7+0.5+6 (N-P-K + microelements) were applied through fertigation at about 1.5 L $m^{-3}$.

The observation included four treatments: control - where no additional polyhalite was applied; $PS_1$, $PS_2$, and $PS_3$, where 1,000, 1,500, and 2,000 kg polyhalite $ha^{-1}$, respectively, was applied pre-planting (Table 1).

The plants were monitored visually. Plant vigor was evaluated by measurements of stem diameter below the uppermost inflorescence. Soil and diagnostic leaves were sampled and analyzed for nutrient content every two months. Marketable fruit yield was weighed and summarized weekly.

## Results

Plant establishment and growth were normal. However, symptoms of Mg

**Table 1.** Nutrient supply vs. anticipated requirements of greenhouse tomatoes under four polyhalite treatments: $PS_0$ (Control), $PS_1$, $PS_2$, and $PS_3$.

| Treatment | | Nutrient | | | | |
|---|---|---|---|---|---|---|
| | | N | $P_2O_5$ | $K_2O$ | CaO | MgO |
| | | *kg ha⁻¹* | | | | |
| | Fertigated nutrients | 580 | 100 | 720 | 350 | 70 |
| | Basal application (chicken manure) | 255 | 119 | 178.5 | 102 | 25.5 |
| $PS_0$ (Control) | Polyhalite 0 kg $ha^{-1}$ | 835 | 219 | 898.5 | 452 | 95.5 |
| $PS_1$ | Polyhalite 1,000 kg $ha^{-1}$ | 835 | 219 | 1,038.5 | 622 | 155.5 |
| $PS_2$ | Polyhalite 1,500 kg $ha^{-1}$ | 835 | 219 | 1,108.5 | 707 | 185.5 |
| $PS_3$ | Polyhalite 2,000 kg $ha^{-1}$ | 835 | 219 | 1,178.5 | 792 | 215.5 |
| | Calculated crop nutrient requirements | 550 | 110 | 660 | 350 | 110 |
| | Primary excess nutrient supply (in $PS_0$) | 285 | 109 | 238.5 | 102 | -14.5 |

deficiency, expressed as typical yellowing of lower leaves, occurred in the control plants as early as mid-November, two months after planting. Plants applied with polyhalite remained green, healthy, and properly functioning (Fig. 2). Minor Mg deficiency symptoms were also observed among plants fertilized with polyhalite at the beginning of harvest in mid-December 2016. In February, after the regular practice of intensive removal of old leaves had taken place, the symptoms disappeared completely among polyhalite treatments, while only slight signs could be observed in control plants. Clear Mg deficiency symptoms returned in the lower leaves of control plants as the weather warmed up during the spring, whereas similar signs were absent among the polyhalite plants.

At the end of May, the polyhalite plants seemed more vigorous than the control plants. Measurements of the stem diameter below the uppermost inflorescence showed that control stems were significantly thinner than those of polyhalite plants (Fig. 3).

Harvest began on 5 Dec 2016 when early fruit clusters were ripe. During the winter months, no differences between treatments were observed, and the accumulating yields averaged 130 Mg ha$^{-1}$ at the end of March 2017. Nevertheless, from April to the end of the season on 18 June 2017, the marketable control yield was consistently lower than those of the polyhalite treatments (Fig. 4). At the end of the season, the marketable yields of the polyhalite treatments were higher than the control yield by 5-7% (Table 2). This advantage was obtained due to the reduced rates of fruit malformation and BER in the polyhalite treatments.

Soil analyses conducted during the season showed a considerable increase in Ca, Mg, K, and S, in accordance with polyhalite applications (Fig. 5). High soil sulphate levels did not affect soil pH, which was stable at 7.4 throughout the experiment

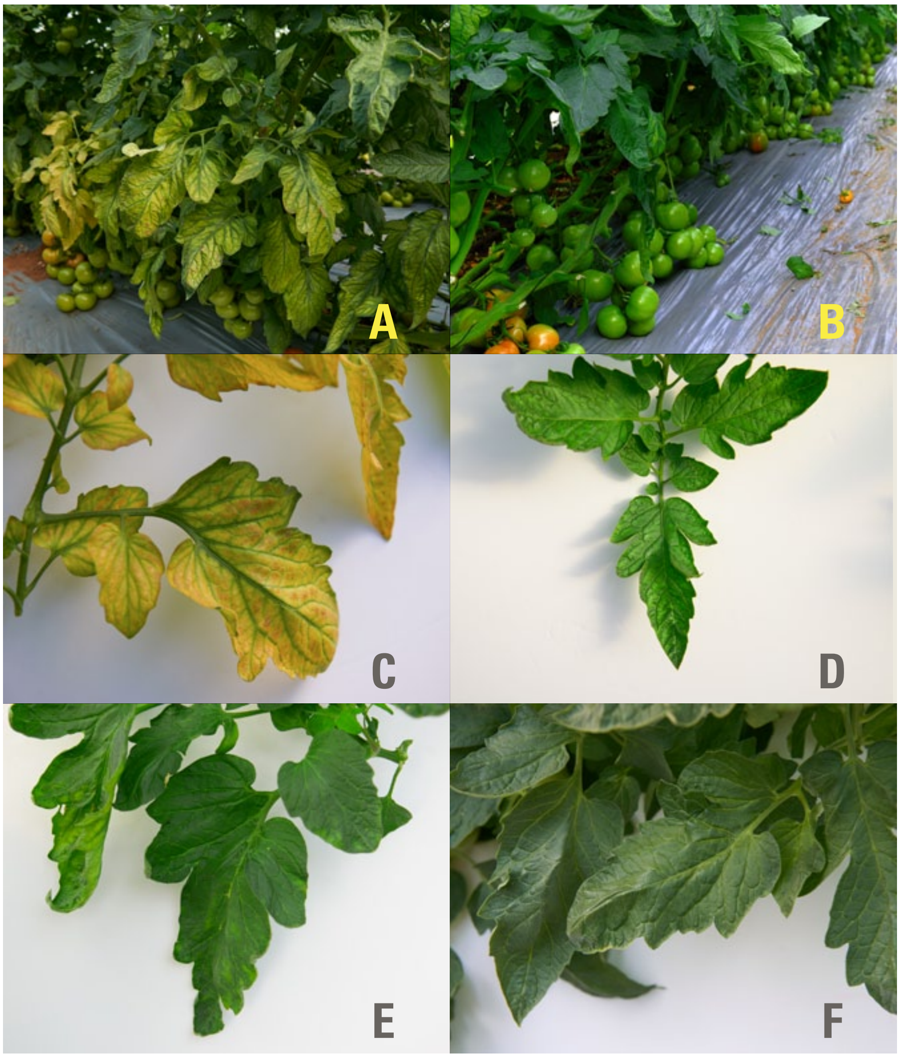


**Fig. 2.** Magnesium deficiency symptoms in tomato leaves, as noticed on 11 Jan 2017. A, Control plants; B, $PS_2$ (polyhalite at 1,500 kg ha$^{-1}$) plants; C, D, E, and F, representative leaves sampled from Control ($PS_0$), $PS_1$, $PS_2$, and $PS_3$ plants, respectively.

**Table 2.** Effects of pre-planting polyhalite application on yield distribution between winter and spring periods.

| | Pre-planting polyhalite rate (kg ha$^{-1}$) | | | |
|---|---|---|---|---|
| | 0 | 1,000 | 1,500 | 2,000 |
| Harvest period | Accumulating marketable yield (Mg ha$^{-1}$) | | | |
| December - March | 129 | 133 | 128 | 133 |
| April - June | 88 | 97 | 103 | 95 |
| December - June (total) | 217 | 230 | 231 | 228 |

in all treatments. While Ca levels remained at the optimum range, Mg and K concentrations were too high. Also, the proportions of Mg and K in the CEC were higher than the optimum (data not shown). Potassium availability was high among all treatments throughout the growing season. Soil levels of all nutrients were

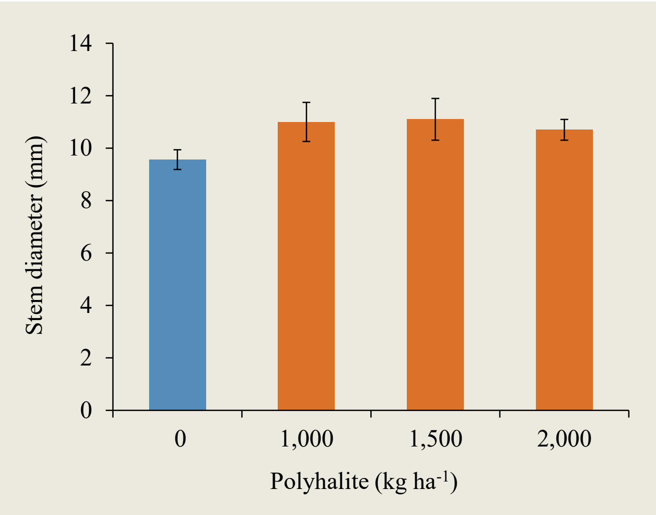


**Fig. 3.** Tomato stem diameter below the uppermost inflorescence on 23 May 2017 as influenced by pre-planting application of polyhalite.

high in September, decreased in November, rose again during January, and steeply declined in June (excluding P), manifesting the seasonal dynamics of crop nutrient uptake. Interestingly, Mg leaf content was lower than the optimum among all treatments throughout the growing season, while all other nutrients were within the sufficiency range.

## Discussion

When optimum mineral nutrition is considered, two goals should be reached: 1. supplying adequate levels of available nutrients throughout the growing season; and, 2. maintenance of balanced cation saturation ratios in the soil solution. Winter greenhouse tomatoes require no less than 550, 110, 660, 350, and 110 kg ha$^{-1}$ of N, P, $K_2O$, CaO, and MgO, respectively, in order to produce a yield of about 350 Mg ha$^{-1}$. In the present study, the crop was sufficiently supplied with N, P, K, and Ca through fertigation alone throughout the growing season (Table 1). The basal application of chicken manure, which aimed to reduce nematode problems, significantly increased all nutrient doses far beyond requirements, however, its real contribution to crop nutrition was unclear. Even though, pre-planting polyhalite application prevented visually determined Mg deficiencies that usually occur during rapid growth periods of greenhouse Ikram cluster tomatoes. Polyhalite application promoted plant vigor, as expressed in stem diameter (Fig. 3), and brought about a 5-7% increase in marketable yield (Fig. 4). On the other hand, the excess soil nutrient levels, particularly of K, might have interrupted Mg uptake due to the imbalanced ratio between those cations in the CEC fraction (data not shown).

Excluding the waste of resources associated with excess N supply, it has additional significant adverse consequences. Excess N supply interrupts the C/N balance in the plant, promoting excess vegetative growth at the expense of reproductive organs. Excess N also reduces fruit firmness, Brix, nutritional value, and storability (Bénard *et al.*, 2009). Furthermore, tomato plants grown under excess N levels are more susceptible to physiological disorders such as BER (Gleason and Edmunds, 2005) and to leaf-miner pests (Han *et al.*, 2014). Much effort is being made in Israel and worldwide to halt and prevent the harmful ecological consequences of excess fertilization on water and soil resources (Min *et al.*, 2012; Jiang *et al.*, 2015).

Potassium availability is essential throughout the season, particularly for greenhouse tomatoes, where indeterminate cultivars are employed and the reproductive phase prevails during most of the crop cycle. High K availability may reinforce crop

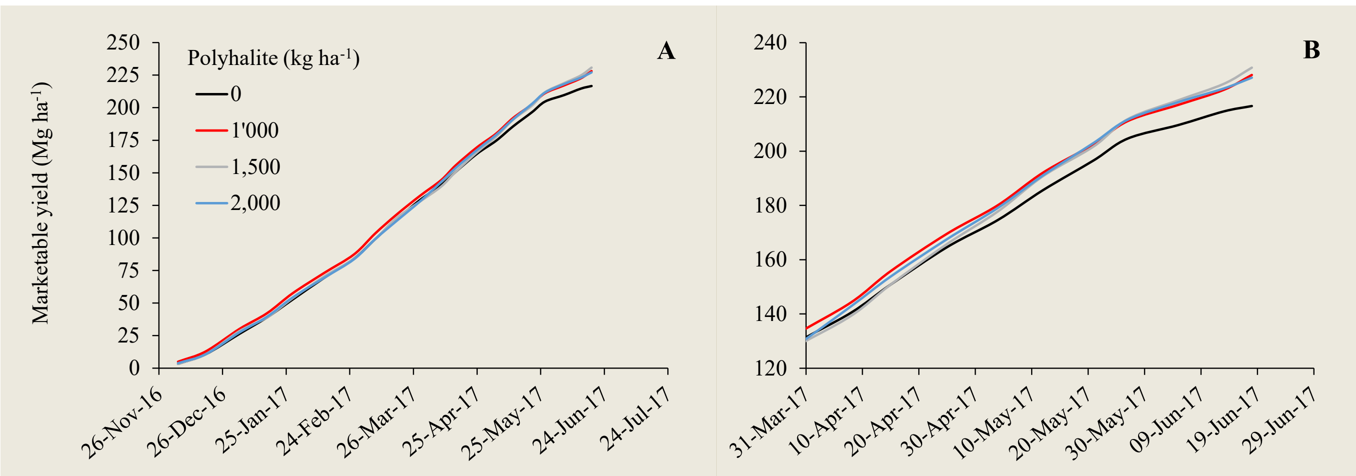


**Fig. 4.** Effects of pre-planting polyhalite application on the accumulating marketable yield of Ikram greenhouse tomatoes throughout the season (A), and during spring (B) (from April to June).

