e-ifc

Electronic International Fertilizer Correspondent *(e-ifc)*
Quarterly publication from IPI

No. 50 | September 2017

INTERNATIONAL POTASH INSTITUTE
SINCE 1952
Optimizing Crop Nutrition

Editorial

Dear readers,

Fertigation has been practiced for more than three decades. It started in places where water was scarce and where micro-irrigation systems (MIS) were installed. The main difference with MIS, compared to regular irrigation where all of the soil surface is irrigated, is that only the soil where the very active root zone thrive is wetted. Typically, this will be between 20% (with drip) to 60% (with micro jets) of the plow layer. This means that, in practice, the flow of nutrients to the plants' roots must be significantly greater than that with flood irrigation. Fertigation allows dosing of nutrients to the limited wetted zone, and therefore increases fertilizer use efficiency.

In this *e-ifc* edition, we feature the story of maize fertigation in China (Enhancing Maize Productivity via Drip Irrigation and Drip Fertigation on a Sandy Soil in Northeast China; by Wu *et al.*). Put simply, water scarcity and unstable seasonal precipitation dictates the use of a drip system, and that implies fertigation. The use of fertigation is being picked up fast, not only in cash crops, but also field crops such as maize in China.

Fertigation technology will capture our attention more and more, as we realize water scarcity and MIS installation.

I wish you an enjoyable read.

Hillel Magen
Director

Photo cover page: Photo by IPI.

Research Findings

Field day at the experimental site. Mr. Dali Wu explaining to Prof. Guohua Mi, researchers and farmers the results and conclusions of his work. Photo by E. Sokolowski.

Enhancing Maize Productivity via Drip Irrigation and Drip Fertigation on a Sandy Soil in Northeast China

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Abstract

In northeast China, maize (*Zea mays* L.) is the major crop, but water levels can become extremely low in the sandy soils on which it is grown. Fertilizer application via side-dressing is difficult and fertilizer use efficiency on sandy soils is low. Drip fertigation is a way to meet the water and nutrient demands of crop growth by dissolving fertilizers in water and delivering them through a drip irrigation system to the root zone. Field experiments were conducted from 2012-2015 to study the effect of drip irrigation and drip fertigation on yield formation and water use efficiency of maize. Three treatments were carried out: conventional (CK), under which all fertilizers were applied as basal fertilizer and the field was not irrigated; drip irrigation (DI), under which all fertilizers were applied as basal fertilizer and the field was irrigated by the drip irrigation system; and surface drip fertigation (DF), under which fertilizers were applied as a basal application plus top dressing, applied during the maize growth period via a drip irrigation system. The results indicate that DI improved soil moisture, increased dry matter accumulation, and increased maize yield in dry years (2014 and 2015) but not in wet years, with no effect on water productivity in both situations. Compared to DI, DF further improved maize growth and increased both

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grain yield and water productivity under years of regular rainfall (2012) and dry years (2014 and 2015). In 2013, when heavy rain events occurred during the growth season, both DI and DF showed no effect on maize growth or grain yield. These results suggest that DF is useful for increasing maize grain yield and water productivity under unstable seasonal precipitation patterns in northeast China.

Keywords: Climate change; drought; water productivity; *Zea mays*.

Introduction

Rain-fed maize is the major crop in northeast China, where drought is frequent in spring and/or summer seasons and is the most crop limiting climate factor (Zhao and Yang, 2009; Dong *et al*., 2011; Lu *et al*., 2014). Precipitation varies widely between seasons and years. The increasing pressure on food security in China necessitates a significant increase in maize production in this region, which in turn is largely dependent on the expansion of irrigated land. The efficiency of drip irrigation has been proved in many crops and therefore should be considered as a major irrigation method, especially in sandy soils where greater economic benefits may be obtained (Sogbedji *et al*., 2000; Bhardwaj *et al*., 2007; Fanish *et al*., 2011). Drip irrigation is mostly applied in fruit and vegetable crops, and in cotton (Lamm, 2016). Some studies have shown that drip irrigation increases yield and water use efficiency of onion, tomato, dry chili pepper, and potatoes compared to traditional furrow irrigation (Hebbar *et al*., 2004; Rajput and Patel, 2006; Kundu and Sarkar, 2009; Lamm, 2016). There is also growing interest in applying drip irrigation to lower-value field crops such as cotton and maize (Lamm *et al*., 2007).

Fertilizer application in the region is very common and often excessive, and, due to dry weather and labor limitations, farmers typically apply the entire seasonal fertilizer dose before or during seed sowing (Gao *et al*., 2008). Excessive nutrient application not only reduces fertilizer efficiency, but also increases soil nutrient loss and results in environmental pollution (Zhang, 2008; Zhang *et al*., 2011; Chen *et al*., 2013). Drip fertigation provides solutions to these problems, enabling water and nutrients supply directly to the root zone and at an amount adjusted to the dynamic plant requirements (Bar-Yosef *et al*., 1989; Bar-Yosef, 1999). Therefore, this approach provides a promising way to a simultaneous increase in maize productivity as well as fertilizer and water use efficiencies (Camp, 1998; Pablo *et al*., 2007; Fanish *et al*., 2011).

Nevertheless, the effect of drip irrigation and drip fertigation on maize production is unclear under the soil conditions and climate of northeast China. This study aims to compare the effects of drip irrigation and drip fertigation on maize productivity, and fertilizer and water use efficiency under different weather conditions on a sandy soil, and understand the relative contribution of water and fertilizer management on maize productivity.

Materials and methods

Location and weather

Field experiments were conducted in Lishu, Jilin province, China (43º21′48”N, 124º05′01”E). The region is under a sub-humid, warm, temperate and continental monsoon climate with an annual mean temperature of 11.6ºC. The annual average (1986-2013) rainfall during the maize growing season is 467mm, with significant fluctuations. During the four experimental years (2012-2015), the rainfall during maize growth season was 431, 550, 342, and 304 mm, respectively (Fig. 1). As a whole, rainfall was adequate and rain distribution was uniform in 2012. Heavy rainfall occurred at grain filling stage in 2013, resulting in a 3-day flooding (Fig. 2A). 2014 and 2015 were dry years (Fig. 2B). Experiments were carried out on a sandy soil with a bulk density of 1.6-1.8 g cm^{-3} in 0-200 cm soil depth.

Field design and experimental treatments

The field experiment was conducted using a randomized complete block design with three irrigation/fertilization treatments in four replications. The treatments were applied as follows: (1) conventional (CK), under which all fertilizers were applied as basal fertilizer and the field was not irrigated; (2) drip irrigation (DI), under which all fertilizers were applied as basal fertilizer and the field was irrigated via drip irrigation; (3) drip fertigation (DF), under which fertilizers were applied as basal application plus top dressing through a drip irrigation system during the maize growth period. Fertilizers were applied according to a target yield level of 12 Mg ha^{-1}. In all the treatment, the total amount of nitrogen (N) fertilizer was 240 kg N ha^{-1}. For phosphorus (P), fertilizer was applied in the form of phosphorus pentoxide (P_2O_5) at 110, 110, 120 and 100 kg ha^{-1} in each year of the experiment, respectively. Similarly, potassium (K) fertilizer was applied in the form of potassium oxide at 112, 112, 120, and 110 kg (K_2O) ha^{-1}. For the CK and DI treatments, all N, P, and K fertilizers were supplied basally using a compound fertilizer (N-P_2O_5-K_2O: 28-12-12), potassium chloride, and super calcium phosphate. For the DF treatment, a compound fertilizer of 15-15-15 was applied as a basal fertilizer, which comprised 30, 77 and 64% of the total N, P, and K input. The remaining N, P, and K was supplied via a fertigation system using urea (46% N) and a soluble compound fertilizer (N-P_2O_5-K_2O:30-6-12) from the company Gaipo. For the irrigated treatments (DI and DF), water supply was calculated according to the water requirement of the plant's developmental stage, minus precipitation. Rainfall was recorded regularly during the experiment.

The plot size was 25×6 m, with 10 rows in each plot. Maize was planted in a wide-narrow pattern (Fig. 3), that is, the distance between rows was 40 and 80 cm, alternately. The main pipes were

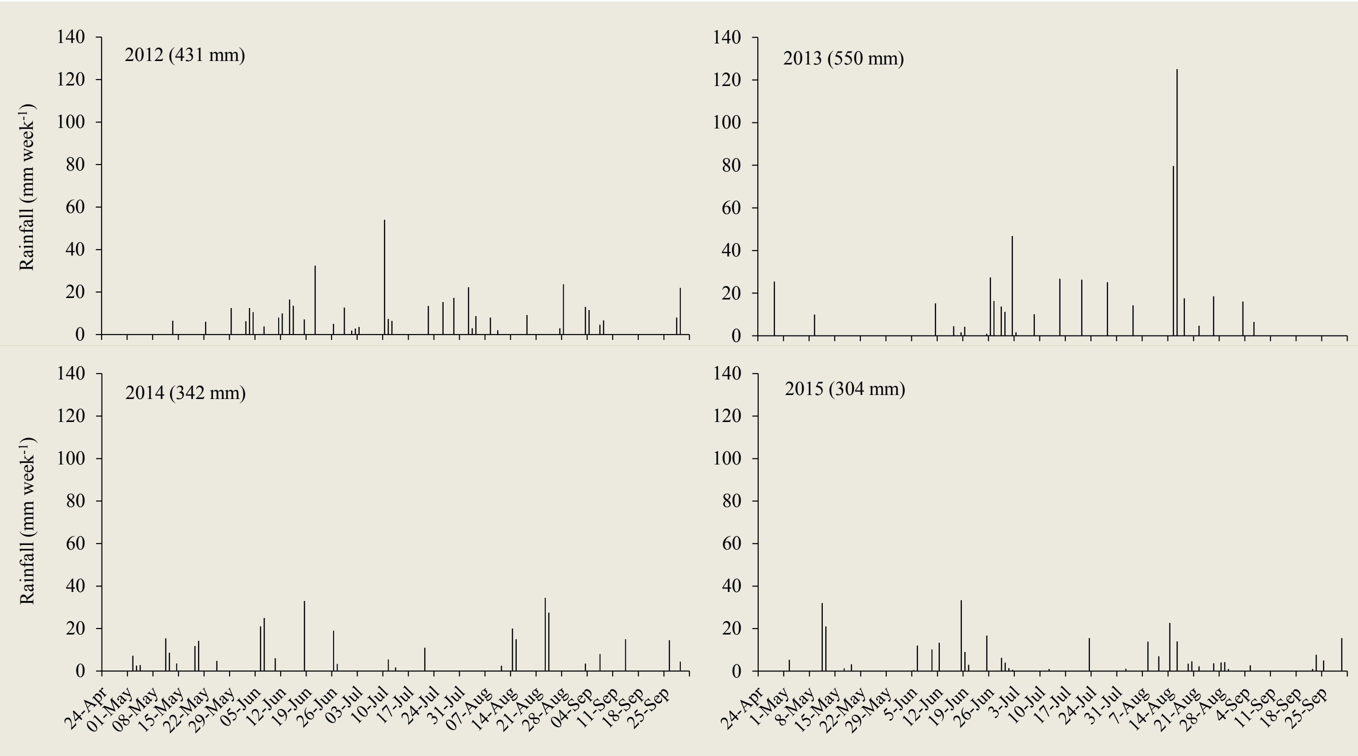

Fig. 1. Rainfall events (quantity and timing) during the 4-year experiment.

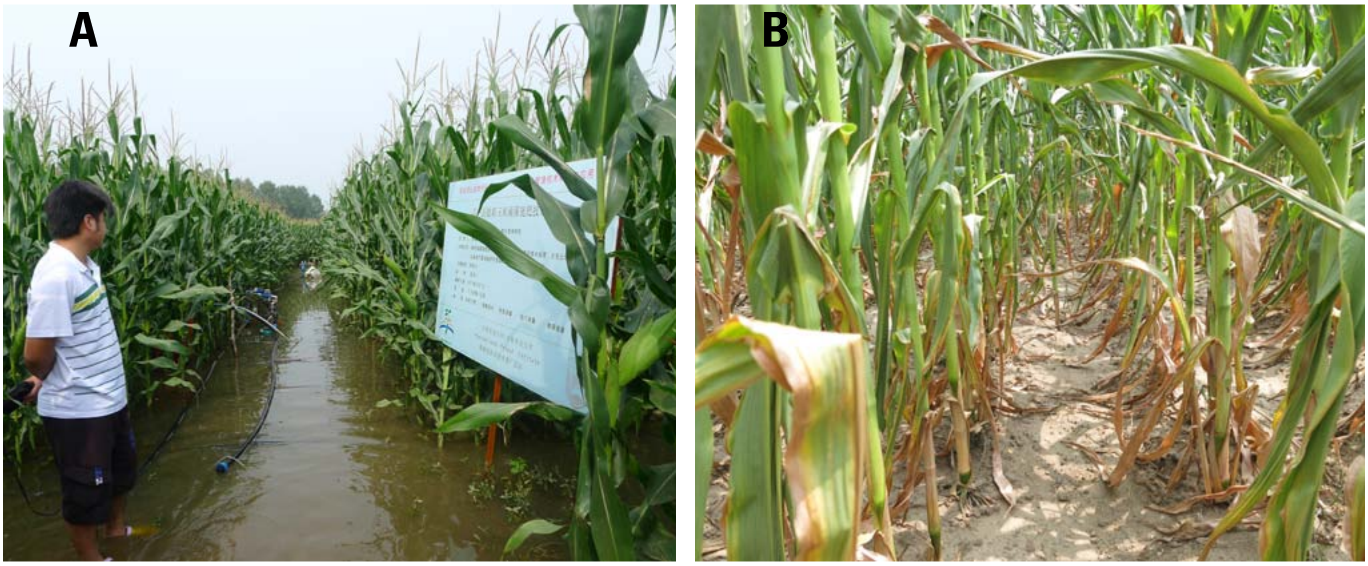

Fig. 2A, B. Flood event during mid-August 2013 at the grain-filling stage (Fig. 2A, left); drought stress impacts on maize during the 2014 season (Fig. 2B, right). Photos by authors.

positioned perpendicular to row direction, in the middle of the plots. The irrigation pipes were placed along the narrow inter-row gaps only. Each plot was equipped with a separate pump.

The maize hybrid cv. Liangyu 11 was planted each year on 1 May at a density of 70,000 plants ha^{-1}, and harvested on 1 October. Weeds, diseases and pests were well controlled by chemicals.

Measurements

Leaf area was measured during the grain filling period. Above-ground plant biomass was measured by harvesting three mature plants per plot. The above-ground plants were separated into leaves, stems (comprising the leaf sheath, tassels, and ear shoots), and grains. The samples were weighed and dried in an oven at

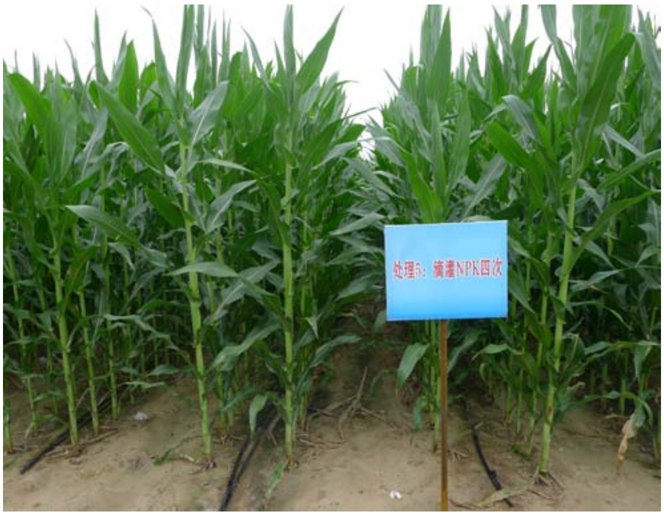

Fig. 3. The wide-narrow (80 and 40 cm gap between rows) pattern of planting. Irrigation pipes were positioned along narrow paths only. Photo by authors.

70°C. Grain yield was determined by harvesting an area of 20 m^2. Grain yield was adjusted to the standard water content of 14%.

Two random soil samples were taken from each plot using an auger at 0-80 cm from the soil surface at VT (tasseling stage, the onset of the reproductive phase). Each sample was divided into four layers at 20 cm intervals. Soil water content was determined by the gravimetric method (oven dry basis).

Water content at 0-2 m soil depth was measured before sowing and at harvest. The total water consumption, i.e. evapo-transpiration (ET), was calculated as ET = precipitation + irrigation + Δs, where Δs is the difference in water content between sowing and at harvest (Lamn *et al.*, 1995). Water productivity (WP) in kg m^{-3} was calculated as WP = (GY/ET) x 100, where GY is grain yield (kg ha^{-1}) for each treatment.

Statistical analyses

Data were analyzed using a SAS software variance analysis. Treatment means were compared using Duncan's multiple test. Probability levels lower than 0.05 or 0.01 were held to be significant.

Results

Grain yield

No significant difference was found in yield under the CK and DI treatments in 2012 and 2013. However, in 2014 and 2015, the DI yield was significantly higher than that of CK, by 38 and 20%, respectively (Fig. 4A; Fig. 5). The DF grain yield was significantly higher than CK in 2012, 2014 and 2015, by 19, 53 and 31%, respectively. However, no significant difference was observed for the DF and CK yields in 2013. There was no significant difference in yield between DF and DI in 2013 and 2014, while in 2012 and 2015, the DF yield was 15 and 9% higher than that of DI, respectively. When pooling the years together, the DI and DF treatments yielded an additional 1,482 and 2,483 kg grains ha^{-1} compared to the CK treatment - 16 and 27% higher, respectively. Nevertheless, the difference between the DI and DF yields remained insignificant (Fig. 4B).