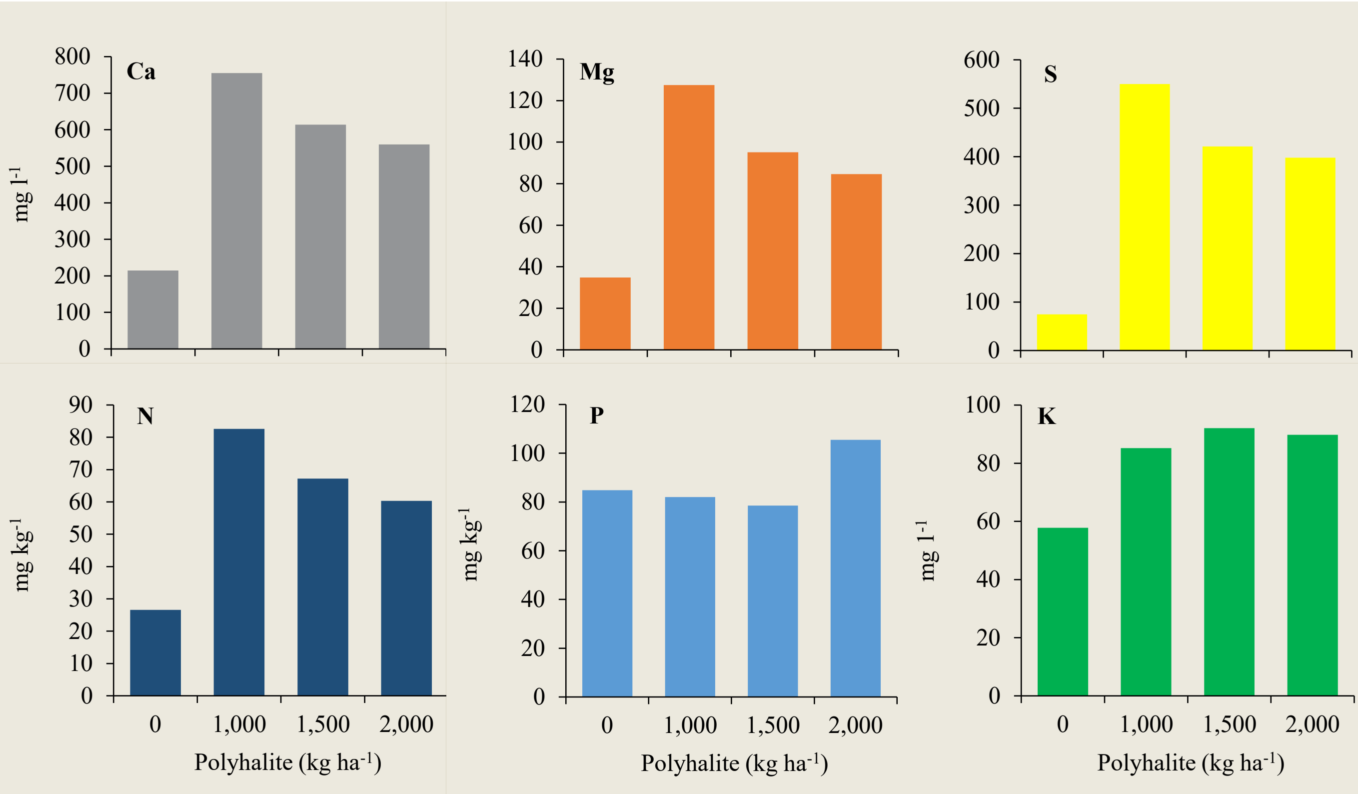


**Fig. 5.** Soil content of N, P (mg kg-1), and K, Ca, Mg, and S (mg 1-1) on 16 Feb 2017; five months after planting.

resistance to high temperature and drought stresses (Wang *et al.*, 2013) that often occur during the transition seasons in the Middle East. However, K is commonly accompanied by chloride (KCl), which above a certain low optimum range, might have adverse effects on tomato yield and quality (Komosa and Górniak, 2015). Alternatively, K can be applied with nitrate, avoiding excess chloride uptake, although this solution is less useful when reduced N uptake is desired. Thus, a constant in-soil source of prolonged release K would be an ideal choice. In fact, applying the required Ca and Mg via fertigation is costly, hence, these two nutrients should preferably be applied directly to the soil.

The opportunity of replacing large amounts of costly liquid fertilizer with a basal application of polyhalite is very promising. It enables the application of Ca and Mg at the pre-planting stage, with no need for additional application during the growing season. This is especially important where the irrigation water lacks these essential nutrients. Polyhalite can provide 33% of the K dose, as well as N-free Mg, thus reducing K-Mg competition and avoiding surplus N nutrition. Given the primality of the present case study and the advantages observed in yield and produce quality during the warmer phase of the growing season, polyhalite appears as a considerable alternative to other fertilizers. Further research is required in order to combine an optimized polyhalite application with other fertilizer inputs in greenhouse tomatoes and hence enhance the benefits to the grower.


## Acknowledgement

We thank Mr. Rahamim Gabai, the tomato grower, for his abundant cooperation in carrying out this trial.


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**The paper "Polyhalite - A Multi-Nutrient Fertilizer Preventing Ca and Mg Deficiencies in Greenhouse Tomatoes under Desalinized Irrigation Water" also appears on the IPI website at:**

**Papers and Presentations**

# Events

August 2017


**Photo 1.** The Andersen Parade, a musical performance of the famous children's stories by Hans Christian Andersen, at the opening ceremony of the 18th IPNC 2017 (Tivoli Centre in Copenhagen, Denmark). Photo by M. Nikolic.

## International Plant Nutrition Colloquium 2017, Copenhagen, Denmark: A Conference Report

Kirkby, E.A.[(1)*], and M. Nikolic[(2)]

### Introduction

The 18th International Plant Nutrition Colloquium (IPNC) took place from 21-24 August 2017, at the magnificent Tivoli Centre in Copenhagen under the capable direction of Professor Jan Schjøerring and colleagues from the University of Copenhagen's Department of Plant and Environmental Sciences. The conference opened on the morning of 21 August 2017 with welcoming speeches from Professor Schjøerring and Thomas Bjørnholm, the University's Pro-rector for research, which was followed by the Hans C. Andersen Parade (Photo 1).

From its inception in the early 1950s, the IPNC, held every four years at a different venue, has become the most important international meeting on fundamental and applied plant nutrition. The main theme of the 18th IPNC was *Plant Nutrition for*

[(1)]Faculty of Biology, University of Leeds, UK
[(2)]Institute for Multidisciplinary Research, University of Belgrade, Serbia
*Corresponding author: eakirkby@yahoo.co.uk

*Global Green Growth* with this theme chosen to highlight the fundamental role of plant nutrients for successful intensification of global crop production.

The event was attended by close to 600 participants from more than 50 countries and was held in conjunction with two satellite meetings on Boron and Manganese, which took place prior to the colloquium itself with around 150 delegates. The colloquium, which was attended by many world authorities, provided an excellent forum for the exchange of knowledge and ideas leading to future collaboration in the fields of plant mineral nutrition, plant molecular biology, plant genetics, agronomy, horticulture, ecology, environmental sciences and fertilizer use. It was also, of course, an opportunity to meet up with old plant nutritionist friends and make new ones.

One of the most attractive features of the colloquium was the Marschner session: *Nurturing the Future* and the award ceremony in which winning young scientists presented their achievements in plant nutrition. Award winners included: Muneta Grace Manzeke from Zimbabwe, who presented on "Role of soil micronutrients and fertilizer management in crop nutrition under variable smallholder cropping"; Kengo Yokosho from Japan, "Identification of transporters involved in metal stress tolerance in plants"; Patrick E. Hayes from Australia, "Proteaceae from severely impoverished habitats preferentially allocate phosphorus to photosynthetic cells"; and Kristian Holst Lauren from Denmark, "Multi-dimensional stable isotope analysis - A novel tool in plant nutrition".

The large and ever increasing number of papers published on various aspects of plant nutrition means that a wide range of topics were included in the colloquium oral and poster presentations, which were divided into ten main themes:

1) Plant-microbe interactions and nutrient acquisition
2) Nutrient functions in plants
3) Nutrient management and fertilizers
4) Nutrient uptake, transport and homeostasis
5) Nutrient availability in soils, toxicity and remediation
6) Roots and genetics of crop nutrient uptake
7) Plant nutrition and food quality
8) Nutrient cycling, ecosystems and climate change
9) New analytical techniques in plant nutrition
10) Novel technologies for fertilizers

The colloquium proceedings of oral and poster presentations, together with those of the Boron and Manganese satellite meetings total just under 1,000 pages of text. Professor Schjøerring and his local organizing committee are to be congratulated for producing the publication in an electronic form, which can be accessed by readers at www.ipnc2017.org. Additionally, the organizers developed an innovative and very useful IPNC application available in the *App Store* and *Google Play*, which resulted in a significant reduction in paper and contributed to the environmental credentials of the colloquium.

To produce a publication relevant for the International Fertilizer Correspondent (*e-ifc*) from the IPNC text of over a 1,000 pages has inevitably meant it is necessary to omit certain sections completely and to be highly selective with the rest. We have only been able to scratch the surface but hope that our short contribution will, at least, provide a flavor of the meeting to whet our readers' appetites to consult the original proceedings and, particularly, the plenary keynote papers which can be accessed as described above. In citing the publications in the *e-ifc* text, plenary papers are denoted simply by the year 2017, whereas the addition of 'O' and 'P' indicates an oral or poster presentation, respectively.

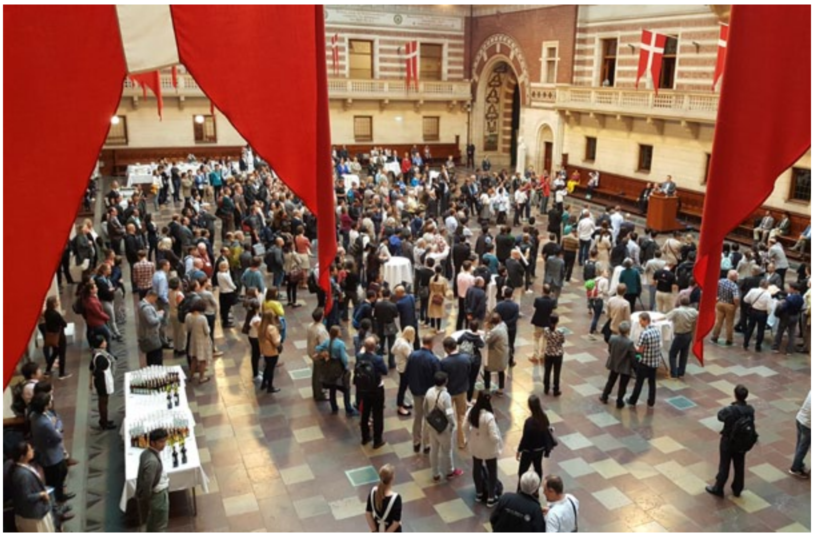


**Photo 2.** Welcome reception in the City Hall hosted by the City Council of Copenhagen. Photo courtesy of J.K. Schjøerring.

The IPNC organizers are to be congratulated on providing an excellent social program, which included a reception in the City Hall hosted by the City Council of Copenhagen on 21 August 2017 (Photo 2) and a canal boat trip via the famous Little Mermaid (Photo 3) to the conference dinner at the Langelinie Pavillonen on 23 August 2017.

### Plant-microbe interactions and nutrient acquisition

Plant roots co-exist in association with microorganisms that constitute the soil-plant microbiome. The plenary keynote of Richardson *et al.* (2017) focused on exploitation of the plant-root microbiome in enhancing the availability of key macro- and micronutrients to plants. The authors presented some examples of successful interactions between roots and microorganisms, such as rhizobia's symbiotic association with legumes for N fixation and P acquisition through mycorrhizal associations. The authors highlighted the importance of microbiome-based approaches that allow comprehensive functional assessment of soil, rhizosphere and root-associated communities using high throughput sequencing techniques. Development of management practices to promote more beneficial microbiomes, such as crop rotation, selection of favorable microbial consortia, or even selection of crop germplasm more readily able to associate with beneficial microbiomes, are of great importance, in particular for low-input agriculture.

Neumann (2017, O1-1) presented the main results of the EU-integrated BIOFECTOR project (www.biofector.org) aiming to reduce the application of mineral fertilizers in European agriculture using microbial and non-microbial bio-effectors (BEs).

**Photo 3.** The Little Mermaid sculpture at the Langelinie promenade in Copenhagen, Denmark. Photo by E.A. Kirkby.

According to the large data set analyzed, high soil fertility was frequently considered a limiting factor for efficient application of BE on agriculture soils (Lekfeldt *et al.*, 2017, O1-7; Neumann, 2017, O1-1). The challenge therefore is to define the soil conditions and identify the management practice for improved integration of BE into agricultural practice.

The current increase in crop yields mainly depends on nitrogen (N) and phosphorus (P) fertilizer application, whereas sustainable approaches require high yields with lower environmental cost. In this regard, the plenary keynote paper of Chen and Liao (2017) introduces the importance of nodule P status for biological $N_2$ fixation in soybean with a pivotal role of high-affinity inorganic P (Pi) transporters (GmPT5 and GmPT7) for controlling Pi transfer from host roots to nodules. The molecular study of de Bang *et al.* (2017, O1-5) provided novel information on the role of small-secreted peptides (SSP) in legume nodulation and adaptation to macronutrient - N, P, potassium (K), sulfur (S) - stress, highlighting the diversity of SSP genes in legumes and their impact on legume-rhizobia symbiosis.

Root exudation of organic anions and phosphatases are the important mechanisms for soil P acquisition in many plant species. However, the benefits of these two exudates are often limited due to their interactions with soil, so it is important to consider space and time close to the P uptake zone (Giles *et al.*, 2017, O1-6). Therefore, strategies that enhance both the distribution and concentration of exudates will be needed, which require spatial and temporal orchestration to achieve their positive complementarity through selection or transgenic approaches, or by close intercropping of plants with a strong expression of traits.

Arbuscular mycorrhizal fungi (AMF) form a symbiotic association with approximately 80% of all known terrestrial plant species including many important agricultural crop species. AMF's role is most remarkable under low P conditions. However, microbes and their metabolites responsible for AMF suppression are unknown. Cruz-Paredes *et al.* (2017, O1-3) presented preliminary results of their ongoing work on AMF suppression by unsterile soil and isolation of AMF suppressive microorganisms and identification of the metabolites responsible for this suppression. Furthermore, using tomato mutant reduced mycorrhizal colonization unable to form associations with AMF, Watts-Williams *et al.* (2017, O1-4) demonstrated the importance of AMF symbiosis for increased zinc (Zn) content in tomato grown on low Zn soil, but with less benefit as soil Zn concentration increased. The acquisition of Zn essential for symbiotic $N_2$ fixation was investigated by Abreu *et al.* (2017, P1-1) in the legume, *Medicago trunculata*. The authors provided evidence that Zn is transported through vascular bundles to the apoplast of the nodule's apical zone and proposed a model of Zn acquisition by rhizobia-infected legume cells mediated by a Zn-iron (Fe) permease (MtZIP6). The beneficial influence of a plant nutrient in stimulating SNF may not only be a direct one. In fact, Peng *et al.* (2017, P1-22) investigated soybean nodulation in water culture experiments comparing increasing magnesium (Mg) supply from extremely low to adequate values. Nodulation was greatly retarded by low supply but neither the Mg concentration nor nitrogenase activity of the nodules was affected. The authors suggest that nodule growth was probably depressed because Mg deficiency decreased carbohydrate transport from shoots to roots.

### Nutrient functions in plants

White *et al.* (2017) discussed the plant ionome defined as the elemental composition of a subcellular structure, cell, tissue or organism, which includes all mineral elements, whether essential or non-essential for life, in whatever chemical form they occur. The functional ionome - and this forms the basis of plant nutrition - comprises the subset of these mineral elements that are essential for plants, which includes the macronutrients N, P, K, calcium (Ca), Mg and S, and the micronutrients chlorine (Cl), boron (B), Fe, manganese (Mn), copper (Cu), Zn, nickel (Ni) and molybdenum (Mo). Additionally there is interest in some elements including cadmium (Cd) and arsenic (As), which can accumulate in plants but are toxic to man.

**Potassium** is a major plant nutrient involved in the crop metabolism, growth, development, yield and quality. It activates numerous enzymes in the cytoplasmic pool including those that control carbohydrate and protein metabolism; the fixation of carbon dioxide ($CO_2$) in photosynthesis; and nitrate assimilation by plants. Potassium in the vacuole plays a key role in water relations in the maintenance of turgor and control of stomatal movement. It is also essential in the regulation of cell growth. In the process of photosynthesis, K functions directly or indirectly at various stages including light interception, $CO_2$ availability and chlorophyll synthesis. $K^+$ is the predominant cation in plants and functions in ionic form in nitrate transport from root to shoot, as well as the loading of assimilates (sucrose and amino acids) into the phloem and their transport to fruit and storage organs. Crops well supplied with K are more resistant to stresses, both biotic (e.g. pest attack) and abiotic (e.g. drought, cold and salt stress). K and N interact in the physiological and biochemical processes described above and are taken up by crops in relatively similar amounts. Appropriate nutrient balanced fertilizers should be applied in order to obtain high quality yields.

Valuable new findings were reported at the colloquium including the need to increase K application to prevent frost damage in wheat in the West Australian grain belt, which was discussed by Bell and Ma (2017, O2-4). Low K in topsoils and subsoils is common and frost is increasing in frequency and severity during spring coinciding with the young microspore stage of pollen development. Current K fertilizer rates on these low K soils are generally too low to meet the various demands for replacing K removal, i.e. increasing soil K to safe levels, meeting demand for high yield crops and achieving ongoing crop protection against stress. Tavakol *et al.* (2017, O2-1) concluded that K supply under osmotic stress in barley mitigated photo-oxidative damage mainly via improved photosynthesis and avoiding reactive oxygen species generation rather than high antioxidant activity. Optimizing K nutrient status under osmotic stress recovered most of the pathway changes back to control conditions.

Root uptake of K is affected by various soil and plant factors. Plasma membrane bound $H^+$-ATPase activity is required for effective K uptake by roots; the enzyme generates a membrane potential gradient across the plasma membranes which contributes greatly to root uptake. On the other hand, B plays an essential role in maintaining membrane integrity. In keeping with these concepts, Ceylan *et al.* (2017, P4-9) reported impaired root growth of canola (oilseed rape) at low B supply. By contrast, plants grown with adequate B had higher root and shoot concentrations of K compared to plants with low B. The authors stress the need to maintain an adequate B supply to ensure a better response to K fertilization and suggest the use of K fertilizer containing B as an agronomic approach to avoid B deficiency.

**Magnesium** deficiency symptoms are commonly observed in agricultural crops with inadequate Mg fertilization leading to yield depression. It is well established that Mg deficiency induces a reduction in sucrose transport from source leaves to roots. In a study of Mg deficiency in maize, however, Jung *et al.* (2017, O2-5) demonstrate for the first time that reduced apoplastic acidification, brought about by changes in the plasma membrane $H^+$-ATPase, is the primary cause of limited plant growth. Macronutrient cations K, Ca and ammonium ($NH_4^+$) compete for uptake with Mg, their effectiveness depending mainly on their concentrations in the root vicinity. In the volcanic ash soils (Andisols) of the southern Chilean grasslands, high winter rainfall solubilizes bases which increases soil acidity. This in turn releases toxic amounts of Mn, while simultaneously decreasing the availability of Mg, which favors the competitive uptake of Mn (Reyes Diaz *et al.*, 2017, P2-20).

**Sulfur** interaction with N and the negative effect of S starvation on N use efficiency (NUE) was studied by Garcia-Mina *et al.* (2017, O2-7) in wheat plants. Shoot nitrate transport was depressed and consequently so too further N metabolism in the leaves leading to a decrease in leaf concentration of active cytokinins. S deficiency led to substantial accumulation of molybdate in both roots and shoots as might be expected to compensate for the anion deficit as has been previously reported. This example of imbalanced fertilization between N and S is also frequently seen between N and K, where inadequate K supply inhibits N uptake and metabolism, and is of very practical importance in limiting crop production.

**Silicon** (Si) is the second most abundant mineral element in the soil and, although not yet generally accepted as an essential element for higher plants, its beneficial effects in the alleviation of various abiotic and biotic stresses have been extensively demonstrated. In addition to two plenary keynote presentations on recent progress in Si transport in rice (Ma and Yamaji, 2017) and Si-mediated transport of other mineral elements (Nikolic *et al.*, 2017), Si pre-treatment was shown to delay N mobilization and senescence processes in the mature leaf of N-deprived canola plants (Arkoun *et al.*, 2017, P2-4). On the other hand, Si addition was effective in mitigation of $NH_4^+$ toxicity in passion fruit (*Passiflora edulis*), as demonstrated by increased NUE and greater plant growth responses (Prado *et al.*, 2017, P2-7). Also Si application was effective in mitigation chilling stress in maize which was mainly attributed to increased distribution of Zn and Mn to the leaf thereby enhancing antioxidant defense (Moradtalab *et al.*, 2017, P2-16). Hosseini *et al.* (2017, O2-6) highlighted the beneficial importance of Si nutrition in maintaining photosynthesis activity under concomitant drought and K deficiency in barley, a Si-accumulating species. In intact ryegrass plants, Si lowered aluminium ($Al^{3+}$) concentration and increased Si uptake by up-regulating root Si transporter genes (Lsi1 and Lsi2) (Pontigo *et al.*, 2017, P4-40). Moreover, Si supply enhanced shoot lignin accumulation in barley plants subjected to Al toxicity (Vega *et al.*, 2017, P7-25). Furthermore, Hinrichs *et al.* (2017, P2-12) demonstrated that Si addition increased the gene expression related to lignin metabolism in rice roots thereby promoting formation of the Casparian band and its barrier functions for radial oxygen loss and elevated Fe uptake. More practically, the use of stabilized monosilicic acid as a Si source for both foliar sprays and fertigation was superior in increasing stress tolerance, growth, yield and quality parameters of various crops such as wheat, cucumber, pepper, tomato, grapes and cardamom (Lanne, 2017, O5-4).

### Nutrient management and fertilizers

In the plenary presentation, McLaughlin *et al.* (2017) highlighted the markedly different patterns of nutrient usage over the past 50 years on a global scale as measured by P consumption from data from the International Fertilizer Industry Association. In developed countries, usage has decreased greatly, whereas in developing countries, such as Latin America, usage continues to increase. Continued increases in fertilizer use are required to close yield gaps. Almost 75% of global areas are not achieving potential yields of staple crops of maize, wheat and rice so fertilizers must be used more efficiently. By marked contrast, Africa has had very low fertilizer usage over the same period. In terms of responses to mineral fertilizer application, Giller (2017) refers to Africa as the plant nutritionist`s paradise because, on these old highly weathered soils, deficiencies of virtually all essential plant nutrients can be found and studied in the field.

One of the major challenges facing *Plant Nutrition for Global Green Growth* as discussed by McLaughlin *et al.* (2017) and Fixen (2017) is the exponential growth of world population. Currently at about 7.6 billion, the global population is expected to reach almost 10 billion by 2050, which means that global green growth must be sufficient to produce more food in the next 50 years than in all human history (Fixen, 2017). This author also draws attention to the difficulties in achieving this aim because of the added pressures of climate change, water insecurity, land use changes and soil degradation. The impact of human conflict may also be added to this list. From lifetime experience in the fertilizer industry, Fixen (2017) also points out that available guidance and nutrient recommendations to farmers are still largely empirical rather than mechanistic.

The use of mineral fertilizers, especially N, are essential for the increase in crop production necessary to meet future food demands. While N is not a limiting nutrient, as it can be fixed from the atmosphere either chemically or biologically, its use has to be carefully monitored because that which is not utilized by the crop can act as a major pollutant by inducing nitrate leaching from the soil, releasing nitrous oxide ($N_2O$) into the atmosphere contributing to greenhouse gas emissions, as well as the release of ammonia ($NH_3$) into the atmosphere. These polluting, well-known effects associated with high N fertilizer usage have been observed in China for example since the 1980s. The world also has large reserves of K which is required by crops in similar amounts to N, but unlike N is harmless to the environment. Phosphorus is the most limiting of the three major plant nutrients in terms of world reserves and the need for its efficient recycled use has long been recognized.

Fertilizer efficiency may be measured in various ways (McLaughlin *et al.*, 2017) but, in terms of nutrient removal by crops over a single growth season, the values for N, P and K are generally $<50\%$ with micronutrients much lower at $<5\%$. Following application, residual effects benefiting crops in subsequent years may be long-lasting, but not in the case of N, S and B which are easily lost from the soil. Aguirre *et al.* (2017, P3-22) in Germany reported field trial experiments with winter wheat in which the efficiency of urea, the dominant form of N used worldwide, was substantially improved by the addition of the new urease inhibitor (2-NPT) to urea fertilizer. This treatment successfully inhibited urea hydrolysis as shown by soil analysis and, due to lower $NH_3$ losses, significantly increased crude protein content and N uptake compared to urea alone. Less spectacular but positive results were obtained by Syed Shah *et al.* (2017, P3-68) in field experiments in the UK, which compared the effects of urea treated with a nitrification inhibitor and urease (UTr) with urea and ammonium nitrate (AN). With a single application of 120 kg $ha^{-1}$, UTr outperformed urea and AN in yield of spring barley averaged over two years and lower yields were obtained for three growing seasons by urea compared to plots treated with UTr. The absence of any significant differences between treatments for winter wheat was attributed to differences in the rooting systems, and growth stages of the two crops at the time of fertilizer application and effects of high rainfall intensity. Other than inhibitors, coatings and less soluble matrices can be used to slow down the rate of release of N from granules.

How much N to apply and when to apply it to benefit the crop without detriment to the environment has long concerned farmers. A valuable and sophisticated contribution to the colloquium in this respect was presented by Leibisch *et al.* (2017, O3-4). These researchers set up a randomized field trial on a commercial sugar beet field with treatments with increasing N supply taking into account soil available N. At harvest, sugar beets were sampled and yield and quality parameters established. Spectral reflectance on ground (proximal) was measured and aerial image spectroscopy was realized. The results obtained confirmed the applicability of spectral proximal and remote sensing techniques to allow the quantification of N fertilizer demand in sugar beet.

The enormous benefits to practical agriculture in Turkey of the long-term research association between the International Potash Institute (IPI) and the University of Ege was discussed by Dilek Anaç (see Anaç 2017, O3-1). At the colloquium, Professor Anaç was deservedly presented with a Sulphate of Potash Information Board (SOPIB) award for her work on K which has featured at the centre of her research. This has included the establishment of rates of application of K for numerous crops, ensuring balanced fertilization and the role of K in NUE. More recently her work has extended to the benefits of K in relation to water and salt stress and the use of K salts in fertigation of outdoor and indoor crops and crop quality. Two most important features of her work should be acknowledged. The first is the stream of young research workers who over the years have benefited from her support and encouragement and finally her ability to communicate her findings to farmers for their practical application.

Giller (2017) suggests that balanced K nutrition plays a key role in adaption to drought and climate change, in citing the findings of Taulya (2013) who showed that alleviation of K deficiency in East African highland banana gave complete protection against the impact of drought on yield.

The marked reduction in S deposition from the atmosphere to soil due to the control of air pollution, together with increased crop removal, has meant that limitation of soil fertility by a lack of S has become a worldwide problem. S is an essential plant nutrient with functions including the formation of plant protein and chlorophyll so that increased application of S fertilizers will be required to avoid deficiency and crop failure. The problem has been exacerbated by the regular use of high grade NP fertilizers lacking in S (Chien and Gearhart, 2017, O3-7). These researchers have evaluated the agronomic effectiveness of ammonium sulfate (AS) in comparison to recent commercial grade granular bentonite type fertilizers for S availability and crop growth. In order to provide an effective source of S, bentonite fertilizers are dependent on the oxidative process of soil microbes to produce sulfate in the soil. From their evaluation, which included a laboratory incubation study, a greenhouse evaluation study and agronomic field trials, they concluded that oxidative activity was nil or virtually absent and that bentonite fertilizers were unable to provide crop growth during the season of application.

**Photo 4.** Prof. Dr. Dilek Anaç presenting her work on K application in the field.
Photo courtesy of D. Anaç.

The efficiency of the fertilizer polyhalite, a hydrated sulfate of K, Ca and Mg with the formula $K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$, was investigated by Yermiyahu *et al.* (2017, O3-13). Several pot experiments were carried out with the fertilizer supplied at different application levels and uptake and yield production by wheat plants was measured. It was concluded that polyhalite is a more efficient fertilizer for supplying K, Ca, Mg and S relative to equivalent soluble salts. To meet the plant requirement ratios for Ca, Mg and K, polyhalite should be supplied to provide sufficient Ca and Mg and additional K fertilizers should be used as a source of K. Transport and leaching of Ca, Mg, K and S in soil following polyhalite application is lower than following the application of equivalent sulfate salts. The residual effect of polyhalite fertilizer on the subsequently grown crop is higher than the effect of the equivalent sulfate salts, especially regarding Ca, Mg and S. Irrigation management, as determined by the leaching fraction, has a strong impact on polyhalite efficiency as a source of K, Ca, Mg and S for plant nutrition. Polyhalite was also tested in comparison to KCl as a nutrient source for alfalfa growing on the highly weathered low-fertile and acid soils of tropical Brazil (de Campos Bernardi *et al.*, 2017, P3-8). It was shown to be an alternative source of K and S and polyhalite was able to meet the nutritional requirements of alfalfa for healthy growth and production.