Leaf area

The effects of DI and DF on plant growth varied between years, affected by seasonal precipitation. No difference in leaf area per plant during the grain filling stage was found among the three

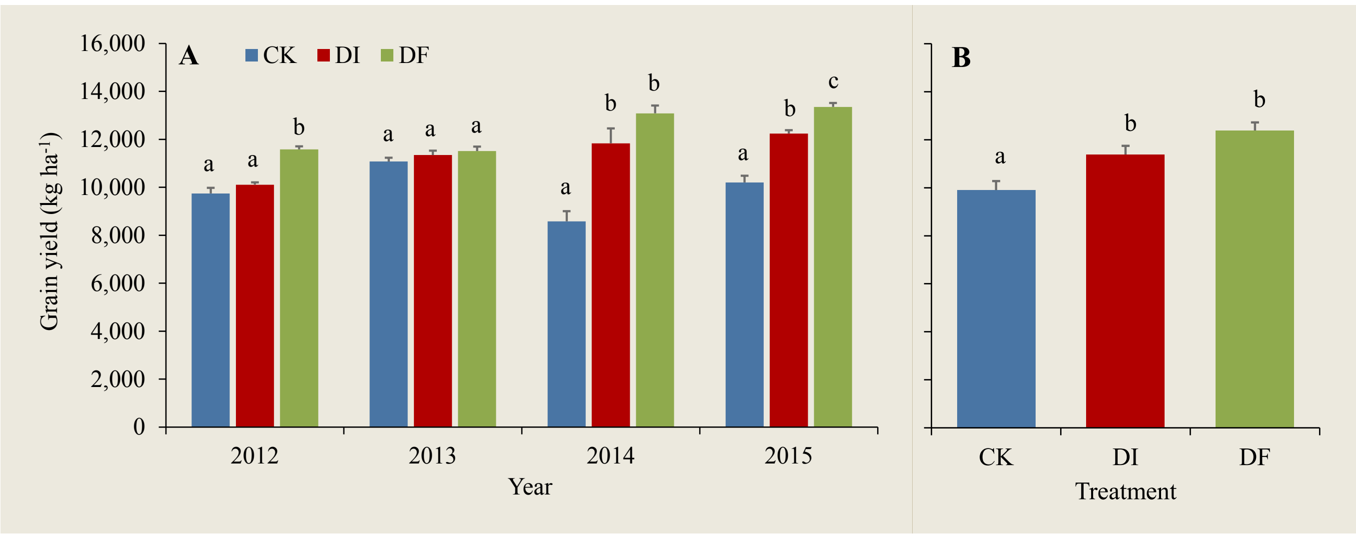

Fig. 4A, B. A: mean yield comparison under the DI, DF and CK treatments during the 4-year experiment; B: multi-annual comparison between treatments. Data in figure A with the same letter within the same year, do not differ at the 0.05 level of significance.

treatments in 2012 and 2013 (Fig. 6). In 2014, however, the leaf area of DI was 79% higher than that of CK (Fig. 5; Fig. 6), and the leaf area of DF was 25 and 124% higher than that of DI and CK, respectively. In 2015, the leaf area of DI and DF were 20 and 23% higher than that of CK, respectively.

Dry matter accumulation and harvest index

In 2012, 2014 and 2015, the dry matter accumulation of DI was 10, 26, and 17% greater than that of CK, respectively (Table 1). DF dry matter accumulation was 9, 38 and 23% higher than that of CK, respectively, while in 2013 no significant difference in dry matter accumulation was observed between the treatments.

In 2012, the harvest index of DI was lower than that of CK, while those of DF and CK did not differ significantly. In 2014, DI and DF had significantly higher harvest indices than CK, whereas in 2013 and 2015, no significant difference in harvest index occurred between the treatments (Table 1).

Soil moisture

Soil moisture was measured at the silking stage (Fig. 7). Excluding 2015, moisture was lowest at the upper soil layer (0-20 cm) and increased at deeper soil layers. In 2012, DF soil moisture at 20-40 cm deep was slightly though significantly higher than that of CK, but no other significant differences occurred between treatments. In the 2013 rainy season (Fig. 1), no treatment seemed to have any effect on soil moisture. On the contrary, during the two relatively dry summers of 2014 and 2015, significantly higher soil moisture contents at most depths were displayed under the DI and DF treatments when compared to CK (Fig. 7).

Water consumption and water productivity

Plant water consumption under the CK treatment varied greatly among years (Table 2) due to large differences in the levels of precipitation (Fig. 1). In contrast, the water consumption rate under the DI and DF treatments was much more stable between years, and significantly higher than that of CK (excluding DI in 2012). Plant water consumption under the DI and DF treatments did not differ.

Fig. 5. Effects of the DI and CK treatments on maize plant vitality (top) and on grain formation at the filling stage (bottom), in 2014.

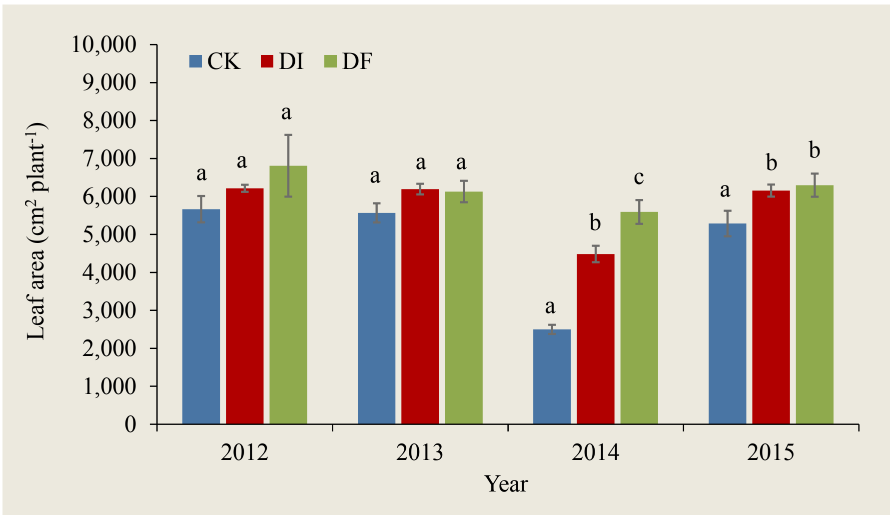

Fig. 6. Effect of DI and DF on leaf area at the grain filling stage. Data within the same year with the same letter do not differ at the 0.05 level of significance.

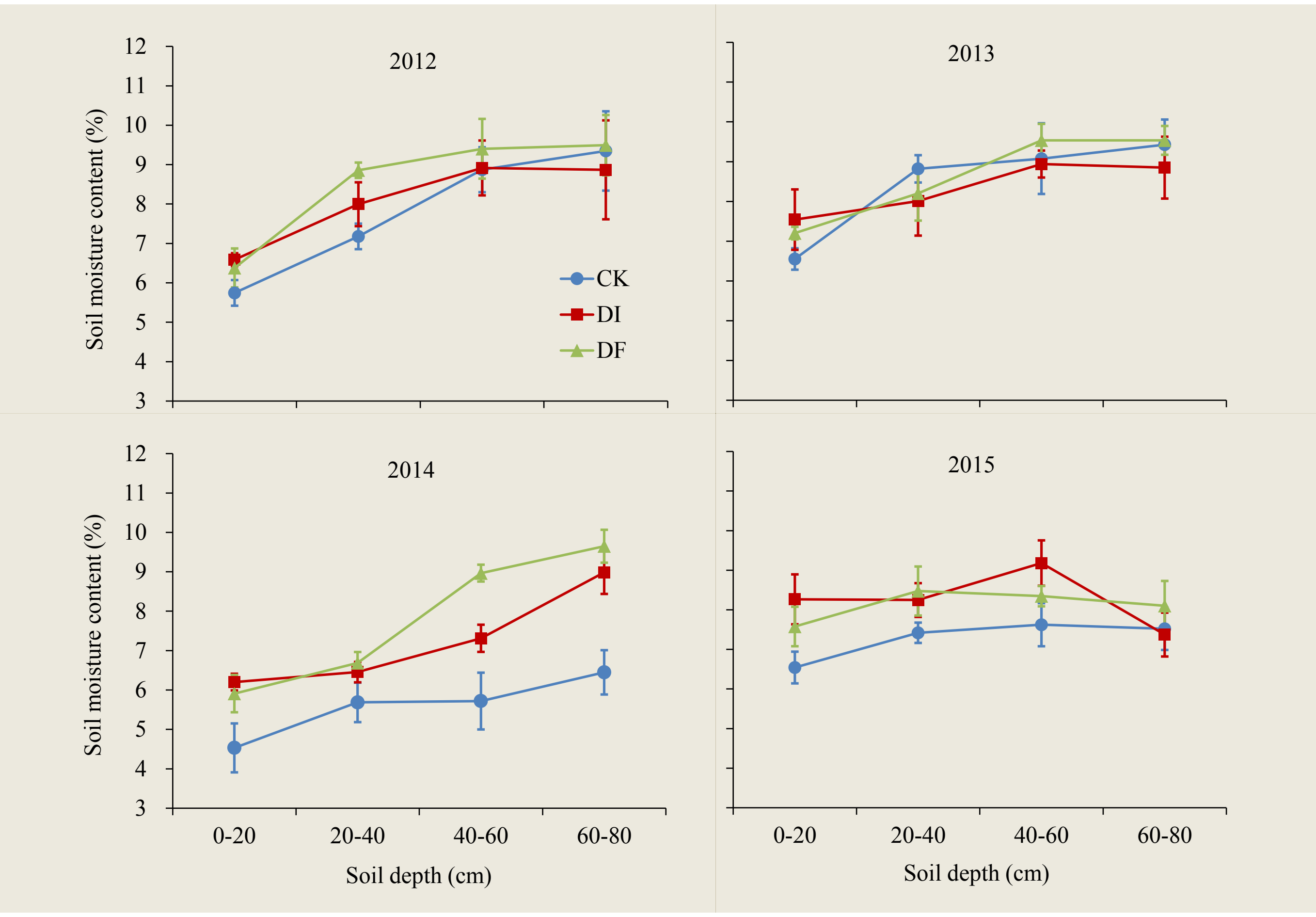

Fig. 7. Soil moisture content at the silking stage. Bars indicate SE.

Table 1. Dry matter accumulation and harvest index at harvest.

Treatment	Dry matter accumulation				Harvest index			
	2012	2013	2014	2015	2012	2013	2014	2015
	-------------------g plant^{-1}-------------------				---------------------%---------------------			
CK	255 b	267 a	222 b	260 b	53 a	54 a	41 b	53 a
DI	280 a	274 a	279 a	303 a	50 b	54 a	53 a	52 a
DF	279 a	262 a	305 a	319 a	51 ab	55 a	54 a	53 a

Note: Data within the same year with the same letter do not differ at the 0.05 level of significance.

Table 2. Plant water consumption and water productivity.

Treatment	Water consumption				Water productivity			
	2012	2013	2014	2015	2012	2013	2014	2015
	---------------------mm---------------------				---------------kg ha^{-1} mm^{-1}---------------			
CK	405 b	416 b	344 b	352 b	24 b	27 a	25 b	29 b
DI	429 ab	446 a	457 a	432 a	24 b	25 a	26 b	28 b
DF	441 a	447 a	418 a	425 a	26 a	26 a	31 a	32 a

Note: Data within the same year with the same letter do not differ at the 0.05 level of significance.

Water productivity was similar under the DI and CK treatments (Table 2). In 2012, 2014 and 2015, DF water productivity was 11, 21 and 11% higher than that of DI, and 9, 26 and 8% higher than that of CK, respectively. In 2013, no differences in water productivity occurred between treatments.

Discussion

Grain yield in corn is comprised of the following components: ears per unit area, kernel number per ear (consisting kernel rows and kernels per row), and kernel weight. Each of these yield components is determined at different stages in the lifecycle of the plant. Sufficient water and nutrient availability is essential for adequate canopy size and high yield.

The number of early reproductive structures is often greater than what the plant is later capable of supporting. The size of yield components is then influenced by the environmental and management stresses of the growing season (Sacks and Kucharik, 2011; Harrison *et al.*, 2014). During the 4-year experiment from 2012 to 2015, rainfall amount and distribution varied considerably (Fig. 1), having significant effects on CK maize yields. These yields fluctuated significantly, from pretty high levels in the rainy year of 2013 to low levels in the relatively dry year of 2014 (Fig. 2).

Rain distribution throughout the growing season, and particularly the timing of sufficient rain events, is sometimes even more important than rain quantity. The tasseling, silking and pollination stages of corn development are extremely critical because after these, the ear and kernel numbers can no longer be increased by the plant, and the potential size of the kernel is determined. Thus, kernel number is at its greatest potential slightly before R1, the earliest reproductive stage; the actual number of kernels formed is determined by pollination of the kernel ovule. Kernel weight, the last yield component, is determined during the first 7-10 days after pollination, at the cell division phase of the endosperm, which determines the potential number of starch accumulating cells. Thus, short drought periods that occur at critical developmental stages may cause significant yield reduction, even if the seasonal precipitation level is sufficient (Lu *et al.*, 2014; Messina *et al.*, 2014). On the other hand, a well-distributed precipitation pattern may sometimes compensate for a relatively dry season, and may explain the differences in CK yields between the dry seasons of 2014 and 2015 (Fig. 2).

Stable, accurate, and sufficient water supply is the major advantage expected from drip irrigation (Bar-Yosef, 1999). Indeed, DI increased soil moisture content (Fig. 7), leaf area (Fig. 6), and dry matter accumulation (Table 1) in 2014 and 2015, with corresponding increases in grain yield by 38 and 20%, respectively, and without any effect on the harvest index. In 2012 and 2013, however, DI did not have the same influence on yield due to adequate precipitation that satisfied plant water demands. In 2012, DI increased dry matter accumulation but the grain yield did not differ from that of CK. The reduced DI harvest index in that year may suggest that in spite of the improved vegetative growth, there were some occasional problems following the reproductive process. Interestingly, DI had no influence on water productivity (Table 2); any increase in dry matter or grain yield was accompanied by a corresponding increase in water consumption. Therefore, drip irrigation alone is a matter of improved water availability rather than of a physiological water use efficiency by the plant. Nevertheless, in order to fully extract the potential of this technology, the implementation of drip irrigation must be carefully attuned to the local soil and environmental conditions, and crop species.

On sandy soils, the profile shape of moist soil under each emitter tends to be deep and narrow, due to the low hydraulic conductivity of sand. The maize root system is usually shallow, as indicated by the pattern of soil moisture in the present study (Fig. 7). In addition, the water retention of sandy soils is very low, 2-8%, v/v. These restrictions dictate small gaps between emitters are required, along with a high-frequency irrigation regime, in order to maintain the steady adequately moist rhizosphere required to realize maize productivity (Djaman *et al.*, 2013).

A major advantage of drip irrigation lies in its ability to deliver soluble nutrients directly to the plant roots at the required amount and timing. This enables accurate nutrition management according to the crop's varying requirements across development stages (Pettigrew, 2008). This advantage is demonstrated by the DF results of the present study. Further to the yield increase observed under DI, the DF treatment displayed an added benefit - significantly higher grain yield in 2012 and 2015, and an obvious same tendency in 2014 (Fig. 4A). On average, DF increased grain yield by 27 and 9% compared to CK and DI, respectively (Fig. 4B). Excluding 2014 - when the maize under DF displayed a significantly higher leaf area - the advantage of DF over DI in the other years seemed to evolve from aggregated insignificant rises in several parameters (leaf area, dry matter accumulation, and harvest index). Consequent to the higher grain yield accompanied by insignificant changes in water consumption (Table 2), the DF water productivity was significantly higher than that of DI in 2012, 2014, and 2015. In contrast, the results in 2013 demonstrate that the advantages of DI or DF may disappear following heavy rain events that coincide with critical stages of development.

In conclusion, DI is remarkably advantageous in dry years, providing sufficient water supply throughout the growing season and enabling the avoidance of water stress during critical stages at the reproductive phase. Thus, DI supports vigorous and productive maize crop growth under environmental uncertainties, but it does not affect water productivity. The direct and continuous nutrient supply to the root system, as under DF, enhances crop performance; plants are more vigorous, build more dry matter and increase water productivity, altogether leading to grain yields higher than those of DI in years of regular rainfall and dry years. Nevertheless, the advantages of DF and DI are expected to decline under a well-distributed and sufficient precipitation regime or diminish under flood events.

Acknowledgement

This project was financially supported by the International Potash Institute (IPI), Switzerland.

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The paper "Enhancing Maize Productivity Via Drip Irrigation and Drip Fertigation on a Sandy Soil in Northeast China" also appears on the IPI website at:

Regional activities/China

Research Findings

Tea plantation in Western Ethiopia. Photo by B. Kassahun.

Potassium Availability in Selected Clayish Soils of the Ethiopian Central Highlands: Reassessment of Soil Testing Methods

Kassahun, B.[1]

Abstract

For a long time, the importance of potassium (K) fertilization in Ethiopian soils has been incorrectly perceived to be unnecessary due to the misconception that K reserves in the soils were sufficient. This study was conducted with the aim of assessing four soil testing methods (NH_4OAc, $CaCl_2$, Mehlich-3 [M-3], and Schofield-Woodruff [ΔF]) to determine plant available K in Ethiopian highland clay soils. Sixty composite (0-20 cm), geo-referenced surface soils were collected from 20 districts in 11 zones of Ethiopia's central highlands. While M-3 and NH_4OAc K extraction methods seem quite similar, but over-estimate soil K availability, the $CaCl_2$ method mainly identifies the soluble K fraction, under-estimating exchangeable K. The ΔF method shows considerable agreement with the $CaCl_2$ method but has additional sensitivity to exchangeable K. ΔF results indicate that 60% of the soils sampled could be considered as sufficient K suppliers, depending in the crop species, while the rest are poor K suppliers. Preliminary mineralogical examination revealed a dominance

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of illite/smectite in most samples but the ratio between the two minerals, which might determine K fixation and release rates, is yet unknown. In the absence of any alternative proven chemical method to evaluate soil K availability, direct measurements of crops' K consumption should be integrated with simultaneous soil-K tests. Also, clay mineralogy should be further investigated on a local basis in order to determine and understand actual and possible dynamics of soil K status and availability, to establish a sufficient basis for practical recommendations.

Keywords: Illite; Mehlich-3; smectite; soil-K availability; soil-K extraction methods.

Introduction

The intensive fertilization approach emphasizes the need for fertilizer inputs to replace crop nutrient removal and to maintain soil nutrient reserves. In Ethiopia K fertilization was deemed to be unnecessary due to the misconception that K reserves in the soils were sufficient and, on the whole, in a form available to plants. Moreover, crops' response to K fertilization was inconsistent or insignificant (Murphy, 1968). In addition, the exchangeable K content of most agricultural soils exceeded the universally accepted critical level, as set by the index based on ammonium acetate extraction method, at 0.25 cmol kg^{-1}.