Boron and S can readily be leached from light soils and crop deficiency of these nutrients is widespread. The possible benefit of applying these nutrients simultaneously as B and S granules 80% fortified with 1.2% B in supplying soybean and cotton in India was investigated by Singh and Goswami (2017, P3-18). Yields and quality of both crops were improved by BSG in comparison with B and S treatments alone.

### Nutrient availability in soils, toxicity and remediation

The plenary keynote of Jensen (2017) critically reviewed the potential and challenges for producing and applying bio-based 'green' fertilizers, and the bias that farmers may have against using recycled materials for crop production. Recycling P from waste as P fertilizers in agriculture has become the ultimate option to overcome P scarcity in the future. Christiansen *et al.* (2017, P3-12), studied P release from struvite crystals ($NH_4MgPO_4 \cdot 6H_2O$; 12.6% P) obtained from sewage sludge. Fine struvite crystal size (powder) showed P release comparable to water-soluble mineral P fertilizer, while bigger crystals (>2 mm) functioned as a slow P release fertilizer. Another substantial nutrient provider for plant growth is Greenlandic rock flour. The work of de Neergaard (2017, O5-2) showed that this material released K, P, S and Mg immediately after addition to soil and, given the low cost of extraction and processing of the material, they suggested its potential use for agronomic application. Soltangheisi *et al.* (2017, O5-1), studied the long-term effect of cover crops in P mobilization for the subsequent crop. They found that none of the cover crops were effective in increasing available P in the soil compared to fallow, but they were important in recycling P and increasing soil organic matter.

Crop production on calcareous soils that occupy about 30% of global agriculture land is often limited due to Fe and P starvation. However, Ding *et al.* (2017, P5-3), suggested that the adverse effect of high pH on lateral root formation of various *Lupinus* species might be the main cause of their sensitivity to calcareous soils. Suzuki and Namba (2017, O5-3) tested the soil application of Fe complexed with deoxymugineic acid (DMA; plant-born phytosiderophore), as an Fe source for upland rice on calcareous soil. Although Fe-DMA was effective in remedying Fe deficiency chlorosis comparable to the synthetic chelate, Fe-EDDHA (ethylenediamine-N,N_bis(o-hydroxyphenyl)acetic acid), the lower stability of DMA in soil might not be appropriate for practical use. On the other hand, in a paddy environment, excess Fe might also limit rice production. Aung *et al.* (2017, P5-2), analyzed Fe distribution in various rice tissues under different excess Fe levels, which elucidated the relationships between excess Fe levels and plant damage, and revealed the molecular mechanism of Fe excess stress response in various rice tissues.

Paddy soils in Asia are often contaminated with As mainly due to irrigation with As-containing groundwater. Therefore, understanding As biogeochemistry in paddy soils, together with the mechanisms of As uptake, transport and detoxification in rice plants is important for both yield (food security) and human health (food safety). The plenary key note of Zhao (2017) gave a comprehensive overview of these processes, highlighting the importance of recently identified As(V) reductase genes (*OsHAC1;1, OsHAC1;2* and *OsHAC4*) that play a key role in As(V) tolerance and As accumulation in rice plants. In practical terms, the recent studies of Zhao's group have shown that the denitrification process is coupled with anaerobic oxidation As(III) to As(V) in anaerobic paddy soils, hence nitrate fertilizers enhanced the denitrifiers population and, in turn, attenuated As bioavailability in flooded paddy soil. Applications of high doses of P, Fe and Si fertilizers in rice ecosystems have shown promising results in many instances, including reducing As bioavailability and enhancing internal detoxification mechanisms and translocation of As to grains (Suriyagoda *et al.*, 2017, P5-17).

Changing the N source from nitrate to ammonium can effectively mitigate Mn toxicity in sugarcane due to decreased Mn-plaque formation in roots and subsequently lower Mn accumulation in the shoot (Ling *et al.*, 2017, P5-9). Lavres *et al.* (2017, P5-8), investigated the effect of S supply on the activity of antioxidant enzymes involved in Cd tolerance and biomass of Massai grass exposed to high Cd. The authors concluded that adequate S supply enhanced Cd phytoextraction potential and can potentially be used in contaminated substrates. Tanoi *et al.* (2017, P5-18) studied uptake of radioactive cesium (Cs) by rice following the Fukushima disaster in Japan. These authors showed that both uptake and grain accumulation of Cs in rice was lowered by high K supply, and they also found a genotypic difference in Cs distribution between husk and grain. The rapid growth of nanotechnology and the increasing applications of nanoparticles are raising environmental concerns as well as potential phytotoxicity risks. Fellmann and Eichert (2017, P5-4) demonstrated the negative effect of silver (Ag) nanoparticles on growth and physiological performance of both maize and canola.

### Plant nutrition and food quality

To a large extent, the quality of food crops is controlled by plant nutrition. In the developing world, in particular 'hidden hunger' for micronutrient deficiencies is a major health problem for human populations (Cakmak, 2017) with around 2 billion people affected. Children are especially prone to Fe, Zn and iodine (I) deficiencies resulting in chronic diseases. These micronutrient deficiencies are commonly associated with regions where soils are low in micronutrients and cereal-based foods of rice, wheat and maize make up the main diet. Despite intervention programs, including the use of iodised salt, inadequate iodine intake is still a growing health concern. Cereal grains are extremely low in I at about 10 µg $kg^{-1}$ grain in comparison with human demand of about 150 µg per day and, for the major wheat consuming countries, grain Zn values commonly range between 15 and 25 mg $kg^{-1}$ which is inadequate as a primary source of dietary Zn (Cakmak, 2017).

Biofortification of micronutrients is another means of increasing micronutrient supply. Cassava roots grown in tropical areas provide a rich source of starch but are naturally low in micronutrients. Under field conditions, Narayanan *et al.* (2017, O-1), using *Arabidopsis thaliana* iron transporter (IRT1) and ferritin (FER) transgenic cassava plants showed 6-12 times higher Fe and 3-9 times higher Zn concentrations compared to non-transgenic controls. The biofortified transgenic plants retained growth characteristics and storage root yields equivalent to the non-modified controls under field conditions. The biofortified plants contributed 45-50% of the estimated average requirement for Fe and 65-70% of the Zn requirement for 1-3 year old children.

Zou *et al.* (2017, O-2), attempted to increase Zn in wheat grains with the aim of raising it to 40 mg $kg^{-1}$ in field grown wheat. Their objective was considered in a conceptual agronomic framework with an integrated strategy to harvest more grain Zn while ensuring high yield and protecting the environment. Genetic biofortification was achieved by using a new cultivar, agronomic biofortification by foliar application of Zn, N fertilizer was optimized, and excessive use of P fertilizer was avoided. Too high P applications, and too low N applications, especially depressed grain Zn concentration.

From preliminary experiments by Torun *et al.* (2017, P2-2), soaking maize seeds in solutions of 5 mM $ZnSO_4$ over increasing periods of time showed that Zn enriched seeds could be reliably used against Zn deficiency. The positive response of Zn seed enrichment of canola, a non-mycorrhizal crop, in improving growth under optimal and low root zone temperature conditions was reported by Mahmood and Neumann (2017, P2-14). These authors have introduced a very practical approach, whereby Zn seed dressing could be used in the canola seed industry.

Soil applications of most micronutrients are ineffective in increasing grain concentrations. Targeting by foliar application, however, provides a highly useful means of contributing to grain accumulation. An update on foliar fertilization was presented at the colloquium by Fernandez *et al.* (2017). During the reproductive stage, when foliar fertilization takes place, there is a need for maintenance of relatively large pools of Zn, selenium (Se), I, and other micronutrients in the leaf tissue during spraying (Cakmak, 2017) because this is the period when extensive assimilate transport to the grains is underway and required to meet the high micronutrient concentration desired for the human diet. The international HarvestPlus program (www.harvestzinc.org) delivered the first biofortified rice and wheat genotypes with an additional 8-12 mg Zn $kg^{-1}$ grain by combining two strategies, genetic and foliar spraying, to allow the possibility of raising grain Zn above 45 mg $kg^{-1}$ grain weight.

Food quality depends not only on the micronutrients but the macronutrients, particularly K. Several reports confirm this. The beneficial effect of an increasing supply of muriate of potash (KCl) on various quality and yield parameters of red delicious apples were reported from experiments from farmers' fields in India (Rather *et al.*, 2017, P3-5). Their results showed that 1,800-2,100 $K_2O$ per tree applied in four-split doses provided the maximum increase in yield and quality of apple fruits. Similarly in grapes in India, the highest average bunch weight was combined with the highest percent fruiting canes confirming the essential role of K in the differentiation of the buds and the formation of the flower primordia in the grapes (Satisha *et al.*, 2017, P3-4). Potassium sulfate was found to be most beneficial in yield and quality for the grapes.

### Reference

Taulya, G. 2013. East African Highland Bananas (*Musa* spp. AAA-EA) 'Worry' More about Potassium Deficiency than Drought Stress. Field Crops Research 151:45-55.

**This report also appears on the IPI website at:**

**Papers and Presentations**

**Conference highlights and other information about the event are available on the IPNC 2017 website.**

# Events

**October 2017**


## Report on the 1st IPI Symposium on "Polyhalite - A New Potassium Fertilizer with Complete Secondary Nutrients", 2017, China

The 1st IPI Symposium on "Polyhalite - A New Potassium Fertilizer with Complete Secondary Nutrients" was held in Sanya, Hainan Province, China on 31 October 2017, with a focus on sharing and discussing academic research on polyhalite relevant to the Chinese market.

### The context

Due to the negative impacts caused by historical excessive application of high concentration macronutrient NPK fertilizers, and the limited application of organic fertilizer, China is now paying greater attention to more balanced fertilization. This new focus is providing an ideal opportunity for development of the secondary nutrients fertilizer industry, which includes sulfur (S), magnesium (Mg) and calcium (Ca). There is a growing body of evidence of the positive performance of polyhalite, within China and from other parts of the world, which needed to be brought together to facilitate a greater and deeper understanding.

Around 150 people from universities, research institutes and other professionals from China and overseas, as well as the main fertilizer dealers and some large farmers, attended the event along with the media. The performance of polyhalite, marketed in China as elsewhere in the world as Polysulphate, was illustrated in a wide range of target crops including grapes, tomato, potato, rice, banana, apple, pomelo, tea, rapeseed, strawberry, soybean, ginger, maize, tobacco, watermelon, hami melon, cherry, leaf vegetables, coffee, mango, citrus, sugarcane, and jackfruit. This evidence was supplemented with the latest results from polyhalite trials in crops elsewhere in Asia, Europe and North and South America.

### Symposium content

Eleven key speakers gave presentations about polyhalite research in China and other parts of the world illustrating the positive results in a wide range of crops and growing systems.

#### Typical Crop Responses to Polyhalite in Various Agro-Climatic Regions: A Global View

*Hillel Magen, Director IPI, Switzerland*

Since the discovery of the mineral polyhalite in Austria in 1818, the understanding of and respect for the commercial and practical uses of this natural fertilizer has widened and deepened. Hillel Magen explained the recent knowledge gained, including: Polyhalite's solubility and extended availability in the soil; the positive effect discovered with young rice seedlings in Brazil; and the positive residual effects on subsequent crops known as the "Poly effect" (where an incremental yield boost in soybeans of up to almost 20% has been reported from two years use of polyhalite). Polyhalite research is now underway in over 21 countries around the world and 38 crops.

#### Strengthening the Study of Secondary Nutrients and Promoting Scientific-Based Fertilization

*Prof. Xinping Chen, China Agricultural University, China*

The rising proportion of Chinese croplands with secondary or micro element deficiencies is having a serious impact on yield. With each decade the recommendation to farmers of what fertilizer to apply has evolved: 1980's-1990's the product recommendation was urea and DAP; 1990's-2000's the product recommendation was amended to include compound and formula fertilizer. Now new recommendations are needed to redress the shortage of micro nutrients and address the problems (soil acidification, water pollution and greenhouse gas emissions) from overuse of nitrogen (N) fertilizer in order to achieve sustainable intensification. New approaches are needed to improve N and P efficiency and achieve controlled-release nutrient supply of major and micro plant nutrients. Latest secondary/micro elements research is improving fertilizer targeting and use. From 2004-2013 China's fertilizer use increased by 27.5% meanwhile grain production increased by 28.2%, vegetable production increased by 33.5% and fruit production increased by 63.6%.

#### Sulfur Consumption in Chinese Agriculture: Situation and Outlook

*Dr. Gao Xiangzhao Gao, National Agriculture Technology Extension Service Center, China*

More than ten provinces in China report sulfur (S) deficiency in soils, and that S fertilizer can increase crop yields significantly. Sulfur dioxide ($SO_2$) emissions peaked in 2007, since when they have started to decline. However sulfur fertilizer use has not been based on crop requirement and soil S levels resulting in over application, particularly in grain crops (rice and wheat). The recommendation from this research is to start nationwide research on soil S fertility and testing. Better forecasting of S demand would be possible as well as efforts to continue use of traditional S fertilizers in production regions and introduce new S fertilizer products for the regions with greatest deficiency and crop demand.

#### Effect of Calcium and Magnesium on Potato Tuber Yield, Quality and Disease Incidence in Inner Mongolia of China

*Associate Prof. Liguo Jia, Inner Mongolia Agricultural University, China*

Increase in potato productivity in the last twenty years is mainly attributed to NPK fertilizer application. However the importance of calcium and magnesium fertilizer for this crop had not been realized. Through trials of the effectiveness of polyhalite four-in-one fertilizer on potato crops, this study showed significant improvements in yield, starch content, plus elimination of common scab.

#### Effects of Polyhalite Application on Seed Yield, Nutrient Uptake and Seed Quality of Winter Oilseed Rape

*Prof. Jianwei Lu, Huazhong Agricultural University, China*

Two field experiments were designed. The first investigated the effects of polyhalite application compared with conventional (NPKB) fertilizer treatment on seed yield, nutrient uptake and seed quality of oilseed rape in Hubei province, central China. The second trial compared six polyhalite fertilizer application rates to determine the optimal rate. Polyhalite increased seed protein concentration and seed yield, but at the highest rate of application it depressed seed yield, demonstrating the need for understanding the correct application rate for the crop.