Analyses of both past and recent information on K status in different woredas (districts) of Ethiopia, however, show that there has been a gradual decline in K status due to continuous mining, leaching, and soil erosion (Wassie, 2009). In its national soil fertility survey initiative, the Ethiopian Soil Information System (EthioSIS, 2013-2016) found K deficiency in key areas that have Vertisols, Nitisols, and other soil types. This has also been supported by crop K response demonstrations. At the same time, crop response to K fertilizer has emerged in many highland Vertisols, despite soil analysis results that show K levels higher than the critical level of 195 ppm, adopted by EthioSIS.

Potassium's significance to plant nutrition is well recognized despite its complex and dynamic nature in soils (Zörb *et al.*, 2014). Long-term intensive cropping in the absence of K inputs, adversely affects K supply to crop plants and consequently reduces crop yields (Swarup and Ganeshmurthy, 1998). Next to nitrogen (N), crops absorb K in greater amounts than any other nutrient. It is indispensable in nearly all processes required to sustain adequate plant growth and reproduction. Potassium plays a basic role in a series of fundamental metabolic and physiological processes in the plant. Its accumulation rate during early growth stages precedes N accumulation. Therefore, its supply to plants seems to be decisive for N utilization. In turn, K significantly affects plant growth rates and governs the degree of realization of yield potential (Grzebisz *et al.*, 2012).

Soil K can be categorized into four main fractions: K in soil solution; exchangeable K; non-exchangeable K, which is fixed but potentially available; and K in the mineral matrix (Hoagland and Martin, 1933). Soil K availability to plants and microbes declines according to its chemical phase and location in the soil, as follows: soil solution > exchangeable K > fixed K (non-exchangeable) > mineral K (Sparks and Huang, 1985; Sparks, 1987; Sparks, 2000). According to Barbagelata (2006), these four categories give a general representation of the potential sources for plant-available K, but no distinct boundaries exist among them. The bulk of soil K is confined to the solid mineral soil phase (Sparks and Huang, 1985), while the exchangeable and the non-exchangeable K comprise a small portion of total soil K, located mostly at the soil solid-solution interphase. There are equilibria and kinetic reactions between the four soil K categories that affect the level of soil solution K at any particular time, hence determine the level of readily available K for plants. Although exchangeable K is widely used to evaluate soil K status and to predict K availability to crops (Krauss, 2003; Samaadi, 2006), such predictions have proven to be a difficult task due to the complexity of the dynamic equilibrium among the various forms of soil K (Barbagelata, 2006).

Potassium availability to plants is related in many ways to the structure and morphology of soil minerals, particularly clay (Zörb *et al.*, 2014). Clay minerals comprise significant diversity of composition, structure, and consequent chemical and physical traits (Barton and Karathanasis, 2002). Thus, K sorption and desorption in soil are largely influenced by the amount and proportions of different clay mineral types. Potassium is readily adsorbed by 2:1 smectite clay minerals, thus plants require a higher dosage of K fertilizer than on other clay minerals, such as 2:1:1, 1:1, oxide, and alophane. Nursyamsia *et al.* (2008) suggested that of the 2:1 clay mineral types, beidelite or smectite has the highest fixation capacity. Bajawa (1987) showed that K fixation declines in the order of smectite > vermiculite > hydrous mica = chlorite = haloysite. The contradiction between the complex, fuzzy dynamics of K soil status, on the one hand, and the need to quantify the soil's ability to supply K for current and future crops, on the other hand, calls for careful methodologies of soil testing. The relevance of total soil K as an indicator for plant nutrition, in many cases, therefore is quite small. However, quantifying K in soil solutions, and estimating the rates at which K is released from the exchangeable K pool, can provide enhanced diagnoses of the readily available K pool, thus supporting decisions regarding fertilizer application.

A wide range of soil extraction methods claim to quantify the readily available K soil fraction, however, each method holds advantages and drawbacks that are derived from the nature of the local soil. The most common soil test procedure at the global level is the use of neutral 1N ammonium acetate (NH_4OAc) extraction

Photo 1. Measuring Ca, Mg and Na from soil extract by AAS (Atomic Arbitration Spectroscopy). Photo by E. Sokolowski.

on air- or oven-dried soil samples (Cox *et al.*, 1999). NH_4OAc extracts mainly soil solution K, exchangeable K, and a portion of interlayer K. This method uses a neutral salt solution to replace the cations present in the soil exchange complex. Therefore, the K concentration determined by this method is referred to as "exchangeable" for non-calcareous soils and "exchangeable plus soluble" for calcareous soils. Though this method mostly reflects the fertilizer K requirements of plants, there is some evidence that the NH_4OAc method is not sensitive enough for Vertisols. Cox *et al.* (1999) also claim that while 1N NH_4OAc soil test values work well for some soils, this approach is not reliable enough for soils with appreciable proportions of non-exchangeable interlayer K^+, such as smectite mineral soils. The situation is even more problematic under intensively cropped agricultural systems (Bansal *et al.*, 2002).

A single soil extraction with 0.01 M $CaCl_2$ appears to be the simplest, most inexpensive, and environmentally-friendly method, the results of which display the least variability among laboratories, compared to some other methods (Houba *et al.*, 1996). Water and weak salt solutions extract K ions in the soil solution that are in equilibrium with those on the exchangeable complex. It is assumed that this method extracts the most readily available K from the exchangeable phase. Together with K in soil solution, the results effectually represent the plant's available soil K pool, providing more precise estimates, compared to methods extracting the total exchangeable K.

The concept of a nutrient potential as a measure of soil K status was first suggested by Schofield (1947). This method uses an indirect measure of the energy input required by a plant to remove nutrients from the soil. Woodruff (1955) related classical thermodynamics to soil exchangeable K^+ and calcium and magnesium ($Ca^{2+}+Mg^{2+}$) release to the soil solution for determining the free energy of K-Ca exchange equilibria in soils. According to Woodruff (1955), the energy of exchange is a measure of the chemical potential of K in the soil relative to the chemical potential of Ca in the same soil. The ability of a soil to supply K to plants is characterized by both the total amount of nutrient present (quantity, Q) and the energy level at which it is supplied (potential, P). The K^+ potential (ΔGK) is a free energy measure of the soil's nutrient availability, expressed as a ratio of the relative activity and exchange between K^+ and $Ca^{2+}+Mg^{2+}$ (Keene *et al.*, 2004). The Schofield-Woodruff (ΔF) method classifies soils according to their K supplying power as follows: soils with high K supplying power: $\Delta F > -2{,}000$ cal $mole^{-1}$; medium K supplying power: $-3{,}500 < \Delta F < -2{,}000$ cal $mole^{-1}$; and, poor K supplying soils: $\Delta F < -3{,}500$ cal $mole^{-1}$.

An alternative method is Mehlich-3 (M-3) (Mehlich, 1984), which has become very common, almost 'universal', as it suits a wide range of soils (Zbiral and Nemec, 2000) and is relatively low cost. M-3 was developed as a multi-element (phosphorus [P], K, Ca, magnesium [Mg], sodium [Na], copper [Cu], zinc [Zn], manganese [Mn], Boron [B], aluminum [Al], and iron [Fe]) soil extraction and is widely used in agronomic studies to evaluate soil nutrient status and to establish fertilizer recommendations, mainly for P and K in humid regions. Several authors (Beegle and Oravec, 1990; Gartley *et al.*, 2002; Wang *et al.*, 2004) showed that both neutral 1N NH_4OAc and M-3 methods remove almost the same amount of K from the soil.

The M-3 soil test is widely accepted and employed throughout Africa, including Ethiopia. The debates that have recently been raised regarding the actual profile of K availability in selected Ethiopian clay soils, and the crucial consequences it might have on fertilization policy and on locally recommended practices, necessitates the reassessment of K extraction methods that are being employed. The objective of the present study, therefore, is to examine and compare various common methods and establish a starting point for further investigation, aiming to adopt the most appropriate method to evaluate K availability of selected Ethiopian highland clay soils.

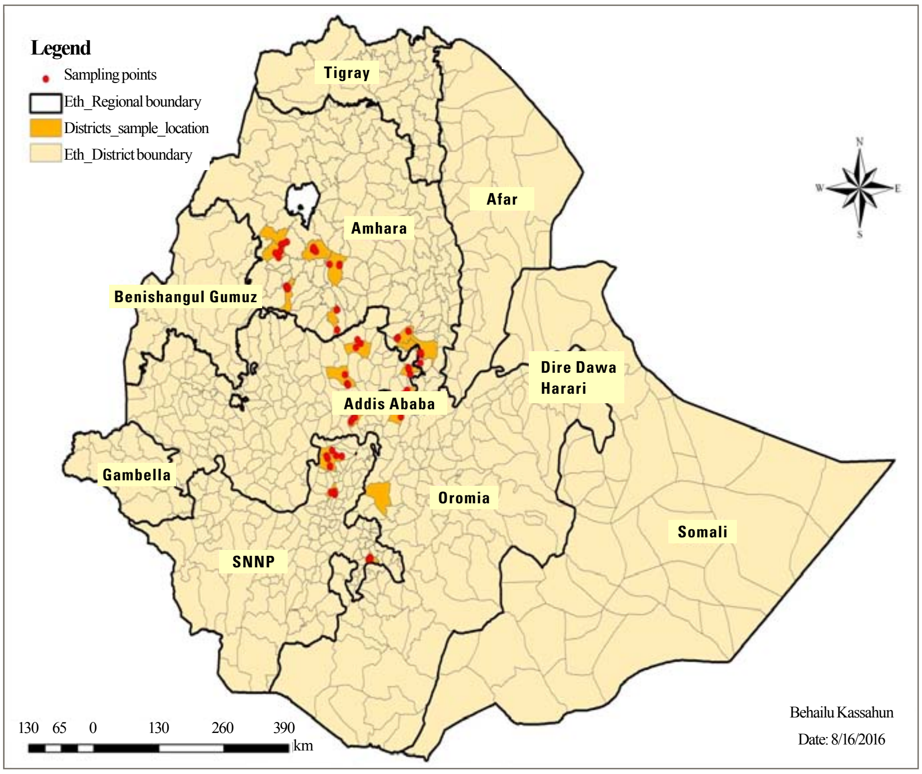

Fig. 1. Soil sampling locations in Ethiopia.

Materials and methods

Soil sampling

Sixty geo-referenced composite surface (0-20 cm) soil samples were collected from 20 districts located in 11 zones within Ethiopia's central highlands (Fig. 1). These areas were Awi zone (Dangila district), East Gojam zone (Aneded, Huleteju Enense districts), East Showa zone (Adea, Gimbichu districts), Gurage zone (Cheha, Enemore Ener districts), Hadiya zone (Limo district), North Shewa zone (Basona Worena, Kimbibit, Kuyu, Moretena Jiru, Siyadeberna Wayu districts), Sidama zone (Hagere Selam district), South West Shewa zone (Becho district), West Arsi zone (Arsi Negele), West Gojam zone (Bure, South Achefer, Yilmana Densa districts) and West Shewa zone (Jeldu district). From each district, three sub-districts were selected based on K^+ levels found (high, medium and low K) in a previous study, using the M-3 method. The present samples, however, were not taken from exactly the same sampling points as the previous study.

Sample preparation, analysis, and K extraction methods

Samples were air-dried, gently crushed and sieved using a 2 mm diameter sieve for analysis. Particle size was determined using a laser diffraction technique at Ethiopia's national soil testing center. Water and chemical extraction was conducted in the laboratories at Gilat Agricultural Research Center, ARO, in Israel. Water content was determined both from saturated paste and air-dried soil, and electrical conductivity (EC) and pH was measured from saturated paste extract. Cation exchange capacity (CEC) and exchangeable K percentage (EPP) were calculated after measuring Ca, Mg and Na from the NH_4OAc extract. Potassium, Ca, Mg and Na in all extracts were determined using atomic absorption spectroscopy (AAS).

Neutral ammonium-acetate extraction

Soil samples were dried and crushed to pass through a 2 mm sieve. Two grams of soil was extracted with 1:10 soil-solution ratio of neutral 1M NH_4OAc at pH 7 after shaking for 15 minutes (Helmek and Sparks, 1996).

Calcium chloride extraction

Air-dried soil samples were extracted for 2 hours with a 0.01 M $CaCl_2$ solution at 20°C, at a 1:10 ratio of sample to extracting solution, respectively. After measuring the pH in the settling suspension, the concentrations of nutritional and polluting elements were measured in the clear filtrate (Houba *et al.*, 1996; Simonis and Setatou, 1996; Salomon, 1998).

ΔF method

This is based on determining the exchange energy of K (ΔF), with the prevalent divalent cations (Ca^{2+}+Mg^{2+}) (Schofield, 1947). The range of ΔF values is usually between -2,000 and -4,000 cal mole^{-1}, where the upper value (-2,000) indicates K sufficiency, and the lower (-4,000) K deficiency. The free energy of replacement (ΔF) is calculated using the formula proposed by Woodruff (1955) where R is gas constant, and T is the absolute temperature (°K):

$$-\Delta F = 2.303\ RT \log \frac{a_k}{\sqrt{a_{Ca} + a_{Mg}}}$$

This concept simulates the measure of the energy a plant must invest to remove K from the soil, and thus can represent K availability to plants.

M-3 method

The M-3 extracting solution is comprised of 0.2 M acetic acid (CH_3COOH), 0.25 M ammonium nitrate (NH_4NO_3), 0.015 M ammonium fluoride (NH_4F), 0.013 M HNO_3, and 0.001 M ethylene di-amine tetra-acetic acid (EDTA). A soil sample of 2.5 g is mixed with the extracting solution at the ratio of 1:10, respectively, and shaken for 5 minutes (Mehlich, 1984).

Clay mineralogy

Clay mineralogy analysis was conducted for 11 selected soil samples in the Ministry of National Infrastructures, Energy and Water Resources Geological Survey laboratory in Israel. These samples were disaggregated and passed through a 2 mm sieve. The clay fraction was collected from thin suspensions according to Stokes Law after carbonate minerals and salts were removed from samples by diluted HCl acid or buffered acetic acid, repeatedly washed, and treated by a low-intensity ultrasonic treatment for a few minutes. Clay suspension was pipetted onto glass slides and analyzed after air-drying, glycolation (at least 8 hours at 60°C and cooling overnight), and heating for 2 hours to 550°C) (Moore and Reynolds, 1989). The mineralogical composition of the clay fraction was analyzed by X-ray diffraction.

Results and discussion

Analytical results for selected physical and chemical soil properties are summarized and presented in Table 1. Soil pH (H_2O) values varied from 4.68 to 8.07, normally categorized from very acidic to moderately alkaline (Bruce and Rayment, 1982). The lowest value (4.68) was observed in South Achefer district in west Gojam zone, while the highest one (8.07) was found in Dangila district in Awi zone.

EC, measured form saturated soil paste extract (ECe), ranged from non-saline (0.11 dS m^{-1}, at Hulet Ej Enese) to moderately saline (5.73 dS m^{-1}, at Yilmana Densa), based on Richards (1954) classification of soil salinity rates.

CEC values ranged from 3.1 at Becho (South West Shewa) to 41.8 meq 100^{-1} g soil at Adea (East Shewa) district. These CEC values are rated as very low to very high. Soils with CEC < 3 meq 100^{-1} g often display low fertility and susceptibility to soil acidification (Metson, 1961).

Soil clay content, determined using laser diffraction, ranged from 25% at Basonaworena district to 83% at Limo and Moretina Jiru districts. While there

Table 1. Physical and chemical soil properties of 60 samples collected from 20 Ethiopian districts.

Sample number	District	Particle size			EC	pH	CEC
		Sand	Silt	Clay			
		----------	%	----------	*ds m⁻¹*	*H₂O*	*meq 100 g⁻¹*
1	Adea	20	14	65	0.3	7.4	35.1
2	Adea	13	12	75	0.3	7.8	36.0
3	Adea	18	18	65	0.5	7.9	41.8
4	Aneded	19	25	57	0.1	7.2	32.9
5	Aneded	21	18	61	0.1	7.5	20.4
6	Aneded	20	37	43	0.4	6.5	12.2
7	Basona Worena	22	42	36	0.2	5.7	10.6
8	Basona Worena	52	24	25	0.2	6.1	7.2
9	Basona Worena	31	37	33	0.2	5.3	6.5
10	Becho	30	40	29	0.2	5.8	5.5
11	Becho	22	45	32	0.4	5.3	3.1
12	Becho	25	44	31	0.4	5.6	6.9
13	Bure	37	27	36	0.7	6.9	5.2
14	Bure	33	21	45	0.4	5.8	7.9
15	Bure	36	28	36	0.3	7.7	6.1
16	Cheha	26	38	37	0.5	5.4	7.4
17	Cheha	33	40	27	0.6	7.6	16.7
18	Cheha	33	34	33	0.8	7.8	20.5
19	Dangilla	23	25	52	0.3	7.5	22.4
20	Dangilla	15	23	61	0.4	8.1	25.1
21	Dangilla	28	31	41	0.3	5.2	6.6
22	Enemor Ener	25	37	38	0.3	5.1	6.0
23	Enemor Ener	28	29	43	0.2	5.8	7.0
24	Enemor Ener	28	31	41	0.2	5.7	4.5
25	Gimbichu	29	30	42	0.2	5.9	8.4
26	Gimbichu	29	35	37	0.2	6.0	9.7
27	Gimbichu	32	30	38	0.1	6.1	7.7
28	Hagere Selam	33	33	34	0.2	5.5	4.0
29	Hagere Selam	26	38	36	0.1	5.1	3.3
30	Hagere Selam	32	31	37	0.1	6.5	6.0
31	Hulet Ej Enese	34	33	33	0.1	6.2	4.9
32	Hulet Ej Enese	40	30	31	0.1	5.2	6.4
33	Hulet Ej Enese	26	31	43	0.3	6.5	4.8
34	Jeldu	31	30	39	1.5	6.6	15.5
35	Jeldu	28	32	40	1.8	5.9	11.9
36	Jeldu	23	30	47	1.8	5.7	9.0
37	Kimbibit	15	13	71	1.3	6.1	7.6
38	Kimbibit	14	24	62	1.2	5.3	8.7
39	Kimbibit	12	12	76	1.2	5.6	14.9
40	Kuyu	23	33	44	0.4	5.0	6.4
41	Kuyu	14	29	58	0.3	5.4	5.5
42	Kuyu	9	22	68	0.3	7.0	26.4
43	Limo	5	14	81	1.6	6.6	24.1
44	Limo	8	9	83	1.4	7.3	33.3
45	Limo	7	10	83	0.2	7.4	32.1
46	Moretna Jiru	8	9	83	0.2	7.4	31.7
47	Moretna Jiru	15	24	61	1.4	5.6	21.2
48	Moretna Jiru	6	23	71	0.6	5.9	20.1
49	South Achefer	16	34	50	0.5	5.4	12.1
50	South Achefer	19	27	54	0.8	5.7	16.6
51	South Achefer	19	26	54	0.6	4.7	15.7
52	Yilmana Densa	11	18	70	0.7	4.8	20.7
53	Yilmana Densa	12	13	74	0.4	5.0	17.7
54	Yilmana Densa	6	12	81	5.7	5.6	26.8
55	Arsi Negele	16	29	55	1.3	6.9	8.4
56	Arsi Negele	16	30	54	1.8	6.4	4.6
57	Arsi Negele	12	28	59	0.7	6.1	4.4
58	Siyadeberna Wayu	20	34	46	2.4	6.4	6.5
59	Siyadeberna Wayu	7	11	82	1.8	7.0	26.3
60	Siyadeberna Wayu	10	11	80	0.2	7.5	29.3

is a wide range of clay contents across districts (30-80%, as an average), the intra-district variation was much smaller, with several exceptions at Aneded, Kuyu and Siyadeberna Wayu (Table 1).

While soil clay content has appreciable positive effects on soil water retention at both situations - air-dried and saturated paste (Fig. 2) - its significance determining soil fertility, and in the present study (soil K availability), is questionable.

Each of the three common methods in use to evaluate soil K availability, namely $CaCl_2$, NH_4OAc, and M-3, showed a very poor linkage between the estimated level of soil K availability and soil clay fraction, even at the wide range presented here (Fig. 3). Furthermore, the fourth method (ΔF), provided a slight indication that the greater the soil clay fraction, the energy required by plants to extract K tended to decrease (Fig. 3). Interestingly, the NA_4OAc and M-3 methods obtained quite similar results, which

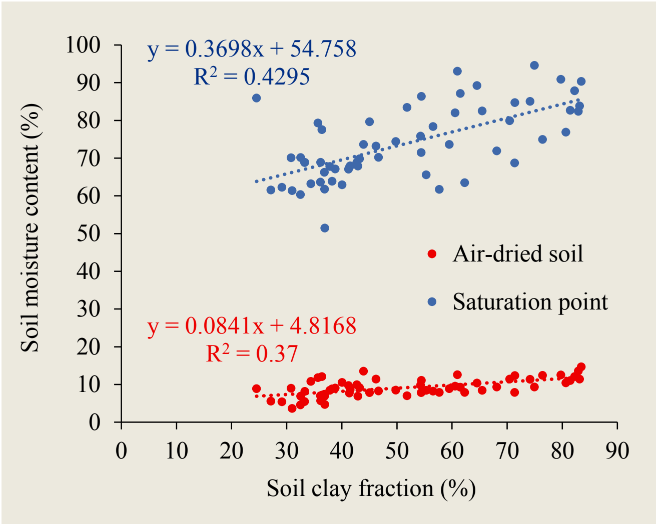

Fig. 2. The effects of soil clay content on water retention of air-dried soil, and saturated soil paste.

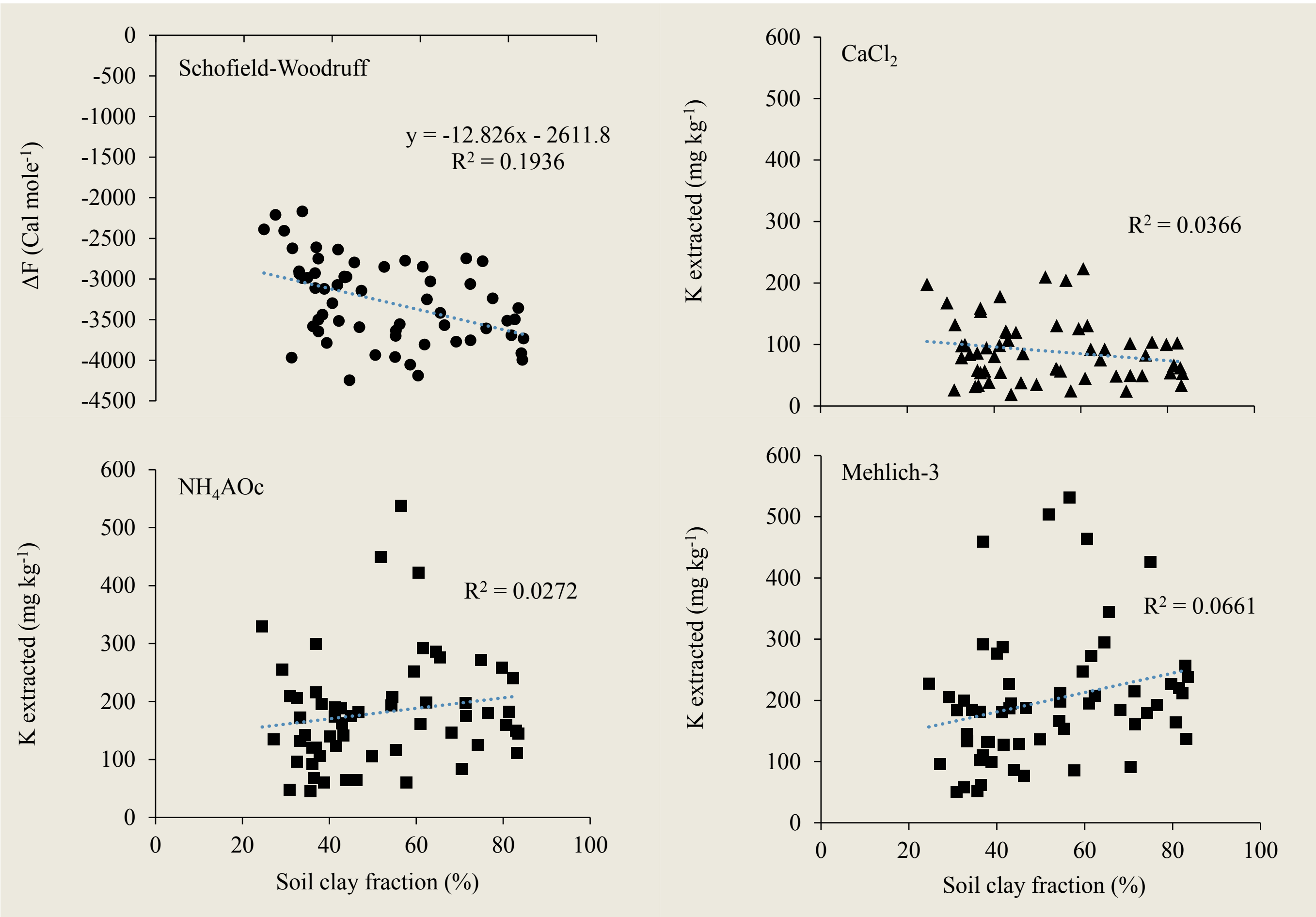

Fig. 3. Relationship between soil clay fraction and K availability, as measured using four distinct extraction methods.

were roughly two-fold higher than the K values obtained using the $CaCl_2$ method.

Indeed, direct pair-comparisons between the soil K extraction methods revealed a very high correlation between M-3 and NH_4OAc, with a coefficient of 0.85 (Fig. 4A). These results indicate that M-3 is somewhat more stringent than NH_4OAc at forcing K ions out from some clay minerals. However, together with their close chemical nature, these two methods appear to have similar chemical mechanisms of mining K out of clay minerals. This is in agreement with previous findings (Beegle and Oravec, 1990; Gartley *et al.*, 2002; Wang *et al.*, 2004), including on Ethiopian soils (Mamo *et al.*, 1996). Unequivocally, the K extraction ability of the $CaCl_2$ method is about 35% and 43% below those of the M-3 and NH_4OAc methods, respectively (Fig. 4B, C). It remains unclear, however, which of the three methods provides a better indication of K availability for plants. While M-3 and NH_4OAc might appear too stringent, releasing a portion of the non-exchangeable K, $CaCl_2$ might be too mild in representing the soluble K, with only a slight depiction of exchangeable K (Houba, *et al.*, 1996; Cox *et al.*, 1999).

Photo 2. Describing soil profile pit in Ethiopia. Photo by B. Kassahun.

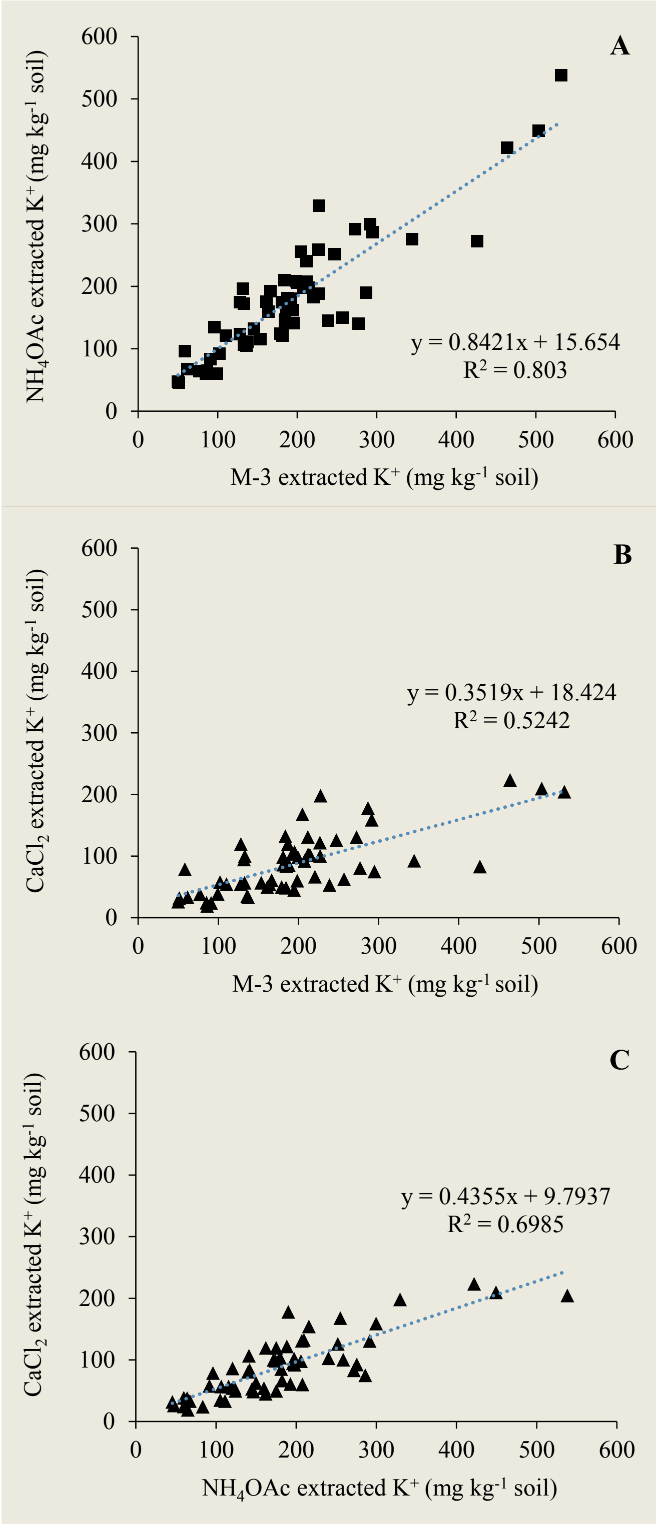

Fig. 4. Pair-comparisons between soil K extraction methods: A) NH_4OAc vs. M-3; B) $CaCl_2$ vs. M-3; and C) $CaCl_2$ vs. NH_4OAc.

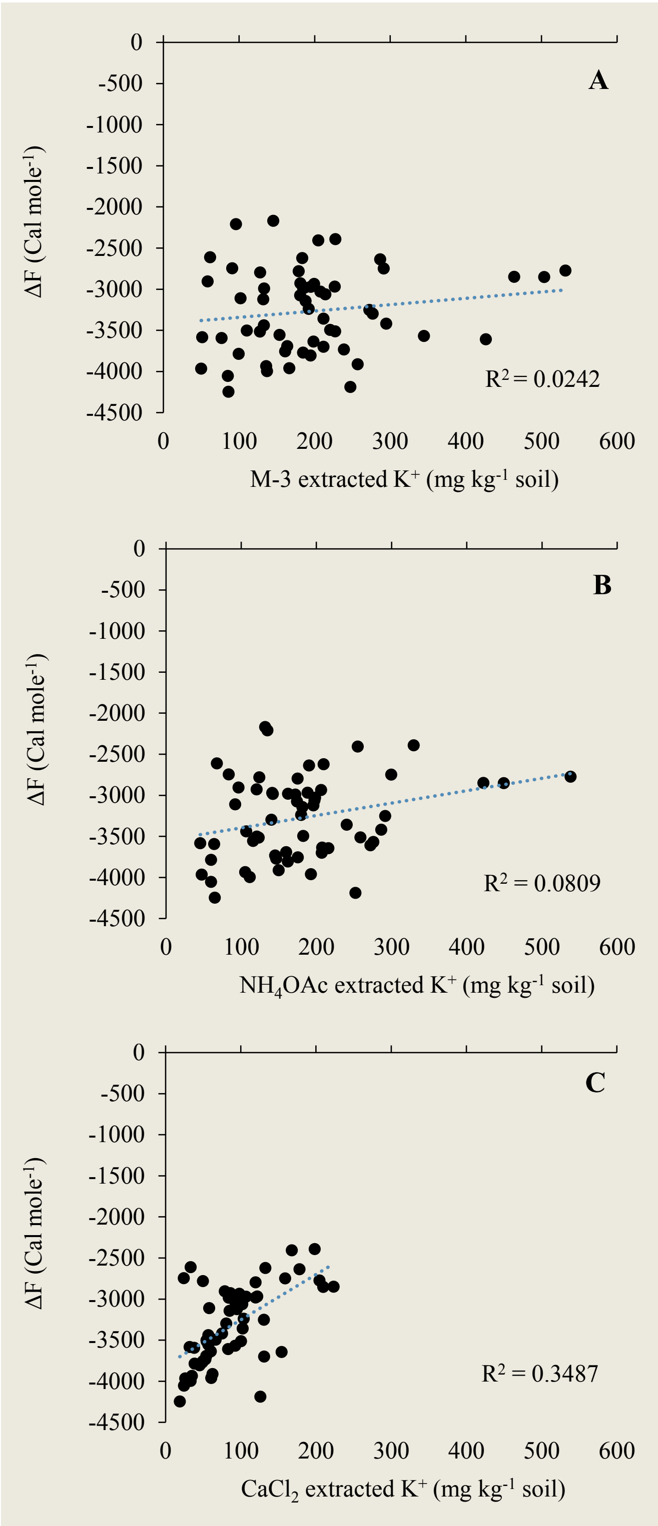

Fig. 5. The ΔF method confronted with K extracted from corresponding soil samples using the M-3 (A), NH_4OAc (B), and $CaCl_2$ (C) methods.

Testing the ΔF method against either M-3 or NH_4OAc revealed an absence of any correlation between them (Fig. 5A, B). In fact, there was a complete discrepancy between the methods in evaluating soil K status, and hence soil fertility. This result suggests intrinsic differences in the mode of action between the methods. While M-3/NH_4OAc methods might indiscriminately pull out K^+ from relevant as well as irrelevant soil phases, the ΔF method seemingly offers a finer approach, which possibly distinguishes between clay minerals corresponding to their chemical affinity to K^+. Thus, soils obtaining relatively low K status according M-3 might significantly differ in their K availability, according to the ΔF method, and vice versa. Excluding a few exceptions, a much better concurrence was found between ΔF and the $CaCl_2$ methods (Fig. 5C), which may indicate the dominance of the soluble K fraction, the most available one, in the results of ΔF.

Sorting the 60 Ethiopian soil samples by their K supplying potential, as determined using the ΔF method revealed that about 60% of them would be considered medium, while the rest are poor K suppliers (Table 2). Note that this sorting method significantly discriminates between neighboring soils, in some cases sending them to distant locations on the list. No linkage between ECe, soil pH or CEC and ΔF can be observed, indicating for the small relevance of these measures (at their detected range here) to the soil K supplying potential. As already mentioned and clearly noticed in Table 2, the relationships between soil total K, as determined by the M-3 or NH_4OAc methods, and ΔF, are absolutely coincidental as long as additional information is provided.

The mineral composition of clay fractions in each soil may provide the information required to interpret differences in K status and availability among them. The dominant minerals (>50%) in most of the 11 samples examined were interstratified illite and smectite (Table 3). Unfortunately, the ratio between the two in each sample was not resolved with the methods employed. While both minerals belong to the 2:1 clay class, they significantly differ in their ability to bind and release K ions (Barton and Karathanasis, 2002). Compared to illite and other clay minerals, smectite has a significantly higher tendency to fix K (Brady, 1984). Furthermore, many clay soils possess a relatively rapid dynamic transformation between the two minerals, which is influenced by temperature, moisture, pH, soil-K status, and plant roots (Scherer *et al.*, 2003). Plant roots display remarkable ability to rapidly absorb K from the rhizosphere (Hinsinger, 2015; Adamo *et al.*, 2016), thus strongly affecting the dynamic transformation between illite and smectite. Crops grown in the absence of K fertilization induced a rapid transformation of illite to smectite, accompanied by accelerated K fixation (Tributh *et al.*, 1987). This situation is quite typical of many arable clay soils in Ethiopia's central highlands; decades of inadequate K supply may have affected the clay mineral composition, favored increased K fixation and

Table 2. The 60 selected Ethiopian soil samples sorted according to the results of the ΔF method (soils with medium K supplying potential [-3,500 > ΔF > -2,000 Cal mole^{-1}] are marked in blue.