#### Improving the Growth and Yield of Crops in Europe and South America with Polyhalite

*Eldad Sokolowski, IPI Coordinator for China*

The importance of tailoring fertilizer combinations to suit crops was reported from trials in Brazil with onions (peak yield reached with 60% KCl and 40% Polysulphate); bananas (peak yield reached with 40% KCl and 60% Polysulphate); and cabbage (peak yield reached with 20% KCl and 80% Polysulphate). The effect of fertilizer placement in soybean showed MAP + MOP + Polysulphate applied in furrows is more effective compared to broadcast. Also in soybean, the relationship between root system, depth, Ca and Mg in soil, and yield were also correlated. From Argentina, strong response to sulfur was reported in wheat and maize. From France, the positive response of alfalfa to Polysulphate at 200 kg $ha^{-1}$ was illustrated. Finally, from Israel, the way that Polyhalite prevents Ca and Mg deficiencies in greenhouse tomatoes irrigated with desalinized water was reported.

**The Nutrient Release Kinetics of Polyhalite and its Biological Effect on Tea Growth and Quality in China**

*Dr. Kang Ni, Tea Research Institute, Chinese Academy of Agricultural Sciences, China*

As the largest tea producing country in the world, Chinese tea farmers are particularly interested in the 5% yield increase that results from magnesium (Mg) fertilization. That combined with the convenience, lower application costs and reduced harmful environmental effects are just some of the reasons for the increasing interest in application of Polysulphate for tea. An experiment was designed to investigate the advantage of using polyhalite compared with normal NPK compound fertilizer, and also whether the additional Ca in polyhalite might have an adverse effect on tea yield and quality. Laboratory leaching was compared with pot and field trials. The prolonged, slow release of nutrients was confirmed, nutrient leaching was reduced, young shoot biomass increased slightly, certain tea characteristics were improved and no adverse effect of higher Ca was shown on autumn tea quality.

**Effects of Polyhalite Application on Honey Pomelo Yield and Quality in Fujian Province of China**

*Associate Prof. Liangquan Wu, Fujian Agriculture and Forestry University, China*

Research in honey pomelo orchards, selected from the 80,000 hectares in Fujian province, showed significant problems such as severe soil acidification and symptoms of magnesium, calcium and sulfur deficiency. Polyhalite application was compared with existing fertilizer practice. Honey pomelo spring growth, yield, and fruit quality, as well as farmer income all improved with the use of polyhalite.

**The Efficiency of Granular Polyhalite to Improve the Growth and Yield of Crops in Malaysia**

*Cheng Siang Seh, ICL Agronomist, Malaysia*

Trials in watermelon comparing the use of compound fertilizer with the use of the same fertilizer plus polyhalite showed that the latter improved watermelon yield by 33%. Trials in chrysanthemum production showed adding polyhalite with compound fertilizer improved root development, leaf size, flower stem length and bloom. Trials in pineapple showed polyhalite led to a reduction in potassium deficiency symptoms, higher sugar content, better shelf life and 11% higher proportion of fruit classified as Grade A. In addition, a trial with paddy rice was reported which showed that using polyhalite with a conventional fertilizer resulted in bigger grains and a yield increase of 25%.

**Effects of Polyhalite Application on Yield and Quality of Apple, Tomato and Maize in China**

*Ning Ma, WZF Agronomist, China*

(Presentation available in Chinese.)


Symposium's field visit to a polyhalite hami-melon greenhouse trial. Photo by IPI.

**Summary of Effects of Polyhalite Application on Different Crops in China**

*Dr. Guohua Li, ICL Agronomist, China*

The multi-nutrient, prolonged release, natural and effective nature of polyhalite, marketed as Polysulphate, was outlined, explaining the rising popularity of Polysulphate around the world. The relevance of Polysulphate to meet Chinese fertilizer requirements in different regions was explained, whether sandy soil with high rainfall, acid soil, saline soils or S deficient soils. Also the positive performance of Polysulphate in a wide range of sensitive agronomic situations was highlighted, including in Ca and Mg demanding crops (potato, citrus, grapes, roots and strawberries), chloride sensitive crops (tea, tobacco and greenhouse crops), oil crops, pasture and forage, N-fixing legumes and for organic crops. The full extent of the latest agronomic research on Polysulphate in China was demonstrated as well as examples of some of the dramatic improvements in yield and quality of a wide range of crops including bananas, grapes, tomatoes, cherries, strawberries, pak choi, melons, peppers, cabbage, chili and maize.

## Extending the understanding of delegates on the current use and future potential of polyhalite in China

As part of the 1st IPI Symposium on Polyhalite in China, the attendees had the opportunity to see the results of using Polysulphate by visiting a hami melon farm. A field visit gave the opportunity to see polyhalite use in practice to share observations and comments with each other.

**Further insight into the content of all the main presentations from the symposium is available on the IPI website at:**

**Papers and Presentations**

# Events (cont.)

**International Symposia and Conferences**

**July 2018**

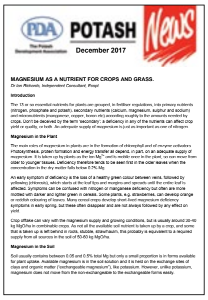
**10th Symposium of the International Society of Root Research (ISRR10), 8-12 July 2018, Yearim Hotel, Israel.**

The symposium, titled: "Exposing the Hidden Half - Root Research at the Forefront of Science", will assemble multiple disciplines in order to facilitate exploration of novel approaches and investigation of complex processes and mechanisms.

For more information visit the ISSR10 website.

# Publications

## Publications by the PDA


PDA POTASH News
December 2017
MAGNESIUM AS A NUTRIENT FOR CROPS AND GRASS.

**Magnesium as a Nutrient for Crops and Grass**

POTASH News, December 2017.

The 13 or so essential nutrients for plants are grouped, in fertiliser regulations, into primary nutrients (nitrogen, phosphate and potash), secondary nutrients (calcium, magnesium, sulphur and sodium) and micronutrients (manganese, copper, boron etc) according roughly to the amounts needed by crops. Don't be deceived by the term 'secondary'; a deficiency in any of the nutrients can affect crop yield or quality, or both. An adequate supply of magnesium is just as important as one of nitrogen. Read more on the PDA website.

*Potash Development Association (PDA) is an independent organisation formed in 1984 to provide technical information and advice in the UK on soil fertility, plant nutrition and fertilizer use with particular emphasis on potash. See also www.pda.org.uk.*

# Scientific Abstracts

## K in the Literature

**Follow us on Twitter on:** https://twitter.com/IPI_potash

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### Soil Fertility and Nutrient Budget After 23-Years of Different Soil Tillage Systems and Winter Cover Crops in a Subtropical Oxisol

Tiecher, T., A. Calegari, L. Caner, and D. dos Santos Rheinheimer. 2017. Geoderma 308:78-85. https://doi.org/10.1016/j.geoderma.2017.08.028.

**Abstract:** Growing cover crops to recycle soil nutrients in no-tillage systems provide nutrients accumulation in more labile forms in the soil surface reducing the demand for fertilizers. This study aimed to evaluate the long-term (23-yrs) effect of soil tillage systems and winter cover crops on (*i*) soil acidity, (*ii*) nutrient availability, and (*iii*) P and K budget in a subtropical Oxisol from Southern Brazil. The experiment was established in 1986 with six winter treatments (blue lupine, hairy vetch, oat, radish, wheat, and fallow) and two tillage systems (conventional tillage - CT and no-tillage - NT) in a very clayey Rhodic Hapludox in Southern Brazil. Nutrient availability (P, K, Ca, and Mg) and soil acidity (pH, potential acidity, base and Al saturation) were evaluated in five soil depths (0-5, 5-10, 10-20, 20-30, and 30-40 cm). Nutrient budget was calculated considering the inputs (amount of P and K applied via fertilizer) and outputs of P and K from the system (exported by the grains), and the soil available P and K before and after 23-years of experiment. Continuous NT system for 23-years resulted in higher soil fertility in the topsoil (0-10 cm) compared to CT, but with some limitations of nutrient availability and soil acidity below 10 cm depth. Long-term NT builds up a strong gradient of nutrient availability, with higher concentration of nutrients on the soil surface layers that abruptly decrease with soil depth, unlike CT. Surface application of lime in NT reduced soil acidity up to 20 cm compared to CT. The budget of P was negative for all treatments, highlighting the P-sink behavior of this strongly weathered subtropical Oxisol. However, NT system resulted in less negative budget compared to CT and, therefore, higher efficiency of use of P. Growing cover crops in the winter is effective to increase P and K availability through plant cycling, but the plants grown in winter did not affect soil acidity. Nutrient cycling by winter cover crops reduced P and K losses, especially when the soil is not plowed. Fallow in the winter decreases the use efficiency of P and K. Among the cover crops tested, black oat stood out by its greater production of biomass, resulting in higher P and K availability in the soil surface. Lupine resulted in a greater cycling of P possibly due to its ability to absorb P from less labile forms in the soil.

### Crop Yield and Soil Available Potassium Changes as Affected by Potassium Rate in Rice-Wheat Systems

Lu, D., C. Li, E. Sokolowski, H. Magen, X. Chen, H. Wang, and J. Zhou. 2017. Field Crops Research 214:38-44. https://doi.org/10.1016/j.fcr.2017.08.025.

**Abstract:** Large areas of the arable soils of the world are deficient in potassium (K) due to the low application rate of K fertilizer. However, current soil test methods cannot precisely determine soil available K changes. From 2009 to 2014, a field experiment was conducted in a rice-wheat cropping system in the Yangtze Plains using five K rates. The objectives were to determine the responses of wheat and rice yield to different K rates and to compare the soil available K changes extracted by three methods (ammonium acetate ($NH_4OAc$), boiling nitric acid ($HNO_3$), and sodium tetraphenylboron (NaTPB)). Long periods without application of K fertilizer markedly decreased wheat yield by 47% and rice yield by 15% compared with local farmers' K practices (FKP, 90 and 120 kg $K_2O$ $ha^{-1}$ for wheat and rice, respectively). The FKP achieved optimal yields for wheat and rice; however, only 160% of FKP achieved a positive K balance for the cropping system. Soil-extractable K consistently decreased with increasing cropping rotations where the K rate was below 160% FKP for the three extraction methods. The extractable and changed amounts for the $NH_4OAC$ and $HNO_3$ methods were significantly lower than that for the NaTPB method. The soil K changes for NaTPB were closer to the theoretical soil available K changes (TAKC) derived from an apparent K balance. The NaTPB method could be useful for accurately determining changes in soil available K in cropping systems.

### Sugarcane Yield Response to Potassium Fertilization as Related to Extractable Soil Potassium on Florida Histosols

McCray, J.M., S. Ji, and G. Powell. 2017. Agron. J. 109(5):2243-2252. DOI: 10.2134/agronj2016.11.0630.

**Abstract:** Sugarcane (*Saccharum* spp.) has a large K requirement and so K fertilizer can be a major cost for growers. Histosols in the Everglades Agricultural Area (EAA) of Florida are shallower with higher pH than when current sugarcane K fertilizer recommendations were established in the 1970s. This study was conducted to determine sugarcane yield response to K fertilizer as related to extractable soil K on Florida Histosols. Six small-plot (83, 120, or 138 $m^2$) field experiments were established as randomized complete block (RCB) designs (four or six replications) with annual K rates ranging from 0 to 279 kg K $ha^{-1}$. There were significant sugarcane and sucrose yield responses to K fertilizer and these were attributable to increases in sugarcane biomass. There was evidence of reduced sucrose concentration at higher K rates in 4 of 14 crop years. Orthogonal contrasts determined significant sucrose yield response to K fertilizer compared to the zero rate in 5 of 14 crop years. Nonlinear regression determined that the acetic acid-extractable soil K value at or above which K fertilization is not required was within 12% of the current value. Maximum K fertilizer requirement determined in the study was 170 kg K $ha^{-1}$ at an acetic acid-extractable K value of 20 g K $m^{-3}$, which is 27% less than the current recommendation. Results of a previously unpublished K rate trial confirmed the results of the current study, which will be used to update K fertilizer recommendations on Florida Histosols.

### Using Topsoil Thickness to Improve Site-Specific Phosphorus and Potassium Management on Claypan Soil

Conway, L.S., M.A. Yost, N.R. Kitchen, and K.A. Sudduth. 2017. Agron. J. 109(5):2291-2301. DOI: 10.2134/agronj2017.01.0038.

**Abstract:** Precise P and K fertilizer management on claypan soils can be difficult due to variable topsoil thickness, or depth to claypan (DTC), across landscapes, nutrient supply from subsoils, and crop removal. Therefore, a study was performed to determine if DTC could be used to improve P and K management for corn (*Zea mays* L.), soybean [*Glycine max* (L.)], and switchgrass (*Panicum virgatum* L.). Research was conducted on a claypan soil at the University of Missouri's (MU) South Farm Research Center in Columbia, MO, from 2009 to 2016. Corn, soybean, and switchgrass were grown each year on 16 plots with constructed DTC ranging from 0 to 94 cm. Surface soil samples for soil test phosphorus (STP) and potassium (STK) were collected in the early spring of 2009, 2015, and 2016. Fertilizer was applied shortly after soil sampling in 2009 and 2015 based on the MU buildup recommendation. Results in the spring of 2015 showed that STP increased 0.53, STK decreased 4.4, and the phosphorus buffering index ($BI_P$) decreased 0.94 kg $ha^{-1}$ with each 1 cm increase in DTC. Most importantly, across the 2015 growing season the amount of fertilizer K needed to raise soil test potassium by 1 kg $ha^{-1}$ ($REQ_K$) was four times greater at DTC of 44 than 0 cm. These relationships show that accounting for DTC could improve current fertility guidelines by applying more, or more frequent P, and less K on shallow soils.

### Chapter Five - Mineral Nutrition of Cocoa: A Review

van Vliet, J.A., and K.E. Giller. 2017. Advances in Agronomy 141:185-270. https://doi.org/10.1016/bs.agron.2016.10.017.