Sample number	District	Clay	EC	pH (H_2O)	CEC	K-soil test results			
						$CaCl_2$	NH_4OAc	M-3	ΔF
		%	*ds m^{-1}*		*meq 100 g^{-1}*	----*K conc. soil mg kg^{-1}*----			*Cal mole^{-1}*
18	Cheha	33	0.8	7.8	20.5		131.8	145.2	-2,169
17	Cheha	27	0.6	7.6	16.7		134.9	96.0	-2,209
8	Basonaworena	25	0.2	6.1	7.2	198.1	329.5	227.4	-2,390
10	Becho	29	0.2	5.8	5.5	167.8	255.0	204.8	-2,406
15	Bure	36	0.3	7.7	6.1	33.2	67.5	61.7	-2,611
12	Becho	31	0.4	5.6	6.9	132.5	209.6	183.7	-2,621
24	Enemor Ener	41	0.2	5.7	4.5	177.9	190.1	286.6	-2,636
52	Yilmana Densa	70	0.7	4.8	20.7	24.2	83.4	91.0	-2,745
26	Gimbichu	37	0.2	6.0	9.7	159.0	299.6	291.3	-2,748
4	Aneded	57	0.1	7.2	32.9	204.5	538.1	531.7	-2,773
53	Yilmana Densa	74	0.4	5.0	17.7	49.5	124.2	179.0	-2,781
14	Bure	45	0.4	5.8	7.9	119.7	175.0	128.0	-2,797
5	Aneded	61	0.1	7.5	20.4	223.4	422.0	463.9	-2,848
19	Dangilla	52	0.3	7.5	22.4	209.7	449.1	503.5	-2,851
11	Becho	32	0.4	5.3	3.1	78.8	96.3	58.4	-2,904
29	Hagere Selam	36	0.1	5.1	3.3	86.2	120.5	181.1	-2,928
9	Basonaworena	33	0.2	5.3	6.5	98.0	206.1	199.4	-2,935
23	Enemor Ener	43	0.2	5.8	7.0	121.9	188.3	226.7	-2,969
33	Hulet Ej Enese	43	0.3	6.5	4.8	106.8	141.1	195.0	-2,971
6	Aneded	43	0.4	6.5	12.2	119.6	162.2	186.7	-2,981
28	Hagere Selam	34	0.2	5.5	4.0	83.8	142.0	184.8	-2,983
31	Hulet Ej Enese	33	0.1	6.2	4.9	99.8	171.8	133.1	-2,990
38	Kimbibit	62	1.2	5.3	8.7	92.4	198.1	207.6	-3,030
37	Kimbibit	71	1.3	6.1	7.6	101.9	197.4	214.3	-3,061
21	Dangilla	41	0.3	5.2	6.6	98.5	174.1	180.9	-3,075
7	Basonaworena	36	0.2	5.7	10.6	57.9	91.9	102.1	-3,111
27	Gimbichu	38	0.1	6.1	7.7	94.6	195.9	132.0	-3,121
36	Jeldu	47	1.8	5.7	9.0	85.1	181.2	188.0	-3,143
39	Kimbibit	76	1.2	5.6	14.9	103.8	179.7	192.3	-3,239
20	Dangilla	61	0.4	8.1	25.1	130.8	291.5	272.4	-3,251
35	Jeldu	40	1.8	5.9	11.9	80.6	140.0	276.9	-3,297
59	Siyadeberna Wayu	82	1.8	7.0	26.3	102.6	240.2	211.8	-3,357
3	Adea	65	0.5	7.9	41.8	75.0	286.3	294.7	-3,417
22	Enemor Ener	38	0.3	5.1	6.0	56.9	106.6	132.8	-3,439
54	Yilmana Densa	81	5.7	5.6	26.8	66.6	182.5	220.4	-3,495
30	Hagere Selam	37	0.1	6.5	6.0	54.4	120.6	110.2	-3,502
60	Siyadeberna Wayu	80	0.2	7.5	29.3	100.3	258.7	227.0	-3,513
25	Gimbichu	42	0.2	5.9	8.4	54.6	123.1	127.8	-3,515
55	Arsi Negele	55	1.3	6.9	8.4	56.9	115.8	153.4	-3,555
1	Adea	65	0.3	7.4	35.1	92.5	275.6	344.4	-3,568
13	Bure	36	0.7	6.9	5.2	31.8	45.5	51.2	-3,582
58	Siyadeberna Wayu	46	2.4	6.4	6.5	37.9	64.1	76.9	-3,593
2	Adea	75	0.3	7.8	36.0	83.0	272.0	426.3	-3,609
50	South Achefer	54	0.8	5.7	16.6	60.2	207.7	198.5	-3,635
16	Cheha	37	0.5	5.4	7.4	154.2	215.9		-3,644
43	Limo	81	1.6	6.6	24.1	54.1	159.7	163.9	-3,693
56	Arsi Negele	54	1.8	6.4	4.6	130.9	207.1	211.8	-3,700
44	Limo	83	1.4	7.3	33.3	53.0	145.1	238.6	-3,733
48	Moretna Jiru	71	0.6	5.9	20.1	49.7	175.1	161.0	-3,755
42	Kuyu	68	0.3	7.0	26.4	48.8	146.5	184.6	-3,771
34	Jeldu	39	1.5	6.6	15.5	38.6	59.9	99.4	-3,786
47	Moretna Jiru	61	1.4	5.6	21.2	45.1	161.9	194.5	-3,807
46	Moretna Jiru	83	0.2	7.4	31.7	62.4	149.9	256.9	-3,912
49	South Achefer	50	0.5	5.4	12.1	34.8	105.2	135.9	-3,936
51	South Achefer	54	0.6	4.7	15.7	60.8	192.7	166.5	-3,960
32	Hulet Ej Enese	31	0.1	5.2	6.4	26.0	47.3	50.0	-3,966
45	Limo	83	0.2	7.4	32.1	33.3	111.3	137.1	-3,995
41	Kuyu	58	0.3	5.4	5.5	24.5	59.9	85.3	-4,053
57	Arsi Negele	59	0.7	6.1	4.4	126.0	251.9	247.2	-4,189
40	Kuyu	44	0.4	5.0	6.4	18.9	64.7	86.2	-4,246

reduced K availability to crops (Abiye *et al.*, 2004).

Concluding remarks

M-3 and NH_4OAc K extraction methods seem quite similar in their ability to partially extract non-exchangeable K, in addition to soluble and exchangeable K. Thus, both methods provide an over-estimate of soil K availability. The $CaCl_2$ method, on the contrary, mainly identifies the soluble K fraction, under-estimating exchangeable K. The ΔF method shows considerable agreement with the $CaCl_2$ method but has additional sensitivity to exchangeable K. Nevertheless, in the absence of any alternative proven chemical method to evaluate soil K availability (Wang *et al.*, 2016) to compare with, the ΔF results only provide indications, not reliable recommendations. A possible solution appears to be integrating chemical methods with biological tests, namely, direct measurements of K consumption by crops with simultaneous soil-K tests, as suggested by Affinnih *et al.* (2014), and more recently by Li *et al.* (2016). In addition, clay mineralogy should be further investigated on a local basis in order to determine and understand actual and possible dynamics of soil K status and availability, to establish a sufficient basis for practical recommendations.

Acknowledgements

Gratitude is given to the late Prof. Tekalign Mamo, and to the Agricultural Transformation Agency (ATA), Ethiopia. Special thanks are given to Prof. Dr. Uri Yermiyahu, Mr. Isaac Zipori, and staff of the Center for Fertilization and Plant Nutrition (CFPN) at the Gilat Research Center for Arid and Semi-Arid Agricultural Research, Agricultural Research Organization (ARO), Volcani Center, Israel, and to Mr. Eldad Sokolowski, IPI Coordinator for SSA/Ethiopia. This study was supported by ATA, Ethiopia, and the International Potash Institute (IPI), Switzerland.

Table 3. Mineralogical composition of the clay fraction of 11 soil samples and the corresponding K-soil tests results (clay minerals: I, illite; S, smectite; Ka, kaolinite; Q, quartz; AM, amorphic material, probably transformed from I/S mixture).

Sample number	Soil properties		Clay mineral composition					K-soil tests			
	Clay	CEC	Dominant	Major	Minor	Traces	Saddle	$CaCl_2$	NH_4OAc	M-3	ΔF
	%	*meq 100 g⁻¹*	*>50%*	*20-50%*	*5-20%*	*<5*		----------*K conc. soil mg kg⁻¹*		----------	*Cal mole⁻¹*
57	59.5	4.4	AM		I, Ka, Q	-	-	126.0	251.9	247.2	-4,189
54	81.4	26.8	I/S		I, Ka	Q	1	60.8	192.7	166.5	-3,960
46	82.9	31.7	I/S		Ka	Q, I	0.8	62.4	149.9	256.9	-3,912
42	68.1	26.4	I/S		Ka	Q	>1	48.8	146.5	184.6	-3,771
44	83.4	33.3	I/S		Ka	Q	0.7	53.0	145.1	238.6	-3,733
2	74.9	36.0	I/S		I, Ka	Q	0.9	83.0	272.0	426.3	-3,609
59	82.2	26.3	I/S		I, Ka	Q	>1	102.6	240.2	211.8	-3,357
39	76.4	14.9	I/S		I, Ka, Q	-	>1	103.8	179.7	192.3	-3,239
19	51.8	22.4	AM		I, I/S	Q, Ka	-	209.7	449.1	503.5	-2,851
5	60.7	20.4	I/S	I	Ka	Q	>1	223.4	422.0	463.9	-2,848
8	24.5	7.2	AM		I, Ka	Q	-	198.1	329.5	227.4	-2,390

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Regional activities/sub-Saharan Africa/Ethiopia

Research Findings

Coffee plantation at Cajibio, Colombia. Photo by A. Salamanca-Jiménez. 2017.

Coffee Crop Fertilization in Colombia: A Mini-Review

Salamanca-Jiménez, A.[(1)]

Abstract

Colombian coffee crops are mostly grown in mountainous areas that are susceptible to soil moisture fluctuations and soil acidity, and are subjected to the effects of climate change. The interactions between nutrients and water availability are complicated and critical determinants of coffee productivity, and hence, designing and implementing appropriate crop nutrition management represents significant challenges. The coffee crop cycle at Colombian plantations is very short; an early and full realization of the yield potential is essential and may be accomplished through suitable nutrition approaches. In terms of fertilization, research has mainly focused on nitrogen, and current recommendations indicate that nutrients should be applied differently during each developmental stage. Compared to the reproductive stage, fewer studies have addressed the nutrition requirements during the seedling and vegetative stages of Colombian coffee.

The present review aims to describe the special case of coffee nutrient requirements in Colombia, and to suggest principles and alternative respective practices of appropriate fertilization management.

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In coffee, both vegetative and reproductive growth takes about 18 months. Fertilization effects may only be fully manifested towards the end of the reproductive stage - at harvest, since nutrient remobilization is involved. For these reasons, nutrient application must never be skipped, particularly during the vegetative phase. Fertilization should be applied when soil water content is near field capacity to guarantee efficient nutrient uptake and to reduce urea volatilization. However, high precipitation in the tropics and the application of very soluble fertilizers lead to environmental risks. Multiple approaches, such as gradual or slow-release fertilizers, including the consideration of shading levels and orchard density, are recommended. A better understanding of how nutrient utilization and water availability affect coffee productivity is also required to achieve efficient nutrient use, enhance crop yields, and to better contribute to farmers' livelihoods.

Keywords: Coffea arabica; liming; magnesium; potassium; soil acidity; tropic crops.

Introduction

The genus *Coffea* is comprised of more than 70 perennial species but is usually represented by the two most grown species - *Coffea arabica* L. and *C. canephora* L. Both cultivars constitute one of the major crops cultivated in more than 70 countries, and represent an important traded commodity in the modern world, generating significant income as well as millions of direct and indirect jobs in many developing countries (DaMatta, 2004; DaMatta *et al*. 2008). In Colombia, coffee crops are grown by about 563,000 families, of which, 96% are smallholders who plant coffee in areas of less than 5 ha (Federacafe, 2017).

Successful cultivation of coffee and high cup quality in Colombia are related to a unique set of environmental conditions; the coffee region is located at altitudes ranging from 1,000 to 2,000 m above sea level, where mean annual temperatures range from between 15 and 23°C, annual precipitation fluctuates between 1,000 and 4,000 mm (Jaramillo, 2005) and almost 50% of soils are originated from or have been altered by volcanic ashes. Under these conditions, coffee crop phenology encompasses four growth stages (Arcila, 2008): germination, from sowing into a sand seedbed up to seedling transplanting into plastic bags (2 months); nursery, from transplanting into plastic bags up to development of at least one pair of branches (6 months); vegetative, from plant transplantation in the field up to first bloom (about 18 months); and, reproductive, comprising 4 or 5 years of harvest (Arcila, 2008). When productivity declines, it is recommended to initiate another crop cycle either by stem trimming or total renewal. A complete crop renovation is only used when the farmer wants to establish a new variety or change crop densities. Thus, depending on the environmental conditions, a whole production life cycle lasts 6-8 years, requiring intensive management and inputs respective to each stage in order to sustain productivity.

In terms of fertilization, recommendations indicate that nutrients must be applied differently during each stage. Compared to the reproductive stage, fewer studies have addressed the nutrition requirements during the seedling and vegetative stages of Colombian coffee. The present review aims to describe the special case of coffee nutrient requirements in Colombia, and to suggest principles and alternative respective practices of appropriate fertilization management.

Germination stage

Upon germination and at the earliest stage of seedling development, all nutrient requirements are supplied by the seed. Initial seedbed disinfection, periodic watering, and maintenance of a dark and warm bed, are the only practices needed. After about 2 months, the seedlings develop the first pair of leaves, reaching the ideal size for transplantation into plastic bags.

Photo 1. Coffee germination in Colombia.
Source: www.yoamoelcafedecolombia.com. 2017

Seedling stage

According to Salazar (1996), the early growth stages are very critical. In consequence to sub-optimal vigor, seedlings develop weak and small canopies that might fail under stresses associated with transplantation into the field 6 months later. As a result, the potential productivity of such trees might decline significantly. Plant growth and development during this stage is largely dependent on adequate and proper mineral nutrition.

At the nursery, nutrient requirements are usually supplied by the substrate in the plastic bag, consisting a mixture of soil and organic manure. Coffee seedlings are sensitive mainly to nitrogen (N), phosphorus (P), and soil pH, but potassium (K), calcium (Ca) and magnesium (Mg) are also significant. There is wide agreement that, depending on its availability at farms, different manure types such as from earthworm-processed cattle or chicken manure, or

Photo 2. Young coffee seedlings at the nursery.
Photo by A. Salamanca-Jiménez. 2017.

Photo 3. A young coffee plantation at the vegetative phase.
Source: www.yoamoelcafedecolombia.com. 2017.

organic residues (decomposed pulp or sugarcane sludge and ash) may be used in a 3:1 proportion of soil and manure, respectively (Salamanca-Jiménez and Sadeghian, 2008). However, the organic manure must be completely decomposed; in-pot decomposition of unripe manure might increase the growth-medium temperature and burn roots with a subsequent loss of plants. Promising new techniques that claim to reduce composting time while improving manure quality require further evaluation prior to their dissemination as a means of obtaining more vigorous seedlings.

Numerous studies have reported that reaching maximum growth rates during the nursery stage, particularly when no organic material is added, requires 0.4-0.5 g N per plant (Arizaleta *et al.*, 2002; Sadeghian and Gonzalez, 2014; Salamanca-Jiménez *et al.*, 2016; 2017b). Doses above that optimum N amount, such as 0.8 or 1.2 g plant^{-1}, gave rise to N luxury consumption causing adverse effects on coffee seedling growth (Salamanca-Jiménez *et al.* 2017b).

Even if organic material is properly used or totally absent in the substrate, P requirements must be satisfied by the addition of 2 g P_2O_5 per plant at 2 and 4 months after planting (Avila-Reyes *et al.*, 2010).

Potassium application should not be avoided during the nursery stage as this nutrient is required to facilitate photosynthesis and carbohydrate translocation, and to support the maintenance of the plant's water status (Zörb *et al.*, 2014). In coffee, a high K:N ratio (at least 1:1) during the early vegetative stage guarantees the desirable seedling growth and development (Wilson, 1985; Jessy, 2011; Gonçalves *et al.*, 2013; Melke and Ittana, 2015). Recently, Frois de Andrade *et al.* (2015) demonstrated the significance of adequately applied K to overcome periods of water shortage and to improve size and quality of coffee seedlings. In that study, K dose ranged from 0.625 to 2.5 kg K_2O m^{-3} substrate, divided into 4 applications, once a month.

Similarly, lime application to the growth substrate was reported to have positive effects on coffee seedling development (Diaz *et al.*, 2008). The suggested dose is around 5 g dolomite lime kg^{-1} substrate, depending on the initial and the target soil pH. According to Cenicafe (2016), 1 gram of lime per kg of soil is required to increase pH by about 0.2-0.3 units, depending on the soil buffer capacity. Seedling growth was significantly limited under no Ca application. In addition, seedling dry biomass was very sensitive to the Ca:Mg ratio, with higher dry biomass values obtained at ratios ranging from 1:1 to 4:1, respectively (Cenicafe, 2016).

Vegetative stage

Following seedling transfer from the nursery to the field soil, coffee response to fertilization is strongly associated to environmental conditions, particularly to soil fertility. Appropriate soil sampling and analyses prior to planting at least once every 2 years are therefore crucial to the successful management of the young plantation.

Coffee fertilization during the vegetative phase has been quite neglected so far, probably due to the fact that the economic significance of fertilizer application at that stage is difficult to measure. Therefore, criteria for nutrient application at the vegetative phase need to be defined further.

Current research of the vegetative stage shows that during the first 2 years, coffee crops respond positively to lime, manure, and N, P, and K applications directly to the planting spot. Thus, nutrient recommendations at this stage should relate to individual trees.

Liming recommendations, to overcome soil acidity, are based on the soil pH and Ca content. The liming doses applied during orchard establishment and 1 year later are presented in Table 1 (Sadeghian, 2013). Different Ca sources, such as calcite, dolomite limes or phosphate rock, can be used instead of lime.