**Abstract:** Cocoa is an important global commodity. It is mostly grown on small farms by millions of cocoa farmers who depend on the crop for their livelihood. Although potential yields exceed 6000 kg/ha, average farm yields are often around 400 kg/ha. Among the production constraints met by farmers is nutrient limitation. In this review, we compile current knowledge on nutrient cycling in cocoa production systems, nutrient requirements of cocoa, and

yield response to fertilizer application in relation to factors such as management, climatic, and soil conditions. Large amounts of nutrients are cycled within cocoa systems, mostly through 5-10 t/ha/yr litter fall. Still, harvesting and small nutrient losses such as leaching lead to nutrient exports causing gradual soil nutrient depletion. Exact nutrient requirements of cocoa are unknown. Leaf and soil test interpretation to identify additional nutrient needs remain ambiguous. Recommended nutrient application rates vary more than 10-fold. In several trials fertilizer application more than doubled cocoa productivity; in other cases response is minimal. Differences in response between regions, fields and even trees have yet to be explained. Interactions with agroecology and management (especially shade) are poorly understood. Without this fundamental knowledge, farm level recommendations have a weak scientific base. Different types of research are recommended to complement current knowledge. Existing data and trials can be exploited through additional analysis and more detailed measurements. Cocoa farms are highly diverse and on-farm trials offer opportunities for understanding variability in production and fertilizer response. Finally, multifactorial shade–fertilizer response trials will be essential to address some of the fundamental knowledge gaps.

### Potassium Solubilization, Plant Growth Promoting Substances by Potassium Solubilizing Bacteria (KSB) from Southern Indian Tea Plantation Soil

Balasubramanian Bagyalakshmi, Ponnusamy Ponmurugan, and Angusamy Balamurugan. 2017. Biocatalysis and Agricultural Biotechnology 12:116-124. https://doi.org/10.1016/j.bcab.2017.09.011.

**Abstract:** A study was undertaken to identify indigenous potassium solubilizing bacteria in southern Indian tea plantation soils. The samples were analysed for various soil edaphic parameters such as pH, Ec, water holding capacity, organic carbon, nitrogen, available phosphorous, exchangeable potassium, exchangeable calcium, sodium and magnesium and potassium solubilizing bacteria were identified. The study revealed that the population density was found to be more in Valparai soils ($18.20\times10^4$/g of soil) followed by Gudalur and least in Koppa region ($5.90\times10^4$/g of soil). The population density of KSB in soils of different cultivars of tea plants revealed that higher population was achieved with China hybrids especially UPASI-9 followed by ATK-1, SMP-1 and SA-6.The results indicated that existence of clonal preference by KSB and rhizosphere effect with very good bonding pattern of root systems. About six efficient KSB strains were selected based on its solubilization efficiency in agar and liquid medium. The strains were characterized and identified through biochemical and molecular level. Higher K solubilization (41.91 mg/l) was observed in the KSB strain isolated from Valparai region. In addition solubilization was more when MOP used as K source followed by SOP and Montmorillonite at 5th day of incubation period. Least K solubilization was recorded with GKSB6 (20.31 mg/l). They also proved to produce plant growth promoting substances. These potent indigenous potassium solubilizers were could be used as bioinoculants in tea plantation inturn reduces the usage of chemical fertilizers and improve soil fertility.

### Potassium Fixation by Oxidized and Reduced Forms of Phyllosilicates

Florence, A., M. Ransomand and D. Mengel. 2017. SSSAJ 81(5):1247-1255. DOI:10.2136/sssaj2016.12.0420

**Abstract:** Potassium fixation traps $K^+$ ions in the interlayer region of phyllosilicates. This study determined if increased negative interlayer charge caused by structural Fe reduction leads to increased $K^+$ fixation. The five reference clays used were illite (IMt-1), kaolinite (KGa-1b), montmorillonite (STx-1b), nontronite (NAu-2), and vermiculite (VTx-1). Soil clays were fractionated from the upper 15 cm of a Belvue loam and a Cherokee silt. Potassium fixation capacities were measured on clay samples of unreduced and reduced forms of each clay. Iron (II) and total Fe contents were determined, and $K^+$ fixation was measured by K saturating the clays, followed by five washes of $MgCl_2$ solution. Iron reduction significantly increased the amounts of $K^+$ fixed by NAu-2 and VTx-1. An increase in Fe(II) content caused increases in layer charge and $K^+$ fixation. Although NAu-2 exhibited a greater increase in Fe(II) content on reduction than VTx-1, the increase in $K^+$ fixation on reduction was greater for VTx-1 because of the tetrahedral location of Fe in VTx-1. For IMt-1, KGa-1b, and STx-1b, Fe reduction did not significantly affect the $K^+$ fixation capacities because of their low Fe contents. The Belvue loam released $K^+$ in both unreduced and reduced forms. The Cherokee silt did not appreciably release or fix $K^+$ in either form. Although much K is removed in the first wash, small amounts of K were removed in subsequent washes, especially for reduced samples of NAu-2 and VTx-1. The washing procedure caused reduced Fe to reoxidize, which resulted in K that was previously fixed to be released.

### Binary Exchanges of Calcium, Magnesium, and Potassium on Thermally Desorbed Soil

Ritter, S., T. DeSutter, P. O'Brien, F. Casey, A. Wick, K. Horsager, and E. Khan. 2017. SSSAJ 81(5):1088-1095. DOI: 10.2136/sssaj2017.01.0028.

**Abstract:** Thermal desorption (TD) remediates hydrocarbon-contaminated soil by heating the soil (200-500°C) to volatilize the hydrocarbons, effectively removing the contaminant from the soil. Knowledge of the effects of TD on remediated soil for agricultural crop production are limited, but cation exchange capacity (CEC) and selectivity for cations can be good indicators of plant productivity potential. In this study, the CEC and selectivity of cations of TD-treated and untreated topsoil and subsoil were compared using binary exchange measurements of Ca-Mg, Ca-K, and Mg-K. The tested soils were illite and smectite-dominated Mollisols that were collected near an active TD-remediation site in northwest North Dakota. Vanselow selectivity coefficients and Gibb's free energies ($\Delta G_{ex}$) were computed. For all three exchanges, significant differences were observed in $\Delta G_{ex}$ between the untreated and TD-treated topsoil. In the Ca-Mg exchange, both the untreated and TD-treated topsoil preferred Ca, whereas both TD-treated and untreated subsoils preferred Mg. For the Ca-K and Mg-K exchanges, all treatments preferred K. Cation exchange capacity values were significantly greater in the untreated subsoil of the Ca-Mg exchange and the untreated topsoil and subsoil of the Ca-K exchange than in the TD-treated soils. The differences may be caused by contrasts in soil organic C and mineralogy. Although CEC and $\Delta G_{ex}$ differed between untreated and TD-treated soils, the cation selectivities were not altered, suggesting that the magnitude of the differences may not require alternative fertility management to retain previous soil productivity.

### Potassium Application Affects Key Enzyme Activities of Sucrose Metabolism during Seed Filling in Vegetable Soybean

Liu, C., B. Tu, Y. Li, B. Tian, Q. Zhang, X. Liu, and S.J. Herbert. 2017. Crop Science 57(5):2707-2717. DOI: 10.2135/cropsci2016.08.0648.

**Abstract:** Pot experiments were conducted in 2014 and 2015 with two vegetable soybean [*Glycine max* (L.) Merr.] cultivars ('Zhongkemaodou 1' and '121') under normal rates of nitrogen and phosphorus application with three potassium (K) fertilization treatments: no K application (K0), 120 kg $K_2SO_4$ $ha^{-1}$ at seeding (K1), and 120 kg $K_2SO_4$ $ha^{-1}$ at seeding + 1% $K_2SO_4$ foliar application at flowering (K2). Potassium application significantly increased seed sucrose concentration, and the highest seed sucrose concentrations were uniformly observed in the treatment of foliar K application after flowering. At 7 wk after flowering, the highest stage of seed sucrose concentration, K1 and K2 treatments increased sucrose concentration by 19.8 to 44% and 29.1 to 86.4% for Zhongkemaodou 1, and 7.2 to 42.1% and 26.2 to 63.8% for 121, respectively. Changes of net activities of sucrose-metabolizing enzymes in seed paralleled the trend of sucrose accumulation. Potassium application increased the activities of sucrose phosphate synthase and sucrose synthase with increased sucrose synthesis but reduced the activity of sucrose synthase with increased sucrose decomposition. Potassium application also reduced the activities of acid invertase and neutral invertase, especially around seed ripening. Potassium fertilization enhanced seed net activities of key enzymes in sucrose metabolism and subsequently induced the increase in sucrose concentration of vegetable soybean.

### A Mixed-Effects Regression Modeling Approach for Evaluating Paddy Soil Productivity

Zou, G., Y. Li, T. Huang, D.L. Liu, D. Herridge, and J. Wu. 2017. Agron. J. 109(5):2302-2311. DOI: 10.2134/agronj2017.02.0089

**Abstract:** Soil productivity (SP) is a description of the soil's inherent capacity for crop production and approximates the long-term average crop yield. Knowledge of the key driving factors of SP is essential for short-term soil management and long-term agricultural sustainability. Representative 50-cm intact soil profiles from high-, moderate-, and low-yielding paddy fields with long rice (*Oryza sativa* L.)-production histories were collected in southern China. Each profile was stratified into 10 layers at 5-cm intervals. Multiple linear (MLM) and mixed-effects (MEM) regression models were developed from the basic soil properties, with the MEM using four different combinations of soil depth of sampling, to evaluate paddy SP. Soil cation exchange capacity (CEC), $Ca^{2+}$, $K^+$, available potassium (AVK), pH, and clay content were correlated with SP ($n = 60$, $r = 0.25$-$0.59$, $p < 0.05$), while soil organic C and N contents were poorly related to SP ($r = 0.03$-$0.07$, $p > 0.05$). A MEM with three fixed effects [log (AVK), CEC, and pH] and two random effects [log ($Na^+$) and clay] with two-layer stratification (0-20 and 20-50 cm) best estimated SP ($n = 12$, $R^2 = 0.96$, $p < 0.001$). We concluded that the combination of soil stratification and mixed effects could make SP assessment in paddy fields more efficient.

### Evaluation of Fertilizer Potential of Different K Compounds Prepared Utilizing Sea Bittern as Feed Stock

Trivedi, K., D. Kubavat, K.K. Ghara, R. Kumar, H. Trivedi, K.G. Vijay Anand, P. Maiti, and A. Ghosh. 2017. Front. Plant Sci. https://doi.org/10.3389/fpls.2017.01541.

*Aim:* Many countries import potassic fertilizers due to dearth of K-mineral deposits. Therefore processes to obtain K-nutrient sources from sea bittern were developed by our Institute. The present investigation evaluated the fertilizer potential of three different sea bittern-derived (SBD) potassium forms developed viz., potassium schoenite, potassium nitrate and potassium ammonium sulfate on maize productivity in two cropping seasons.
*Methods:* The pot and field experiments consisted of four treatments, wherein the three K forms were applied at the recommended rate of 40 kg $K_2O$ $ha^{-1}$ and were compared with commercially used sulfate of potash. The effect of these fertilizers on different parameters of plant and soil were evaluated.
*Results:* The application of SBD-potassic fertilizers led to

enhancement in growth, productivity and quality of maize which related well with higher photosynthesis, nutrient uptake and soil quality parameters. On an average all the three forms of sea bittern-derived potash enhanced yield of maize over control by 22.3 and 23.8%, respectively, in pot and field trials. The best performance was under SBD-$KNO_3$, which also recorded the highest benefit: cost ratio of 1.76.
*Conclusion:* The K-fertilizers derived from sea-bittern - a waste product of salt industry - can thus be economically used to improve crop production sustainably.

### Potassium in the Grape (*Vitis vinifera* L.) Berry: Transport and Function

Rogiers, S.Y., Z.A. Coetzee, R.R. Walker, A. Deloire, and S.D. Tyerman. 2017. Front. Plant Sci. https://doi.org/10.3389/fpls.2017.01629.

**Abstract:** $K^+$ is the most abundant cation in the grape berry. Here we focus on the most recent information in the long distance transport and partitioning of $K^+$ within the grapevine and postulate on the potential role of $K^+$ in berry sugar accumulation, berry water relations, cellular growth, disease resistance, abiotic stress tolerance and mitigating senescence. By integrating information from several different plant systems we have been able to generate new hypotheses on the integral functions of this predominant cation and to improve our understanding of how these functions contribute to grape berry growth and ripening. Valuable contributions to the study of $K^+$ in membrane stabilization, turgor maintenance and phloem transport have allowed us to propose a mechanistic model for the role of this cation in grape berry development.

### Potassium and Phosphorus Fertilization Impacts on Bermudagrass and Limpograss Herbage Accumulation, Nutritive Value, and Persistence

Silveira, M.L., J.M.B. Vendramini, H.M.S. da Silva, B.M.M.N. Borges, V.S. Ribeirinho, J.J.J. Lacerda, M.V. Azenha, P.R.A. Viegas, and A.D. Aguiar. 2017. Crop Science 57(5):2881-2890. DOI: 10.2135/cropsci2017.03.0147.

**Abstract:** Despite scientific evidence suggesting that warm-season grasses can respond favorably to K and P fertilization, the increasing costs of fertilizers limit the extent to which these nutrients are used in pastures and hayfields. Two field studies evaluated 'Jiggs' bermudagrass [*Cynondon dactylon* (L.) Pers.] and 'Floralta' limpograss (*Hemarthria altissima* Stapf. and Hubbard) herbage accumulation (HA), nutritive value, and persistence to reduced fertilization strategies during 2012 to 2014. Treatments were allocated in a split-plot design with N (90 or 180 kg N $ha^{-1}$, bermudagrass study) or harvest frequency (6 vs. 12 wk, limpograss study) as the main factors and P (0, 8.7, and 17.4 kg P $ha^{-1}$) and K (0, 33, and 66 kg K $ha^{-1}$) levels as subplots. Bermudagrass HA increased linearly (up to 377% in Year 3) as K level increased. Similarly, K fertilization increased limpograss HA from 8.4 to 11.6 Mg $ha^{-1}$ in 2013 and from 5.8 to 15.7 Mg $ha^{-1}$ in 2014 as K levels increased from 0 to 66 kg K $ha^{-1}$; however, no effect was observed in 2012. Bermudagrass HA and ground cover decreased from 2012 to 2014 in all K treatments. Conversely, decreases in limpograss HA and ground cover over time were observed only in the control (no K) treatments. Bermudagrass and limpograss crude protein concentrations generally decreased with increased K level. No effects of N or P were observed. Continuous aboveground removal without proper K fertilization is detrimental to bermudagrass and limpograss production and persistence.

### *OsHAK1*, a High-Affinity Potassium Transporter, Positively Regulates Responses to Drought Stress in Rice

Chen, G., C. Liu, Z. Gao, Y. Zhang, H. Jiang, L. Zhu, D. Ren, L. Yu, G. Xu, and Q. Qian. 2017. Front. Plant Sci. https://doi.org/10.3389/fpls.2017.01885.