Nitrogen is perceived as the dominant nutrient during the vegetative phase of coffee. Therefore, most recommended fertilizer practices suggest surface applications of increasing N doses from 2 to 18 months after planting, once every 4 months. The organic matter (OM) content of a soil and the precipitation regime must be carefully considered when determining the N dose. A threshold of soil OM content of 8% was defined (Sadeghian, 2013), below which the recommended N doses are higher, and vice versa (Table 2). In general, the common N source is urea due to its high N concentration (46%), however, under low soil P content, di-ammonium phosphate (18% N) may be preferred.

During the first 15 months (650 days after planting), N uptake by coffee trees may fluctuate from 8.6 to 19.4 g plant^{-1}, representing an accumulated extraction ranging from 33.4 to 75.6 kg N ha^{-1} at a density of 3,906 plants ha^{-1}, respectively. Such variation may be associated with the interaction between the plant's environment and genotype. In a comparison of three locations, plants accumulated 1,362 g dry biomass at Paraguaicito - the warmer location, 576 g at Santa Helena - the wet and colder place, and 812 g at Naranjal - where intermediate temperatures prevail. The ratio of N uptake to biomass accumulation was similar among the three locations - 0.0145 g N g^{-1} dry matter, which indicates a strict genetic regulation of N uptake. Environmental differences, therefore, seem to play an important role in the rate of biomass accumulation and in the way it is distributed among plant organs (Riano *et al.*, 2004).

Ramalho *et al.* (1997) stated that N fertilization causes changes in photosynthesis and in the composition of foliar pigments, thus preventing damage in the leaves of young plants (1.5-2 years) when they were exposed to successive days of high light intensity. The same authors found that a photon flux density of 1,500 µmol m^{-2} s^{-1} for a maximum period of 8 hours increased protein content after 1.5 h, a process that must have required N. Also, N application to young plants increased anti-oxidative activity, promoted the development of photo protective pigments (e.g. lutein, neoxanthin) (DaMatta, 2004), and also changed the fatty acid composition of chloroplast membranes (Ramalho *et al.*, 2000). Consequently, N availability might be considered a key factor for plant acclimation to full sunlight exposure.

These are the main reasons why currently, total N application during the vegetative stage ranges from 100 to 125 g urea plant^{-1}, and reaches rates of up to 1,250 kg urea ha^{-1} at a density of 10,000 plants ha^{-1}. However, as fertilizer is usually applied to the soil surface due to steep slopes, at least 30% N from urea may be lost by volatilization (Leal *et al.* 2010), causing adverse environmental and economic impacts. Research aimed at increasing N use efficiency as well as reducing the costs and the negative risks evolving from the current N fertilization practices in young coffee plantations is, therefore, a must. Alternative new practices should synchronize N application with plant demand and reduce N losses without compromising crop productivity (Salamanca-Jiménez *et al.*, 2016).

According to current recommendations in Colombia (Sadeghian, 2013), P, K, and Mg should be applied during the vegetative phase when soil analyses indicate contents

Table 1. Lime dose recommendation for coffee crop establishment based on soil analyses.

pH	Doses of liming material (g plant^{-1})		
	Ca ≤ 1.5	1.5 < Ca ≤ 3.0	Ca > 3.0
		cmol$_c$ kg^{-1}	
pH ≤ 4.0	120	100	80
4.0 ≤ pH < 5.0	100	80	60
5.0 ≤ pH < 5.5	40	0	0

Table 2. N, P, K and Mg recommendations for coffee at the vegetative stage based on soil analyses. Adapted from Sadeghian, 2013.

Application time (months after planting)	Nutrient doses (g plant^{-1})						
	N		P_2O_5	K_2O		MgO	
	OM ≤ 8%	OM > 8%	P ≤ 30	K ≤0.2	0.2 < K ≤ 0.4	Mg ≤ 0.3	0.3 < Mg ≤ 0.9
2	7	5	4	-	-	-	-
6	9	7	-	-	-	-	-
10	12	9	5	5	-	2	-
14	14	12	-	-	-	-	-
18	16	14	6	10	10	3	3

Note: OM, organic matter; soil P, mg kg^{-1}; and, K and Mg, cmol$_c$ kg^{-1}.

are below the critical values (as shown in Table 2). An N:K ratio of 1:1 during the vegetative phase has also been mentioned by several authors (Khan *et al*., 2001; Jessy, 2011; Gonçalves *et al*., 2013; Melke and Ittana, 2015). Other principles and aspects of coffee fertilization with K are broadly presented in the section related to the reproductive phase.

Reproductive stage

Data reported by Riano *et al.* (2004) for the vegetative stage show that a 5.5 year-old coffee crop may extract 547, 51, 508, 234 and 59 kg ha^{-1} of N, P, K, Ca and Mg, respectively, supporting the notion that coffee production is very sensitive to N and K inputs. These values also indicate the importance of Ca, which sometimes is not returned to the soil since farmers rarely re-apply lime every 2 years.

However, N is the primary nutrient applied in coffee ecosystems, with doses of N fertilizers usually ranging between 100 and 300 kg N ha^{-1} yr^{-1} (Bornemiza, 1982; Sadeghian, 2013). According to Sadeghian (2013), when N fertilizers are not applied, adverse effects start to emerge after 2 years, reducing crop yield by 49% in plantations under full sunlight, and by 40% under partial shade. Nevertheless, due to the frequent applications, and when previous applications and possible residual effects are considered, most coffee cropping systems are N saturated (Cannavo *et al*., 2013). This may provide a partial explanation for the poor N use efficiency - below 25% - during the reproductive phase.

These values are also supported by different studies about the N cycle processes, which show that when urea is applied to the soil surface, at least 30% is lost by volatilization (Leal *et al*., 2010) and from 30 to 55% is leached as NO_3^- (Cannavo *et al*., 2013). Other authors such as Fenilli *et al.* (2007) and Silva *et al.* (2015) report that coffee plants may absorb up to 43% N from the volatilized ammonia (NH_3), whereas Salamanca-Jiménez *et al.* (2017a), found that N recovery rates from urea applied either to the soil surface or incorporated close to the tree, were only 5%. When put into an N balance, these findings indicate that most of the fertilizer applied is wasted, resulting in environmental and economic impacts that have not accurately been determined yet, threatening sustainability of coffee production and coffee farmers' livelihoods.

Current recommendations to reduce volatilization, to improve N plant uptake, and to maximize nutrient efficiency, advise that fertilizer be applied to wet soil during predictably rainy periods (Sadeghian *et al*., 2014). However, rain distribution patterns have undergone significant changes in recent decades due to the global warming. DaMatta and Ramalho (2006) evaluated the strong impacts of climate change - both water deficit and excess precipitation - on coffee cultivating regions worldwide. In Colombia, more intense heavy rains coupled with longer droughts have damaged crops and farmers across the country (Salamanca-Jiménez *et al*., 2016). This climate instability confounds farmers regarding the best timing for agricultural activities, including fertilization (Lobell and Gourdji, 2012).

Recent studies reviewed by Sadeghian (2013) focused mostly on dose response curves and nutrient soil contents, and may suggest that coffee crop fertilization in Colombia - during the reproductive stage - must follow four important criteria: soil analysis, plant demands, plant density, and shade level. This approach enables a broader perspective to all macronutrients in addition to just N.

Soil analyses, when carried out frequently enough, provide significant information about the nature of the local soil, its fertility, and moreover, on the dynamics of soil macronutrients during and after the cropping season. Coffee is grown mainly in tropical climates, where soil acidity tends to increase rapidly. Under these conditions, soluble nutrients such as N and K become extremely mobile in the soil, providing only a brief opportunity for plant uptake. Therefore, critical macronutrient thresholds in the soil should be determined and should be strictly followed to prevent soil fertility collapse with consequent yield decline (Havlin *et al*., 2015).

Plant demand for N rises during the vegetative growth period that takes place towards bloom, while K demands climb during bloom and fruit development to reach a climax at fruit maturity (Jessy, 2011). However, K is stored in the foliage and is easily remobilized to reproductive organs (Sadeghian *et al*., 2014). Therefore, the annual K dose should be wisely distributed during the year with careful considerations of soil moisture content, as was concluded also in Vietnam, under unstable tropic conditions and high soil acidity (Tien *et al*., 2015). Under continuous drought periods, K application should be delayed since the nutrient is unavailable to plants in dry soil. During the wet season, however, K application should be applied at the end of a rain event, when the soil is wet but runoff has finished. Where irrigation is employed, K should be applied with the water toward the end of the irrigation session.

High plant densities respond better to fertilization, whereas low densities exhibit a poor response, even under higher fertilizer doses (Sadeghian, 2013). The difference may be attributed to soil surface application of a fertilizer, the effectivity of which depends on root distribution in the orchard. Under high planting densities, the chances of a fertilizer encountering roots are much higher than under low tree densities, where large proportions of fertilizer are wasted due to root scarcity. On the other hand, when exposed to full sunlight or under shading levels lower than 35%, coffee trees positively respond to maximum fertilizer doses (Farfan and Mestre, 2004). Nevertheless, trees under significant shade levels - above 55% - display a negligible response to fertilizer application suggesting that the latter is not the limiting factor and hence, should be avoided.

Due to such factors, coffee fertilization should follow Sadeghian's (2013) recommendations for each nutrient (Fig. 1).

Excluding N, soil analyses are key when determining recommended macronutrient doses (Fig. 1). Recommended K, P, and Mg doses decline steeply as soil content of these nutrients rises. Unfortunately, this important tool of soil testing is ignored by most coffee growers. In such cases, the maximum dose is recommended for each nutrient (Sadeghian, 2013), in spite of the vast economic and environmental consequences.

Shading level is another important parameter to consider (Fig. 1); below 35% shade, the recommended nutrient doses are at maximum, but as the shading levels increase above 45%, doses are cut down by half, significantly reducing fertilization costs. However, pruning must be considered here also, as productivity is expected to decline as well under increasing shading levels. Plant density on the other hand, seems to play a relatively minor role in the formula determining nutrient recommendations during the reproductive phase (Sadeghian, 2013).

Beyond these sophisticated considerations, most Colombian farmers need simple and clear-cut recommendations to follow. Therefore, founded on the environmental and economic impacts and concepts described above, and considering the economic and biological optimums calculated from the dose response curves (Havlin *et al.*, 2015), it is estimated that farmers applying 250, 30, 220, 100 and 35 kg ha^{-1} of N, P_2O_5, K_2O, CaO, and MgO, respectively, split into two or three applications, are likely to obtain profitable and environmentally-friendly yields.

These nutrient requirements can be supplied by a complex fertilizer with a grade of 18(N)-3(P_2O_5)-17(K_2O)-7(CaO)-3(MgO)-5(S)-0.3(B)-0.2(Zn), prepared using slow-release urea, triple-

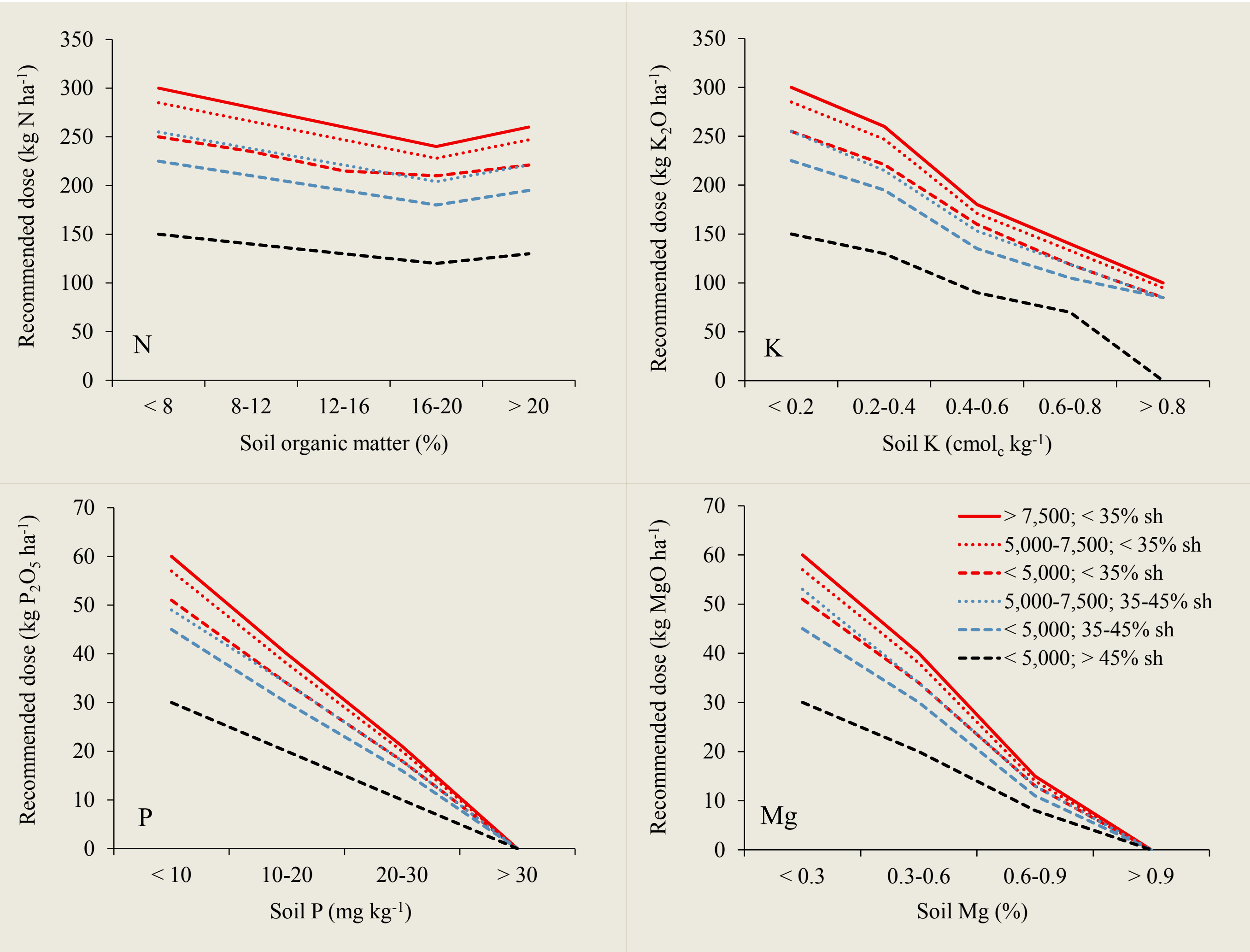

Fig. 1. Recommended doses of macronutrients for coffee fertilizers in Colombia during the reproductive phase, as affected by soil nutrient content, plant density (> 5,000; 5,000-7,500; and < 7,500 trees ha^{-1}), and level of shade (sh).

Photo 4. A young coffee tree at the reproductive stage.
Source: www.yoamoelcafedecolombia.com. 2017.

superphosphate, potassium chloride, micronutrients, and about 20% polyhalite in the mixture. Thus, an approximate dose of 90 g plant^{-1} twice a year, or 60 g plant^{-1} up to three times a year, may satisfy the requirements of plantations at a density of 7,500 plants ha^{-1}. It may be argued, however, whether or not maintaining a balanced ratio between nutrient supply and demand, as proposed here, would be sufficient for enhanced crop performance in the absence of soil nutrient status monitoring.

While efficient N fertilization of coffee crops under humid tropical conditions still represents a significant challenge, the application of K, Ca, Mg, and S may be enhanced using polyhalite. According to Imas (2017), polyhalite is a completely soluble, natural, multi-nutrient mineral, which is low in chlorides, salinity index, and carbon footprint. Moreover, it is accepted in organic agriculture, exhibits prolonged availability (thus reduces leaching) and performs well either through direct application, physical blends or chemical mixtures. Due to its balanced formula and gradual nutrient release, polyhalite provides crops with a more balanced nutrition and high availability throughout the growing season, including during stages of high nutrient demand (Vale and Serio, 2017). In a recent experiment in Vietnam, also under humid tropical conditions and high soil acidity, polyhalite application increased yield and enhanced quality traits of the coffee (PVFCCo, 2016). Under such balanced slowly-released nutrition, a healthier crop should be better able to tolerate abiotic stresses and pathogen impacts, and to maintain or enhance yield and harvest quality.

Concluding remarks

In coffee, both vegetative and reproductive growth take about 18 months. Fertilization effects may only be fully manifested towards the end of the reproductive stage at harvest, since nutrient remobilization is involved. This explains why yields decrease only after 2 years of no fertilization (Sadeghian, 2013). For these reasons, nutrient application must never be skipped, particularly during the vegetative phase.

Fertilization should be applied when soil water content is near field capacity to guarantee efficient nutrient uptake and to reduce urea volatilization. However, high precipitation in the tropics and the application of very soluble fertilizers may lead to environmental risks of leaching, and therefore fertilization requires careful management. Multiple approaches, such as gradual or slow-release fertilizers, that consider shading level and orchard density among other factors (Cannavo, 2013), should be examined.

Photo 5. Polyhalite application. Photo by A. Salamanca-Jiménez. 2017.

Photo 6. Dense coffee plantation without shade.
Photo by A. Salamanca-Jiménez. 2017.

Colombian coffee crops are mostly grown in mountainous areas that may be more susceptible to soil moisture fluctuations, and are subjected to the effects of climate change. The interactions between nutrient and water availability are critical determinants of coffee productivity that future crop management practices should address (Salamanca-Jiménez *et al*., 2016). Finally, a better understanding of how nutrient utilization and water availability affect coffee productivity is required to achieve efficient nutrient use, enhance crop yields, and to better contribute to farmers' livelihoods.

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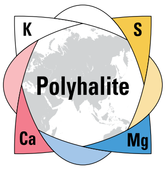

1st IPI Symposium on Polyhalite
第一届国际钾肥研究所硫酸钾钙镁研讨 会
A New Potassium Fertilizer with Complete Secondary Nutrients
全中量元素解决方案
31 October 2017, Sanya, Hainan, China
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The 1st Polyhalite Symposium: A New Potassium Fertilizer with Complete Secondary Nutrients. 31 October 2017, Wyndham Sanya Bay, Sanya, Hainan, China.
Reports on the effect of polyhalite application in Brazil, Europe and Israel; reports from China on tea, rapeseed, maize and various horticulture crops.

Please see the program and further updates on the IPI website/Events. For more details contact Mr. Eldad Sokolowski, IPI Coordinator China.

Publications

Teff Compendium

Nutrient deficiency symptoms

IPI. 2017. 24 p.