**Abstract:** Drought is one of the environmental factors that severely restrict plant distribution and crop production. Recently, we reported that the high-affinity potassium transporter *OsHAK1* plays important roles in K acquisition and translocation in rice over low and high K concentration ranges, however, knowledge on the regulatory roles of *OsHAK1* in osmotic/drought stress is limited. Here, transcript levels of *OsHAK1* were found transiently elevated by water deficit in roots and shoots, consistent with the enhanced GUS activity in transgenic plants under stress. Under drought conditions, *OsHAK1* knockout mutants (KO) presented lower tolerance to the stress and displayed stunted growth at both the vegetative and reproductive stages. Phenotypic analysis of *OsHAK1* overexpression seedlings (Ox) demonstrated that they present better tolerance to drought stress than wild-type (WT). Compared to WT seedlings, *OsHAK1* overexpressors had lower level of lipid peroxidation, higher activities of antioxidant enzymes (POX and CAT) and higher proline accumulation. Furthermore, qPCR analysis revealed that *OsHAK1* act as a positive regulator of the expression of stress-responsive genes as well as of two well-known rice channel genes (*OsTPKb* and *OsAKT1*) involved in K homeostasis and stress responses in transgenic plants under dehydration. Most important, *OsHAK1*-Ox plants displayed enhanced drought tolerance at the reproductive stage, resulting in 35% more grain yield than WT under drought conditions, and without exhibiting significant differences under normal growth conditions. Consequently, *OsHAK1* can be considered to be used in molecular breeding for improvement of drought tolerance in rice.

### Common Reed Absorbs $K^+$ More Selectively than Rice Against High $Na^+/K^+$ Ratio in Nutrient Solution

Higuchi, K., and K. Hara. 2017. Soil Science and Plant Nutrition 63(5):483-487. https://doi.org/10.1080/00380768.2017.1381573.

**Abstract:** The introduction of an active $Na^+$ excretion system from salt-tolerant plants in salt-sensitive crop plants might necessitate enhancement of the robustness of $K^+$ homeostasis and lead to improved plant growth under salt stress. To address this issue, we compared the acquisition and retention of $K^+$ under excess $Na^+$ concentrations in the common reed, which possesses excellent $Na^+$ excretion ability, and low-$Na^+$ excreting rice. Under excess $Na^+$ concentrations, common reed maintained constant $K^+$ content in all plant parts, whereas $K^+$ content in rice decreased with increasing $Na^+$ concentration. Preferential uptake of $K^+$ against high $Na^+/K^+$ ratio in nutrient solution was approximately 10 times higher in common reed than in rice. The impact of excess $Na^+$ on net $K^+$ absorption rate of common reed was small. On the other hand, the net $K^+$ absorption rate of rice was decreased by excess $Na^+$ concentration. However, after the $Na^+$ concentration in the nutrient solution was decreased from 50 to 1 mM, $K^+$ absorption in rice recovered immediately. Thus, selectivity of $K^+$ transporters or channels for $K^+$ over $Na^+$ in roots could be involved in the differences in $K^+$ accumulation in rice and common reed.

### Harvest Stubble Height and K Fertilization Affect Performance of Jiggs and 'Tifton 85' Bermudagrasses

Kohmann, M.M., L.E. Sollenberger, J.M.B. Vendramini, M.L. Silveira, and L.S.B. Moreno. 2017. Crop Science 57(6):3352-3359. DOI: 10.2135/cropsci2017.05.0308.

**Abstract:** Use of Jiggs bermudagrass [*Cynodon dactylon* (L.) Pers.] for hay has increased in warm climates like southern Florida, but effects of defoliation and K fertilizer management on Jiggs adaptation to environments with frequent winter freezes are not known. During 2 yr, K fertilization (0, 17, and 34 kg K $ha^{-1}$ $harvest^{-1}$) and cutting stubble height (SH, 8 and 16 cm every 28 d) effects on herbage accumulation (HA), ground cover, K removal, and tissue and soil K were evaluated for Jiggs and 'Tifton 85' (*Cynodon* spp.) bermudagrasses. All treatments received 240 kg N $ha^{-1}$ $yr^{-1}$. Herbage accumulation was greater for 8- than 16-cm SH (8050 and 7330 kg $ha^{-1}$ $yr^{-1}$, respectively) and increased linearly from 7040 to 8120 kg $ha^{-1}$ $yr^{-1}$ with increasing K fertilization. Potassium fertilization did not affect grass percentage ground cover, but Jiggs had 17 (2014) and 40% (2015) greater cover than Tifton 85. Increasing K fertilization increased tissue K concentration (15 to 19 g $kg^{-1}$ in 2014 and 13 to 25 g $kg^{-1}$ in 2015) and K removal in HA (from 104 to 149 kg $ha^{-1}$ in 2014 and 88 to 216 kg $ha^{-1}$ in 2015). During 2 yr, soil-extractable K declined 6 mg $kg^{-1}$ for the zero K level but increased 6 mg $kg^{-1}$ when K was applied. In a cooler subtropical region characterized by frequent winter freezes and across a range of K fertilizer and SH levels, Jiggs sustained ground cover better than Tifton 85, but K fertilization did not affect persistence.

### Effect of Potassium Application in Drought-Stressed Tobacco (*Nicotiana rustica* L.) Plants: Comparison of Root with Foliar Application

Bahrami-Rad, S., and R. Hajiboland. 2017. Annals of Agricultural Sciences. https://doi.org/10.1016/j.aoas.2017.08.001.

**Abstract:** Effect of potassium (K) application through leaves (LA) or roots (RA) was studied in tobacco plants grown under K deficiency and drought stress conditions. Application of K was effective in improving the shoot growth only under drought conditions, whereas root biomass and length responded under both watering regimes. Under drought conditions, photosynthesis and transpiration activities increased upon K application leading to a reduced water use efficiency. Both RA and LA increased the leaf water potential, relative water content and turgor under both well-watered and drought conditions; RA was more effective than LA in the recovery of leaf turgor. Analyses of water relation parameters in different aged leaves showed lower susceptibility of the middle-aged leaves to both K deficiency and drought stresses than the upper and lower leaves; this phenomenon was accompanied by a more conservative control of water loss in the middle-aged leaves. In contrast, proline was accumulated in the young leaves, and K application increased it further. Although various organic osmolytes were accumulated under the combinative effect of K deficiency and drought stress, they did not exceed the amounts found in the control (well-watered +K) plants and were merely a result of the concentration effect. Collectively, our results revealed that the majority of leaf biochemical responses to drought stress are developmentally regulated processes. In addition, the alleviating effect of both RA and LA despite higher water loss indicated that an improved stomatal function upon K application allowed carbohydrates synthesis, thus, enhancing plant growth under water stress.

### Effect of Phosphorus and Potassium Foliage Application Post-Anthesis on Grain Filling and Hormonal Changes of Wheat

Lv, X. J. Han, Y. Liao, and Y. Liu. 2017. Field Crops Research 214:83-93. https://doi.org/10.1016/j.fcr.2017.09.001.

**Abstract:** Foliage application of fertilizer is an important supplement for soil application fertilizer. Phosphorus (P) and Potassium (K) are important nutrient elements that significantly affect the grain weight and grain yield of wheat, and foliage application of K and P is mainly used for wheat production in the northern dryland region of China. However, the mechanism underlying the regulation of grain filling by foliage application of

K and P is not understood. In the present study, monopotassium phosphate ($KH_2PO_4$), monosodium orthophosphate ($NaH_2PO_4$) and potassium chloride (KCl) were used for foliage application at the anthesis of wheat, and the changes of IAA, ABA, Z + ZR, GAs and ETH in wheat grain were measured during the grain filling process. The objective of this study was to investigate the effect of P and K foliage application on the grain filling process of wheat and to determine how changes in the endogenous hormones of the developing grains of winter wheat under P and K foliage application are related to the grain filling process. The results indicate that the effect of P and K foliage application on the grain filling of wheat is the difference. The K foliage application significantly increased the Z + ZR and ABA contents and decreased the ETH evolution rate in inferior grains, which promoted sink strength and increased the grain filling rate and the grain weight. In comparison, the P foliage application significantly promoted the activities of SOD, POD, and CAT and decreased the MDA content in the flag leaves and relieved the premature senility of the plant, which increased the active grain-filling period and the grain weight. For the heavy panicle cultivar, foliage P had a reasonable effect on grain filling, and for the light panicle cultivar, foliage K had a reasonable effect on grain filling. The mixture of P and K had an additive effect and prevented P and K deficiencies. Foliage application of $KH_2PO_4$ is an effectual measure for promoting the grain weight of wheat.

### Cultivar Sensitivity of Cotton Seed Yield to Potassium Availability is Associated with Differences in Carbohydrate Metabolism in the Developing Embryo

Hu, W., Z. Dai, J. Yang, J.L. Snider, S. Wang, Y. Meng, Y. Wang, B. Chen, W. Zhao, and Z. Zhou. 2017. Field Crops Research 214:301-309. https://doi.org/10.1016/j.fcr.2017.09.022.

**Abstract:** Storage lipids and proteins in cottonseed have important industrial values and carbohydrate metabolism is the basis for the biosynthesis of oil and protein in cottonseed. In order to investigate the effects of potassium (K) fertilizer on carbohydrate metabolism of cottonseeds in two cotton (*Gossypium hirsutum* L.) cultivars with different K sensitivities, a two-year field experiment was conducted with a low K-tolerant cultivar (Simian 3) and a low K-sensitive cultivar (Siza 3) under three K levels (0, 150 and 300 kg $K_2O$ $ha^{-1}$). Results showed that boll number and seed index were higher in the K application treatments (150 and 300 kg $K_2O$ $ha^{-1}$) than in the 0 kg $K_2O$ $ha^{-1}$, resulting in high cottonseed yield. Embryo weight was increased by K application, but seed coat weight was not influenced. K application did not change protein content, but markedly increased oil and non-structural saccharide contents, and K concentration was positively correlated with oil and non-structural carbohydrate contents. In addition, higher non-structural carbohydrate content in the K application treatments than in the 0 kg $K_2O$ $ha^{-1}$ was attributed to higher contents of starch, sucrose and fructose, and sucrose increased to a greater extent than other carbohydrates with K application. Higher fructose content in the K application treatments was closely related to higher sucrose synthase (SuSy) and acid invertase activities. Compared with Simian 3, the sensitivity of Siza 3 to K was evidenced in the following ways: (1) boll number, cottonseed yield, embryo biomass, and the seed coat to embryo ratio were increased more by K application for Siza 3 than Simian 3; (2) oil and carbohydrate accumulations in embryo were more responsive to K concentration in Siza 3 than Simian 3; (3) the increases in the contents of sucrose, starch and fructose and the activities of enzymes (SuSy and acid invertase) caused by K application were larger in Siza 3 than Simian 3; (4) the increases in sucrose phosphate synthase and alkaline invertase activities resulting from K application was only detected in Siza 3.

### Optimization of Nitrogen and Potassium Nutrition to Improve Yield and Yield Parameters of Irrigated Almond (*Prunus dulcis* (Mill.) D. A. Webb)

Saiful Muhammad, S., B.L. Sanden, S. Saa, B.D. Lampinen, D.R. Smart, K.A. Shackel, T.M. DeJong, and P.H. Brown. 2018, Scientia Horticulturae 228:204-212. https://doi.org/10.1016/j.scienta.2017.10.024.

**Abstract:** An experiment was conducted to evaluate the effect of nitrogen (N) and potassium (K) fertilization rates and fertilizer sources on almond yield and yield related parameters- fruit and kernel weight, number of fruits per tree, crackout percentage and leaf nutrient status by individually monitoring 768 trees. The experiment was carried out between 2008 and 2012 with four rates (140, 224, 309 and 392 kg N $ha^{-1}$) and two sources (UAN and CAN) of N and three rates (112, 224 and 336 kg K $ha^{-1}$) and sources (SOP + KTS, SOP and KCl) of K. Nitrogen fertilizer rate had a significant effect on yield in the second through the fourth year of the experiment. Tree yield was maximized at 18.5 kg and 23.7 kg kernel per tree in 2010 and 2011 season respectively when July leaf N was in the range 2.4-2.5% corresponding to an N application rate of 309 kg N $ha^{-1}$ and there was no increment in yield above 2.5% leaf N. Source of N had no significant effect on yield response. Potassium fertilization rate had no significant effect on yield while K sources had significant effect in 2010 only. Increasing N application resulted in lighter fruit, and kernel weight decreased with increasing N application under moderate yield conditions, and increased under high yield conditions. Yield increase with increasing N application was due to an increase in number of fruits and increased crackout percentage. Leaf K above 1% did not increase yield and there was no consistent effect of K supply and K source on yield parameters. There was a strong relationship between total yield and number of fruits per tree, which increased with increasing N application. Crackout percentage was also positively correlated to kernel yield. Nitrogen

and potassium fertilization rate should be based on expected yield and tree N and K status. For a well productive mature orchard, N application of 309 kg $ha^{-1}$ with either UAN or CAN can meet crop N needs. K fertilization should consider K contribution from soil. Under condition of 100-150 mg $kg^{-1}$ soil exchangeable potassium, K application of 112 kg $ha^{-1}$ with any K fertilizer source can satisfy crop K demand.

### Potassium Rates Affected Potassium Uptake and Use Efficiency in Drip-Irrigated Tomato

Zhu, Q., M. Ozores-Hampton, Y.C. Li, K.T. Morgan, and Y. Lu. 2017. Agron. J. 109(6):2945-2956. DOI: 10.2134/agronj2017.04.0206.

**Abstract:** Knowledge regarding K accumulation and partitioning is essential for improving potassium use efficiency (KUE). The objective of this study was to determine K uptake, distribution, and KUE in tomato (*Solanum lycopersicum* L.) production with multiple K rates. Field trials were conducted during the winter seasons of 2014 and 2015. Potassium was applied at 0, 56, 93, 149, 186, and 223 kg $ha^{-1}$ and divided into pre-plant dry fertilizer and weekly drip fertigation. Total potassium uptakes (TKU) at 30 d after transplanting (DAT) were not significantly affected by K rates, and averaged 5 and 14 kg $ha^{-1}$ in 2014 and 2015, respectively. The response of TKU at 95 DAT was predicted by a linear-plateau model with a critical rate of 192 kg $ha^{-1}$ and a maximum uptake of 264 kg $ha^{-1}$ in 2014, whereas a linear response was observed in 2015. The highest proportion of TKU at 95 DAT was accumulated in fruit, which ranged from 66 to 80% and 37 to 54% in 2014 and 2015, respectively. The ratio of fruit K uptake to TKU decreased with increasing K rate predicted by linear-plateau models with critical rates of 187 and 218 kg $ha^{-1}$ in 2014 and 2015, respectively. Results indicated the efficiency of converting K fertilizer into marketable yield also decreased with increasing K rate. Therefore, 192 kg $ha^{-1}$ was considered the sufficient K fertilizer requirement for tomato production on calcareous soils with 99 to 112 mg $kg^{-1}$ of Mehlich-3 extractable K.

### Promoting Potassium Allocation to Stalk Enhances Stalk Bending Resistance of Maize (*Zea mays* L.)

Xu, Z., T. Lai, S. Li, D. Si, C, Zhang, Z. Cui, and X. Chen. 2018. Field Crops Research 215:200-206. https://doi.org/10.1016/j.fcr.2017.10.020.

**Abstract:** Potassium (K) is an essential macronutrient for crop growth but it catches less attention than either nitrogen or phosphorus regarding their role in escalating crop yield. However, increasing evidences support the fact that K application enables crop to enhance resistance to lodging, but little is known about how maize resistance to lodging is affected by K distribution in shoot. We conducted a two-year field experiment including 6 levels of K application, monitored K uptake and distribution in different parts of shoot, and examined the effect of K application on stalk bending resistance of maize. K application significantly enhanced above-ground K uptake of maize. Across growing season, maize increased K uptake in the vegetative period while leveled off after anthesis. Stalk contained greater proportion of K than other parts, and stalk increased but ear rarely altered the K proportion with K application increase. K application significantly enhanced the bending resistant strength of maize stalk. The bending resistant strength was positively correlated with the diameter/length ratio, dry matter linear density and stalk K concentration, but those two internode morphological traits played more important role. We concluded that K application promoted K allocation to stalk and enhanced maize resistance to stalk lodging by modifying the internode traits. The study provides evidence for the importance of K application in maize production on soils with high stalk lodging risk.

### The Rice High-Affinity $K^+$ Transporter OsHKT2;4 Mediates $Mg^{2+}$ Homeostasis under High-$Mg^{2+}$ Conditions in Transgenic *Arabidopsis*

Zhang, C., H. Li, J. Wang, B. Zhang, W. Wang, H. Lin, S. Luan, J. Gao, and W. Lan. 2017. Front. Plant Sci. https://doi.org/10.3389/fpls.2017.01823.

**Abstract:** Rice (*Oryza sativa*; background Nipponbare) contains nine HKT (high-affinity $K^+$ transport)-like genes encoding membrane proteins belonging to the superfamily of Ktr/TRK/HKT. OsHKTs have been proposed to include four selectivity filter-pore-forming domains homologous to the bacterial $K^+$ channel KcsA, and are separated into OsHKT1s with $Na^+$-selective activity and OsHKT2s with $Na^+$-$K^+$ symport activity. As a member of the OsHKT2 subfamily, OsHKT2;4 renders $Mg^{2+}$ and $Ca^{2+}$ permeability for yeast cells and *Xenopus laevis* oocytes, besides $K^+$ and $Na^+$. However, physiological functions related to $Mg^{2+}$ *in planta* have not yet been identified. Here we report that OsHKT2;4 from rice (*O. sativa*; background Nipponbare) functions as a low-affinity $Mg^{2+}$ transporter to mediate $Mg^{2+}$ homeostasis in plants under high-$Mg^{2+}$ environments. Using the functional complementation assay in $Mg^{2+}$-uptake deficient *Salmonella typhimurium* strains MM281 and electrophysiological analysis in *X. laevis* oocytes, we found that OsHKT2;4 could rescue the growth of MM281 in $Mg^{2+}$-deficient conditions and induced the $Mg^{2+}$ currents in oocytes at millimolar range of $Mg^{2+}$. Additionally, overexpression of OsHKT2;4 to *Arabidopsis* mutant lines with a knockout of *AtMGT6*, a gene encoding the transporter protein necessary for $Mg^{2+}$ adaptation in *Arabidopsis*, caused the $Mg^{2+}$ toxicity to the leaves under the high-$Mg^{2+}$ stress, but not under low-$Mg^{2+}$ environments. Moreover, this $Mg^{2+}$ toxicity symptom resulted from the excessive $Mg^{2+}$ translocation from

roots to shoots, and was relieved by the increase in supplemental $Ca^{2+}$. Together, our results demonstrated that OsHKT2;4 is a low-affinity $Mg^{2+}$ transporter responsible for $Mg^{2+}$ transport to aerials in plants under high-$Mg^{2+}$ conditions.

### Transgenic Approaches for Improving Use Efficiency of Nitrogen, Phosphorus and Potassium in Crops

Teng, W., X. He, and Y.P. Tong. 2017. Journal of Integrative Agriculture 16(12):2657-2673. https://doi.org/10.1016/S2095-3119(17)61709-X.

**Abstract:** The success of the Green Revolution largely relies on fertilizers, and a new Green Revolution is very much needed to use fertilizers more economically and efficiently, as well as with more environmental responsibility. The use efficiency of nitrogen, phosphorus, and potassium is controlled by complex gene networks that co-ordinate uptake, re-distribution, assimilation, and storage of these nutrients. Great progress has been made in breeding nutrient-efficient crops by molecularly engineering root traits desirable for efficient acquisition of nutrients from soil, transporters for uptake, redistribution and homeostasis of nutrients, and enzymes for efficient assimilation. Regulatory and transcription factors modulating these processes are also valuable in breeding crops with improved nutrient use efficiency and yield performance.

### Mechanisms for High Potassium Selectivity of Soils Dominated by Halloysite from Northern California, USA

Takahashi, Y., R.A. Dahlgren, H. Kanno, M. Nanzyo, and T. Takahashi. 2017. Soil Science and Plant Nutrition. https://doi.org/10.1080/00380768.2017.1411167.

**Abstract:** Mechanisms contributing to unusually high cation exchange capacity and potassium ion selectivity in several halloysite-rich soils remain a topic of intense debate. In spite of the large number of studies, a unifying mechanism to explain the high charge and $K^+$ selectivity has not been elucidated. High $K^+$ selectivity occurs in several soils from northern California whose clay fraction is dominated by hydrated tubular halloysite (1.0 nm) and abundant Fe (hydr)oxides. To investigate the mechanism(s), we measured $K^+/Ca^{2+}$ selectivity and charge properties of the clay-size fraction of two California soils following various pretreatments, including organic matter removal by $H_2O_2$, Fe (hydr)oxide removal by citrate-dithionite (CD), and alteration of the basal spacing by dehydration (reduced-pressure drying). Transmission electron microscopy and X-ray diffraction indicated a predominance of tubular halloysite morphology with a 1.0-nm peak following Mg-saturation. In contrast, reduced pressure-dried samples showed a 0.7-nm peak without a 1.0-nm peak, indicating effective dehydration. The $K^+$ selectivity was strongly linked to the interlayer spacing (1.0 vs 0.7 nm) of halloysite and the presence of Fe (hydr)oxides. The 0.3 nm larger interlayer spacing in hydrated halloysite appears to contribute to $K^+$ selectivity as the weakly hydrated $K^+$ can readily dehydrate and enter into the interlayer space while the strongly hydrated $Ca^{2+}$ is too large to enter, a mechanism similar to $K^+$ selectivity of ion channels in human nerve and muscle tissue. The Fe (hydr) oxides may reduce the permanent negative charge and enhance $K^+$ selectivity via physically blocking interlayer exchange sites and repulsing cations, especially divalent cations, due to their positive charge. Results of this study suggest the occurrence of a high-charge, $K^+$-selective halloysite for which hydration/dehydration and Fe (hydr)oxides strongly influence the charge and selectivity characteristics by altering ion access to interlayer exchange sites.

### Evaluation of Nonexchangeable Potassium Content of Agricultural Soils in Japan by the Boiling $HNO_3$ Extraction Method in Comparison with Exchangeable Potassium

Kitagawa, Y., J. Yanai, and A. Nakao. 2017. Soil Science and Plant Nutrition. https://doi.org/10.1080/00380768.2017.1411168.

**Abstract:** The nonexchangeable potassium (neK) content of 178 agricultural soils in Japan was determined by subtracting the amount of K extracted with 1 mol $L^{-1}$ ammonium acetate, i.e., exchangeable K (exK) from that extracted with boiling 1 mol $L^{-1}$ $HNO_3$. The statistical relationships between the neK content and physico-chemical properties of the soils were examined to investigate the factors controlling neK content. The neK content of agricultural soils in Japan ranged from 0 to 1120 mg $kg^{-1}$ with an arithmetic mean and median of 303 and 255 mg $kg^{-1}$, respectively. It showed a significant positive correlation with the total K content, fixed ammonium content, and silt content ($p < 0.01$) and a significant negative correlation with Alo+1/2 Feo content and total carbon content ($p < 0.01$). These results suggest that the controlling factors of neK are mainly the total K content and 2:1 type phyllosilicates such as mica and vermiculite, with the indirect negative influence of organic matter and amorphous materials. Terrestrial Regosols, Brown Lowland soils, and Dark Red soils had relatively high neK contents. In contrast, Andosols, Wet Andosols, and Volcanogenous Regosols had relatively low neK contents. The neK content showed no significant correlation with exK content, suggesting that neK is a moderately to slowly available fraction of soil K, which is independent of exK. In conclusion, evaluation of nonexchangeable K in combination with exchangeable K would enhance the rational management of agricultural soils in terms of K fertility by taking account of longer term K-supplying power of soils.

### Melatonin is Involved in Regulation of Bermudagrass Growth and Development and Response to Low $K^+$ Stress

Chen, L., J. Fan, Z. Hu, X. Huang, E. Amombo, A. Liu, A. Bi, K. Chen, Y. Xie, and J. Fu. 2017. Front. Plant Sci. https://doi.org/10.3389/fpls.2017.02038.

**Abstract:** Melatonin (*N*-acetyl-5-methoxytryptamine) plays critical roles in plant growth and development and during the response to multiple abiotic stresses. However, the roles of melatonin in plant response to $K^+$ deficiency remain largely unknown. In the present study, we observed that the endogenous melatonin contents in bermudagrass were remarkably increased by low $K^+$ (LK) treatment, suggesting that melatonin was involved in bermudagrass response to LK stress. Further phenotype analysis revealed that exogenous melatonin application conferred Bermudagrass enhanced tolerance to LK stress. Interestingly, exogenous melatonin application also promoted bermudagrass growth and development at normal condition. Furthermore, the $K^+$ contents measurement revealed that melatonin-treated plants accumulated more $K^+$ in both shoot (under both control and LK condition) and root tissues (under LK condition) compared with those of melatonin non-treated plants. Expression analysis indicated that the transcripts of $K^+$ transport genes were significantly induced by exogenous melatonin treatment in bermudagrass under both control and LK stress conditions, especially under a combined treatment of LK stress and melatonin, which may increase accumulation of $K^+$ content profoundly under LK stress and thereby contributed to the LK-tolerant phenotype. In addition, we investigated the role of melatonin in the regulation of photosystem II (PSII) activities under LK stress. The chlorophyll fluorescence transient (OJIP) curves were obviously higher in plants grown in LK with melatonin (LK+Mel) than those of plants grown in LK medium without melatonin application for 1 or 2 weeks, suggesting that melatonin plays important roles in PSII against LK stress. After a combined treatment of LK stress and melatonin, the values for performance indexes ($PI_{ABS}$, $PI_{Total}$, and $PI_{CS}$), flux ratios ($\varphi P_0$, $\Psi E_0$, and $\varphi E_0$) and specific energy fluxes ($ET_0/RC$) were significantly improved compared with those of LK stress alone, suggesting that melatonin plays positive roles in protecting PSII activity under LK stress. Collectively, this study reveals an important role of melatonin in regulating bermudagrass response to LK stress.

# Clipboard

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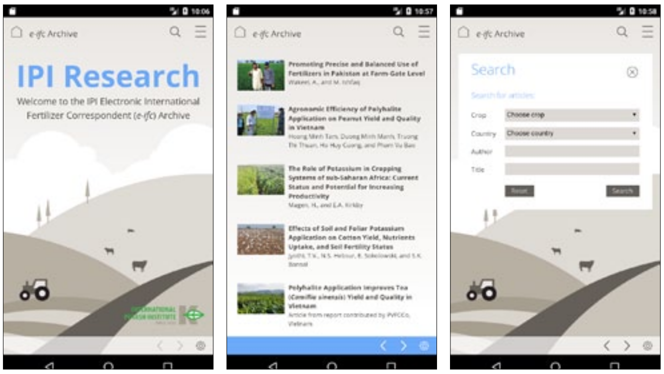


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# Clipboard (cont.)

## New IPI Coordinator for France: Frederic Carnec

Mr. Frederic Carnec is the IPI Coordinator for IPI activities in France. He has over 20 years' experience working with farmers and agro-dealers on crop nutrition throughout the country; balanced and efficient nutrition has always been his approach to crop farming.

Mr. Carnec works for ICL Fertilizers as a regional agronomist promoting the development of potash and Polysulphate through regular and specialty fertilizer solutions on numerous cultivated crops, including cereals, rapeseed, sugar beet, potato, vegetable and grape vine. Before his current position at ICL, Mr. Carnec worked first at the Le Comité Interprofessionnel du vin de Champagne for the development of "balanced management in vine growing" (soil erosion reduction, fungicide and fertilizer optimization), before then moving to an organic fertilizer company working in the Alsace, Burgundy and Champagne regions.

Mr. Carnec has a BSc and is an agronomic engineer with specialization in plant life from the Higher School of Agriculture in Angers where he completed a research project titled 'Mildew forecast model for grapevine protection'.

Mr. Carnec's expertise will be invaluable in the coordination of IPI's projects and extension programs in France.

Mr. Frederic Carnec can be contacted at:
frederic.carnec@icl-group.com

c/o ICL Fertilizers Europe C.V.
1, impasse Lundy
F-51100 Reims, France
T +33 3 26 47 64 40
M +33 6 07 30 26 02

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Editors: Amnon Bustan, Israel; Susanna Thorp, WRENmedia, UK; Patrick Harvey, Green-Shoots, UK; Hillel Magen, IPI
Layout and design: Martha Vacano, IPI
Address: International Potash Institute
Industriestrasse 31
CH-6300 Zug, Switzerland
Telephone: +41 43 810 49 22
Telefax: +41 43 810 49 25
E-mail: ipi@ipipotash.org
Website: www.ipipotash.org

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