This leaflet is a summary of an experiment conducted to explore the deficiency symptoms in teff.

The experiment took place in a green house using 3 liter pots, filled with perlite. Each nutrient was tested at three levels: zero, low and optimal level.

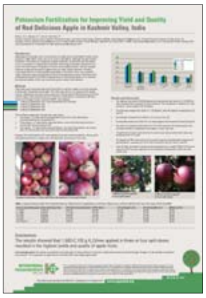
The treatments were based on the nutrient omission method where all but one nutrient was omitted at a time. The nutrients that were tested were N, P, K, S, Ca, Mg, Fe, Zn, Mn, Mo and Cu.

The application rates of each nutrient were none or "zero concentration" of the tested nutrient, "low concentration" - contains 10% of what is considered adequate concentration of the tested element - and adequate "optimal concentration" of the tested element.

The optimal nutrient solution was derived from the original protocol developed by Hoagland and Arnon (1938), where a typical growth solution consisting of the essential macro-elements: N, K, P, Ca, Mg and S; and micro-elements: a soluble form of Fe, B, Cu, Mn, Ni, Zn, Mo, Cl.

The results are summarized in the leaflet. To download the publication go to the IPI website/Publications/Leaflets.

To obtain a hardcopy of the compendium please contact Mr. Eldad Sokolowski, IPI Coordinator for SSA/Ethiopia and China.



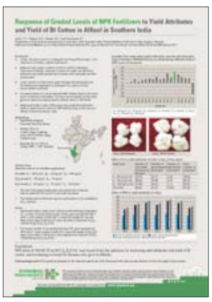
Potassium Fertilization for Improving Yield and Quality of Red Delicious Apple in Kashmir Valley, India

Poster by Rather, G.H., S.K. Bansal, B. Pal, and P. Imas. 2017.

Introduction: Apple plays an important role in the economy of India's Jammu and Kashmir state, which produces 1.966 million metric tons on an area of 162,000 ha. Although the agro-climatic conditions of the state are congenial for apple production, productivity and fruit quality is low; non-adoption of appropriate fertilization technology, particularly potassium (K), is one of the main reasons. Potassium is known as the quality nutrient, and has a greater influence on growth and yield of apples than any other nutrient element. However, crop requirements of K varies greatly depending on the nature of the crop, rootstock, stage of growth, environmental factors and soil management practices. Field trials were conducted during 2015 and 2016 to determine the most efficient dose of K to improve the yield and quality of the most commonly grown variety, Red Delicious.

This poster was presented at the IPNC 2017, Copenhagen 21-24 August 2017.

The poster is available for download at the IPI website/Publications/Posters. For more details contact Dr. Patricia Imas, IPI Coordinator for India.



Response of Graded Levels of NPK Fertilizers to Yield Attributes and Yield of Bt Cotton in Alfisol in Southern India

Poster by Jyothi, T.V., N.S. Hebsur, S.K. Bansal, and E. Sokolowski. 2017.

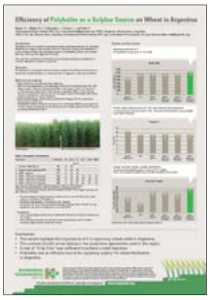
Introduction:

- Cotton, also known as 'white gold' and 'king of fibre crops', is an industrial commodity of global importance.
- Balanced use of plant nutrients corrects nutrient deficiency, improves soil fertility, increases nutrient and water use efficiency, enhances crop yields and farmer's income, and crop quality and the environment.

- Cotton farmers in India mainly apply nitrogen (N) and phosphorus (P) fertilizers but application of potassium (K), sulphur (S) and micronutrients is limited.
- At present there is no recommended NPK fertilizer dose for Bt cotton grown in Alfisols in Karnataka. The dose recommended for Bt cotton grown in Vertisols is being used for Alfisols which is 100:50:50.
- Keeping all these in view a field study was conducted on farmers' fields to determine the optimum NPK fertilizer dose.

This poster was presented at the IPNC 2017, Copenhagen 21-24 August 2017.

The poster is available for download at the IPI website/Publications/Posters. For more details contact Dr. Patricia Imas, IPI Coordinator for India.



Efficiency of Polyhalite as a Sulphur Source on Wheat in Argentina

Poster by Magen, H., R.J. Melgar, L. Ventimiglia, L. Torrens, and F. Vale. 2017.

Introduction: Polyhalite is one of a number of evaporate minerals containing potassium (K). Polyhalite (dihydrate) is a single crystal complex with two molecules of water of crystallization. It is not a mixture of salts. The chemical formula is: $K_2Ca_2Mg(SO_4)_4{\cdot}2(H_2O)$, and contains 48% SO_3, 14% K_2O, 6% MgO and 17% CaO. One important characteristic of polyhalite is the prolongued release and availability of nutrients, especially in relation to sulphur (S).

This poster was presented at the IPNC 2017, Copenhagen 21-24 August 2017.

The poster is available for download at the IPI website/Publications/Posters. For more details contact For more details contact Dr. Fabio Vale, IPI Coordinator for Latin America.

Comparing Polyhalite and KCl in Alfalfa Fertilization

Poster by Bernardi A.C.C, G.B. Souza, F. Vale, and H. Magen. 2017.

Introduction:

- Balanced nutrients supply = key factor for alfalfa high quality and yield.
- Potassium fertilization = the most common nutrient input for alfalfa crop in the high weathered, low-fertile and acid soils of the tropical region.
- Minerals commonly explored as K sources: sylvite (KCl), sylvinite (KCl + NaCl), and carnallite ($KMgCl_3{\cdot}6H_2O$).
- Potassium chloride potash (58 to 62% of K_2O) = the most potash fertilizer used in Brazil accounting for over 95% of the market.
- However, there are other minerals composed of sulfates = langbeinite, kainite, and polyhalite.
- Polyhalite ($K_2Ca_2Mg(SO_4)_4{\cdot}2(H_2O)$) is a mineral of naturally occurring mineral with large existing deposits and has potential to be a multi-nutrient (ratio of 11.7%-K, 19%-S, 3.6%-Mg, and 12.1%-Ca) fertilizer for forage crop production.
- Little information is available for the response of alfalfa to polyhalite.
- Polyhalite may provide a slow-release fertilizer source of K, Ca, Mg, and S.

This poster was presented at the IPNC 2017, Copenhagen 21-24 August 2017.

The poster is available for download at the IPI website/Publications/Posters. For more details contact For more details contact Dr. Fabio Vale, IPI Coordinator for Latin America.

Evaluation of Polyhalite as a Fertilizer Influencing Yield and Health in Cabbage Crop

Poster by Vale, F. 2017.

The poster summarizes a recent experiment. The experiment explored how cabbages respond to polyhalite fertilizer, a natural, multi-nutrient mineral containing four key plant nutrients: sulphur, potassium, magnesium, and calcium.

Introduction: Cabbage is usually cultivated on highly fertile soils. Thus, a low response to the use of nutrients in fertilization is expected.

Soils usually present high amounts of chloride and sodium, so the use of less saline fertilizer sources may be an alternative for higher yields and also for quality.

This poster was presented at CBCS (XXXVI Congresso Brasileiro de Ciência do Solo) in July 2017.

The poster is available in *English* and *Portuguese*. To download the poster go to the IPI website/Publications/Posters. For more details contact Dr. Fabio Vale, IPI Coordinator for Latin America.

Scientific Abstracts

K in the Literature

Follow us on Twitter on: https://twitter.com/IPI_potash
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In Vitro Protein Synthesis of Sugar Beet (*Beta vulgaris*) and Maize (*Zea mays*) is Differentially Inhibited when Potassium is Substituted by Sodium

Faust, F., and S. Schubert. 2017. Plant Physiology and Biochemistry 118:228-234.

Abstract: The substitution of potassium ions (K^+) by sodium ions (Na^+) in the nutrition of plants is restricted. It was shown earlier that net protein synthesis is the process which is most sensitive to the substitution of K^+ by Na^+ in young sugar beet. We hypothesized that the activity of ribosomes is inhibited by the substitution. This hypothesis was tested in an *in vitro* approach. Cytosolic polysomes were isolated from growing leaves of sugar beet and maize by means of differential centrifugation. *In vitro* systems of both plant species were tested for functionality and comparability. Translation was quantified by the ^{35}S-methionine incorporation in TCA-precipitable products. The effect of different substitution levels (0%, 20%, 40%, 60%, and 80% substitution of K^+ by Na^+) on *in vitro* translation was measured. Translation by polysomes of both plant species was significantly inhibited by the substitution. However, the translation by maize polysomes was more negatively affected by the substitution. A significant decrease in the translation by maize polysomes was observed already when 20% of K^+ were replaced by Na^+, whereas in the case of sugar beet, the translation was inhibited firstly at the substitution level of 40%. The *in vitro* results show that the process of translation itself is disturbed by the substitution and indicate a higher tolerance of sugar beet polysomes to increased Na^+ concentrations and Na^+/K^+ ratios compared to polysomes of maize. We propose that this tolerance contributes to the salt resistance of sugar beet.

Regulation of Potassium Transport and Signaling in Plants

Yi Wang, and Wei-Hua Wu. 2017. Current Opinion in Plant Biology 39:123-128. https://doi.org/10.1016/j.pbi.2017.06.006.

Abstract: As an essential macronutrient, potassium (K^+) plays crucial roles in diverse physiological processes during plant growth and development. The K^+ concentration in soils is relatively low and fluctuating. Plants are able to perceive external K^+ changes and generate chemical and physical signals in plant cells. The signals can be transducted across the plasma membrane

Residual Effect of Polyhalite Fertilizer for Maize Grown on Sandy Soil

Poster by Vale, F., and I. Döwich. 2017.

This poster looks at the residual effect of polyhalite fertilizer. The aim of the research was to evaluate the residual effect of the mineral fertilizer polyhalite on maize yield, when it was applied on soybean planted as the previous crop.

Introduction: Sandy soils in Brazil present low amounts of nutrients such as phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). Normally, soybean and maize fertilizers are made to supply only P and K, as well as nitrogen (N) for maize. The use of fertilizers containing these other nutrients (S, Ca and Mg) is important for crop management in order to get greater sustainability in yields.

Polyhalite is a natural single crystal complex with two molecules of water of crystallization. It is not a mixture of salts. The chemical formula is: $K_2Ca_2Mg(SO_4)_4 \cdot 2(H_2O)$. The fertilizer contains 14% K_2O, 19.2% S, 12% Ca and 3.6% Mg.

An important characteristic of polyhalite is the prolonged release rate and availability of nutrients over a longer period.

The poster is available for download at the IPI website/Publications/Posters. For more details contact For more details contact Dr. Fabio Vale, IPI Coordinator for Latin America.

Publications by the PDA

Sulphur as a Nutrient for Crops and Grass

POTASH News, September 2017.

Sulphur is an essential nutrient for all plants, and certain crops are more vulnerable to deficiency than others.

Historically, in the UK sulphur was deposited on land from the atmosphere in quantities which were adequate for our crops. However, as the burning of UK coal (high S) in power stations was switched to imported coal (low S) and natural gas, aerial deposition declined dramatically. 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.

and into the cytosol, and eventually regulates the downstream targets, particularly K^+ channels and transporters. As a result, K^+ homeostasis in plant cells is modulated, which facilitates plant adaptation to K^+ deficient conditions. This mini review focuses on the latest research progress in the diverse functions of K^+ channels and transporters as well as their regulatory mechanisms in plant response to low-K^+ stress.

Potassium Partitioning and Redistribution as a Function of K-use Efficiency under K Deficiency in Sweet Potato (*Ipomoea batatas* L.)

Ji Dong Wang, Pengfu Hou, Guo Peng Zhub, Yue Dong, Zhang Hui, Hongbo Ma, Xian Ju Xu, Yunwang Nin, Yuchun Ai, Yongchun Zhang. 2017. Field Crops Research 211:147-154. https://doi.org/10.1016/j.fcr.2017.06.021.

Abstract: Interactions exist between environmental factors and potassium use efficiency (KIUE) in crops, while controversy exists on the relationship between KIUE and other crop characteristics. In field experiments conducted during 2012–2014, genotypes 'Xu28' (high KIUE) and 'Ji22' (low KIUE) were identified and analyzed under conditions of K deficiency (K0) and adequate K supply (K1). Variation in KIUE at different growth years and correlations between KIUE and other parameters were studied in field trials in 2013 and 2014, combined with a greenhouse experiment in 2015. 'Xu28' and 'Ji22' showed a consistent ranking in terms of traits involving K-use efficiency, but marked variations in KIUE were observed between field trials and greenhouse experiments, as well as at different stages of plant development in the field experiments. KIUE exhibited a significant negative correlation with whole-plant K concentration under both field and greenhouse conditions, while KIUE was significantly positively correlated with the potassium harvest index in the field experiments, although no significant correlation was observed between root tuber yield and biomass production. 'Xu28' exhibited faster K concentration declines than did 'Jin22' from plantlet stage to harvest in both the 2014 field experiment and the 2015 greenhouse experiment. In the 2014 field experiment, under K0 conditions, 'Xu28' shoot and root K concentrations declined from plantlet stage to harvest by 178% and 142%, respectively. In contrast, 'Ji22' shoot K concentration declined from plantlet stage to harvest by 86%, while root K concentration remained stable. The percentage of fallen litter K content to whole-plant K content varied from 4.5% ('Ji22' K0) to 8.9% ('Xu28' K1) under greenhouse conditions, and 'Xu28' exhibited significantly higher fallen litter K (as a percentage of the whole plant) than did 'Ji22' under K0 and K1 conditions. The root:shoot ratio of K accumulation at harvest in 'Xu28' was significantly higher than that in 'Ji22' in both the 2014 field experiment and the greenhouse trial. KIUE was positively correlated with whole-plant K concentration at harvest of sweet potato, whereas root tuber yield was not significantly correlated with KIUE. The high-KIUE 'Xu28' had a more optimal partitioning of K at harvest than did the low-KIUE 'Ji22', as well as better K translocation in the shoots and roots at different growth stages, and these traits were of crucial importance for achieving high KIUE.

Two NHX-type Transporters from Helianthus tuberosus Improve the Tolerance of Rice to Salinity and Nutrient Deficiency Stress

Yang Zeng, Qing Li, Haiya Wang, Jianliang Zhang, Jia Du, Huimin Feng, Eduardo Blumwald, Ling Yu, and Guohua Xu. 2017. Plant Biotechnol. J. DOI: 10.1111/pbi.12773.

Abstract: The NHX-type cation/H^+ transporters in plants have been shown to mediate $Na^+(K^+)/H^+$ exchange for salinity tolerance and K^+ homoeostasis. In this study, we identified and characterized two NHX homologues, *HtNHX1* and *HtNHX2* from an infertile and salinity tolerant species *Helianthus tuberosus* (cv. Nanyu No. 1). *HtNHX1* and *HtNHX2* share identical 5′- and 3′-UTR and coding regions, except for a 342-bp segment encoding 114 amino acids (L_{272} to Q_{385}) which is absent in *HtNHX2*. Both hydroponics and soil culture experiments showed that the expression of *HtNHX1* or *HtNHX2* improved the rice tolerance to salinity. Expression of *HtNHX2*, but not *HtNHX1*, increased rice grain yield, harvest index, total nutrient uptake under K^+-limited salt-stress or general nutrient deficiency conditions. The results provide a novel insight into NHX function in plant mineral nutrition.

Leaf Gas Exchange Physiology and Ion Homeostasis of Oilseed Rape (*Brassica napus* L.) under Mediterranean Conditions: Associations with Seed Yield and Quality

Tsialtas, I.T., A.N. Papantoniou, T. Matsi, and D.K.Papakosta. 2017. Agriculture, Ecosystems & Environment 247:225-235. https://doi.org/10.1016/j.agee.2017.06.036.

Abstract: For two growth seasons, four oilseed rape cultivars were tested in two locations under Mediterranean conditions in order to identify leaf physiological [gas exchange and related traits, chlorophyll content (assessed by SPAD), carbon isotope discrimination (Δ), canopy area index] and elemental traits (K, Na, Ca, Mg, their sum and ratios) related to yield and quality. Determinations took place at one vegetative (stem elongation-BBCH 33 stage) and two reproductive stages (50% flowering of the central inflorescence-BBCH 65 stage and end of flowering-BBCH 69 stage). Yield and seed quality were strongly affected by growth season and location; cultivars differed only in quality traits [seed oil concentration (Oil), protein concentration (Prot), glucosinolates in seed meal (Glu), and erucic acid concentration (Eru)]. Exempting SPAD, cultivars did not also differ in physiological traits and this is a possible reason for the lack of significant differentiation in yield. Cultivars that excluded Na

more effectively were those with higher SPAD. Across growth seasons and locations, heavy-textured soil, lower temperatures and high precipitation in winter resulted in higher yield and quality. Larger canopy area at BBCH 65 stage led to higher oil yield (OY). In contrast, higher CO_2 assimilation rate (at BBCH 65 stage) and SPAD (BBCH 65 and 69 stages) were indicative of stressful conditions (high temperatures and low rainfall) since these two traits were negatively correlated with OY. Moreover, SPAD at BBCH 65 stage was also negatively correlated with Oil. CO_2 assimilation rate was strongly controlled by stomata and was almost the half of that previously reported for temperate environments. In accordance with previous works, K was the most effective osmoticum accumulated in oilseed rape leaves under stressful conditions. As a result, leaf K concentration was correlated negatively with Oil and positively with protein concentration; these two quality traits are inversely affected by stressful conditions. Exclusion of Na by K (higher leaf K/Na ratio) at the reproductive stages was related to lower Oil in oilseed rape, which is a salinity tolerant species. A negative correlation found between leaf K and Ca concentrations can be indicative of a partial substitution of K by Ca, in its osmotic role, in oilseed rape grown on calcareous soils under semi-arid conditions.

Effects of Polymer-coated Potassium Chloride on Cotton Yield, Leaf Senescence and Soil Potassium

Xiuyi Yang, ChengliangLi, Qiang Zhang, Zhiguang Liu, Jibiao Geng, Min Zhang. 2017. Field Crops Research 212:145-152. https://doi.org/10.1016/j.fcr.2017.07.019.

Abstract: Potassium (K) is one of the most important nutrients influencing plants, including cotton growth and metabolism. Because of toxicity from chloride ions, potassium sulfate (K_2SO_4) usually is used instead as a potassium fertilizer, especially for cotton, although it is lower in K_2O content and dearer than potassium chloride (KCl). The objective of this study was to investigate the effects of polymer-coated potassium chloride (PCPC) fertilization on cotton yields, yield components, fiber qualities, potassium use efficiencies and leaf senescence under saline conditions. A 2-yr field experiment was conducted in the Yellow River Delta of China with a high-yielding cotton cultivar ('Guoxin 99-1'). The experiment had the following six treatments with varying potassium fertilization: 70% PCPC mixed with 30% K_2SO_4 applied once before planting; PCPC applied once before planting; K_2SO_4 (KCl) applied twice with one application (40%) before planting and second application (60%) during first bloom stage; K_2SO_4 (KCl) applied once before planting; and fertilization none potassium as the control. The release rate of PCPC appeared to be slow before the squaring stage, but accelerated between the first bloom and boll-setting stages, and then decreased during the late stage including harvest. The number of cotton bolls was 8.99–19.71% higher and seed yields 4.39–28.10% higher, in 70% PCPC mixed with 30% K_2SO_4 treatment than in the other potassium fertilizer treatments. Also, the potassium recovery efficiency and net profits were increased by 3.38-40.90% and 5.77-137.26%, respectively, in the 70% PCPC mixed with 30% K_2SO_4 compared with the other potassium fertilizer treatments. Available soil potassium contents, fiber qualities and leaf photosynthetic indices were all significantly improved by using PCPC instead of the more standard potassium fertilizers. Hence, combining PCPC with K_2SO_4 at a 7:3 potassium ratio can delay leaf senescence, increase yields and fiber qualities, and improve potassium use efficiencies and economic benefits in cotton.

Effects of Olive Root Warming on Potassium Transport and Plant Growth

Benlloch-González, M., R. Sánchez-Lucas, and M. Benlloch. 2017. J. Plant Physiol. 218:182-188. https://doi.org/10.1016/j.jplph.2017.07.018

Abstract: Young olive (*Olea europaea* L.) plants generated from seed were grown in liquid hydroponic medium exposing the roots system for 33 days or 24 h to high temperature (37 °C) while the aerial part to 25 °C aiming to determine the prolonged and immediate effects of root warming on $K^+(Rb^+)$ transport in the root and consequently on plant growth. The exposition of the root system to 37 °C for 24 h inhibited K^+ (Rb^+) transport from root to shoot having no effect on its uptake. However, when the root system was exposed permanently to 37 °C both the K^+ (Rb^+) uptake and translocation to the aerial part were inhibited as well as the growth in all plants organs. The ability of the root system to recover K^+ (Rb^+) uptake and transport capacity after being exposed to high temperature was also evaluated. Plants grown in a root medium at 37 °C for 31 days were transferred to another at 25 °C for 48 or 96 h. The recovery of K^+ (Rb^+) root transport capacity after high root temperature was slow. Any signal of recovery was observed after 48 h without stress: both potassium root uptake and subsequent transport to above organs were inhibited yet. Whereas 96 h without stress led to restore potassium upward transport capacity although the uptake was partially inhibited yet. The results obtained in this study have shown that the root system of young olive plants is very sensitive to high temperature related to root potassium transport and growth of the plant. Taking into account the two processes involved in root potassium transport, the discharge of K^+ to the xylem vessels was more affected than the uptake at the initial phase of high root temperature stress. However, it was the first process to be re-established during recovery. All this could explain the symptoms frequently observed in olive orchards when dry and high temperature spells occur: a reduction in shoots growth and leaves with low levels of potassium contents and dehydration symptoms.

Kinetics of Soil Potassium Release under Long-term Imbalanced Fertilization in Calcareous Soils

Fatemi, A. 2017. Pedosphere. In Press. https://doi.org/10.1016/S1002-0160(17)60380-1.

Abstract: The kinetics of potassium (K^+) release under continuous fertilization with urea and triple superphosphate without K^+ was investigated in chloritic and kaolinitic soils. The kinetics of K^+ release from the soils in the N and P treatments was also studied in order to compare the obtained results. The results showed that the kinetics of K^+ release included an initial reaction and a slow reaction. The phosphate- and ammonium-induced K^+ release followed the same rate process during initial (2-192 h) and (192-1090 h) reaction periods. There were no significant differences between cumulative K^+ released amount from chloritic and kaolinitic soils among all treatments. The cumulative K^+ released was correlated positively with P adsorption capacity for chloritic (r = 0.461, $P \geq 0.05$) and kaolinitic soils (r = 0.625, $P < 0.01$) and negatively with fixation potential for chloritic (r = 0. 720, $P < 0.01$) and kaolinitic soils (r = -0.513, $P < 0.01$). There was a significant ($P < 0.001$) interactive effect of fixation potential × P adsorption capacity on cumulative K^+ released amount for both soil groups. Initial rate release (IRR), for chloritic soils were significantly (P < 0.05) more under P and NP application. The IRR followed the order as: NP=P > N=C for chloritic and N=P > NP > C for kaolinitic soils. This study showed that the fixation of ammonium and P adsorption capacities control K^+ release from soils. This information could be helpful for the precise fertilizer recommendation for the studied soils.

Potassium Deficiency Alters Growth, Photosynthetic Performance, Secondary Metabolites Content, and Related Antioxidant Capacity in *Sulla carnosa* Grown under Moderate Salinity

Chokri Hafsi, Hanen Falleh, Mariem Saada, Riadh Ksouri, and Chedly Abdelly. 2017. Plant Physiology and Biochemistry 118:609-617. https://doi.org/10.1016/j.plaphy.2017.08.002.

Abstract: Salinity and K^+ deficiency are two environmental constraints that generally occur simultaneously under field conditions, resulting in severe limitation of plant growth and productivity. The present study aimed at investigating the effects of salinity, either separately applied or in combination with K^+ deficiency, on growth, photosynthetic performance, secondary metabolites content, and related antioxidant capacity in *Sulla carnosa*. Seedlings were grown hydroponically under sufficient (6000 µM) or low (60 µM) K^+ supply with 100 mM NaCl (C + S and D + S treatments, respectively). Either alone or combined with K^+ deficiency, salinity significantly restricted the plant growth. K^+ deficiency further increased salt impact on the photosynthetic activity of *S. carnosa*, but this species displayed mechanisms that play a role in protecting photosynthetic machinery (including non photochemical quenching and antioxidant activity). In contrast to plants subjected to salt stress alone, higher accumulation of phenolic compounds was likely related to antioxidative defence mechanism in plants grown under combined effects of two stresses. As a whole, these data suggest that K^+ deficiency increases the deleterious effects of salt stress. The quantitative and qualitative alteration of phenolic composition and the enhancement of related antioxidant capacity may be of crucial significance for *S. carnosa* plants growing under salinity and K^+ deficient conditions.

Minerals Profile of Two Globe Artichoke Cultivars as Affected by NPK Fertilizer Regimes

Lombardo, S. G. Pandino, and G. Mauromicale. 2017. Food Research International 100(2):95-99. https://doi.org/10.1016/j.foodres.2017.08.028.

Abstract: Globe artichoke is a proven source of various minerals (such as K, Fe and Zn) in the Mediterranean diet, but their content in response to fertilizer regime has not yet been investigated sufficiently. Thus, we monitored the effect of two contrasting nitrogen/phosphorus/potassium (NPK) fertilizer regimes (one balanced and the other excessive) on the minerals accumulation of 'Apollo' and 'Tema 2000' cultivars, grown in three Sicilian locations ('Landolina', 'Iannarello' and 'Zotto') - South Italy. Except for total nitrogen, the balanced fertilizer regime favoured the accumulation of both macro- and micro-minerals, but with a different extent depending especially on trial location. Particularly, plants grown at 'Iannarello' responded more strongly to the fertilizer regime with respect to K, P, Ca, Fe and Zn accumulation, as a result of its different soil characteristics than the other locations. Providing a balanced supply of nitrogen/phosphorus/potassium via fertilization can enhance the nutritive value of globe artichoke, but taking into account especially soil characteristics.

Induction of Barley Silicon Transporter *HvLsi1* and *HvLsi2*, Increased Silicon Concentration in the Shoot and Regulated Starch and ABA Homeostasis under Osmotic Stress and Concomitant Potassium Deficiency

Seyed A. Hosseini, S.A., A. Maillard, M.R. Hajirezaei, N. Ali, A. Schwarzenberg, F. Jamois, and J.-C. Yvin. 2017. Front. Plant Sci. https://doi.org/10.3389/fpls.2017.01359.

Abstract: Drought is one of the major stress factors reducing cereal production worldwide. There is ample evidence that the mineral nutrient status of plants plays a critical role in increasing plant tolerance to different biotic and abiotic stresses. In this regard, the important role of various nutrients e.g., potassium (K) or silicon (Si) in the mitigation of different stress factors, such as

drought, heat or frost has been well documented. Si application has been reported to ameliorate plant nutrient deficiency. Here, we used K and Si either solely or in combination to investigate whether an additive positive effect on barley growth can be achieved under osmotic stress and which mechanisms contribute to a better tolerance to osmotic stress. To achieve this goal, barley plants were subjected to polyethylene glycol (PEG)-induced osmotic stress under low or high K supply and two Si regimes. The results showed that barley silicon transporters *HvLsi1* and *HvLsi2* regulate the accumulation of Si in the shoot only when plant suffered from K deficiency. Si, in turn, increased the starch level under both osmotic stress and K deficiency and modulated the glycolytic and TCA pathways. Hormone profiling revealed that the beneficial effect of Si is most likely mediated also by ABA homeostasis and active cytokinin isopentenyl adenine (iP). We conclude that Si may effectively improve stress tolerance under K deficient condition in particular when additional stress like osmotic stress interferes.

Phosphorus and Potassium Uptake, Partitioning, and Removal across a Wide Range of Soybean Seed Yield Levels

Gaspar, A.P., C.A.M. Laboski, S.L. Naeve, and S.P. Conley. 2017. Crop Sci. 57(4):2193-2204. DOI: 10.2135/cropsci2016.05.0378.

Abstract: Maintenance of adequate soil phosphorus (P) and potassium (K) levels is critical for profitable soybean [*Glycine max* (L.) Merr.] production. To accomplish this, precise knowledge of soybean P and K uptake, utilization, and removal is critical, yet a comprehensive study characterizing these requirements across wide-ranging seed yield environments is nonexistent for modern soybean production systems. Using six site-years and eight soybean varieties, plants were sampled at six growth stages, partitioned into their respective plant parts, and analyzed. Distinctly different uptake patterns and rates were found between P and K, where soybean accumulated greater relative amounts of K by R1 and 91 to 100% of its season-long K total by R5.5, compared with only 68 to 77% of its season-long P total. Removal of P (0.0054 kg P kg^{-1} grain) and K (0.016 kg K kg^{-1} grain) with the seed was consistent across environments and varieties and displayed strong relations with yield (R^2 = 0.89-0.92). For each kilogram increase in yield, total P and K uptake increased by 0.0054 kg and 0.017 to 0.030 kg, respectively. The difference between total uptake and removal for each nutrient resulted in average nutrient harvest indices of 81 and 49% for P and K, respectively. However, significant variation in total uptake and nutrient harvest indices existed due to the environment, not variety, and was more pronounced for K, resulting in significant variability in the amount of K removed in stover. These results can be incorporated into future fertility recommendations to improve P and K management for profitable and environmentally sound soybean production.

Root Potassium and Hydrogen Flux Rates as Potential Indicators of Plant Response to Zinc, Copper and Nickel Stress

Palm, E., W.G. Nissim, C. Giordano, S. Mancuso, and E. Azzarello. 2017. Environmental and Experimental Botany 143:38-50. https://doi.org/10.1016/j.envexpbot.2017.08.009.

Abstract: The practice of phytoremediation often requires that the plants used be exposed to a combined stress of multiple heavy metals. While the uptake and translocation abilities of roots is of primary importance, the direct effect of elevated concentrations of multiple heavy metals on the root physiology, including ion fluxes, is not often measured or compared between species in these studies.

Four plant species (poplar, willow, hemp and alfalfa) that were selected for a long-term phytoremediation project were grown hydroponically in the presence and absence of a combined heavy metal stress (zinc, copper and nickel), resembling field conditions. Short- and long-term root potassium and hydrogen flux rates were measured with non-invasive ion selective electrodes. Anatomical observations of root and shoot tissues, as well as accumulations of heavy metals were made with transmission electron microscopy. Biomass, gas exchange parameters and pigment concentrations were all evaluated to assess whole-plant effects of the heavy metal treatment.

Differences in the short-term induction of increased K^+ efflux and decreased H^+ influx from the roots among the four species were reflective of the long-term declines in photosynthetic capacity and growth observed in poplar and willow, but not in hemp. Tissue degradation patterns and increased K^+ efflux in poplar, willow and alfalfa due to heavy metal stress are consistent with reports in the literature of an imbalance in ROS and efficient scavenging of hydroxyl radicals. Taken together, results indicate that ion flux measurements can predict heavy metal stress sensitivity and support their potential use for describing root-level responses to the combined contaminant conditions often observed in sites selected for phytoremediation.

Relative Contribution of Na^+/K^+ Homeostasis, Photochemical Efficiency and Antioxidant Defense System to Differential Salt Tolerance in Cotton (*Gossypium hirsutum* L.) Cultivars

Ning Wang, Wenqing Qiao, Xiaohong Liu, Jianbin Shi, Qinghua Xu, Hong Zhou, Gentu Yan, and Qun Huang. 2017. Plant Physiology and Biochemistry 119:121-131. https://doi.org/10.1016/j.plaphy.2017.08.024.

Abstract: In this study, the role of specific components of different coping strategies to salt load were identified. A pot experiment was conducted with four cotton (*Gossypium hirsutum* L.) cultivars (differing in salt-sensitivity) under salinity stress. Based on observed responses in growth performance and physiological characteristics, CZ91 was the most tolerant of the four cultivars,

followed by cultivars CCRI44 and CCRI49, with Z571 being much more sensitive to salt stress. To perform this tolerant response, they implement different adaptive mechanisms to cope with salt-stress. The superior salt tolerance of CZ91 was conferred by at least three complementary physiological mechanisms: its ability to regulate K^+ and Na^+ transport more effectively, its higher photochemical efficiency and better antioxidant defense capacity. However, only one or a few specific components of these defense systems play crucial roles in moderately salt tolerant CCRI44 and CCRI49. Lower ROS load in CCRI44 may be attributed to simultaneous induction of antioxidant defenses by maintaining an unusually high level of SOD, and higher activities of CAT, APX, and POD during salt stress. CCRI49 could reduce the excess generation of ROS not only by maintaining a higher selective absorption of K^+ over Na^+ in roots across the membranes through SOS1, AKT1, and HAK5, but also by displaying higher excess-energy dissipation (e.g., higher ETR, P_R and qN) during salt stress. Overall, our data provide a mechanistic explanation for differential salt stress tolerance among these cultivars and shed light on the different strategies employed by cotton cultivars to minimize the ill effects of stress.

Read On

This Quiet Agricultural 'Moonshot' Could Change the Future of Food

Gallegos, J. 24 June 2017. The Washington Post.

The Zoo Beneath our Feet: We're Only Beginning to Understand Soil's Hidden World

Higgins, A. 9 August 2017. The Washington Post.

Open Soil Science: Technology is Helping us Discover the Mysteries under our Feet

Bridgen, M. 1 September 2017. The Conversation.

View On

Feast on Facts - Food Evolution

Check this new documentary film "Food Evolution" on the choices we need to make when it comes to feeding a planet of, by 2050, more than 9 billion hungry people?

Narrated by Neil deGrass Tyson. 2017. Food Evolution.

Clipboard

Obituary for Professor Tekalign Mamo (1956–2017)


IPI remembers Professor Tekalign Mamo

The death of Professor Tekalign Mamo brought deep sadness to all of us who knew him. He completed his BSc in Plant Sciences (with Distinction) at the Alemaya College of Agriculture (Haramaya University), Ethiopia and then his MSc and PhD in Soil Chemistry and Fertility at the University of Aberdeen, Scotland. Returning to Ethiopia was very important to him, where he focused his work on Ethiopia's priority soil and land productivity problems. His research helped to arrest land degradation, resolve waterlogging problems in Ethiopia's extensive dark clay soils (Vertisols), tackle soil acidity, transform the fertilizer advisory service through implementing soil test based fertilizer recommendations, add value to nitrogen use efficiency by changing the urea fertilizer granule size, and tackle the lack of information about Ethiopia's potassium fertilizer needs.

Prof. Mamo started working with IPI in 2011. At the time he was State Minister, Advisor to Ethiopia's Minister of Agriculture and Program Leader for two national projects that he proposed to the government; the National Soil Fertility Mapping Project and the Fertilizer Blending Project. Prof. Mamo also worked as the Program Leader for the Agricultural Commercialization Clusters program which was implemented and coordinated by the Ethiopia Agricultural Transformation Agency.

Prof. Mamo spent his life improving Ethiopian agriculture. He paid great attention to 'real-life' situations in agriculture and received many awards for his contribution to improving soil health. These included the 2016 IFA Norman Borlaug Award and an award from IPI in 2014 in recognition of his contribution to the advancement of knowledge in potash research in Ethiopia, and for his collaboration with IPI. As a result of his expertise in potassium fertilization, he was asked to act as Senior Advisor for IPI in East Africa in 2015.

Alongside pushing state policies, he always guided and supported young students in the study of soil fertility. He supervised numerous MSc and PhD students, but was called 'Prof' by everyone as he taught everybody he met; he was a teacher and mentor to many. He always insisted on being involved, whether it was joining a field visit to a project in a rural area, or delivering a paper at a scientific meeting.

He loved practical science and appreciated those people who wanted to apply their scientific knowledge to agriculture to help farmers grow more and better crops. When he visited rural areas, he liked to listen to the farmers so that he could address the specific issues or problems that they experienced. From these close contacts with farmers and agronomists he often generated new ideas and challenged state-wide solutions. As a result, his name is known among politicians, consultants, agronomists and leading farmers in Ethiopia and abroad.

He was proud of almost everything Ethiopian; from a good cup of coffee, to teff and even the national air carrier which he preferred to use. He was always very busy and frequently spent all night completing yet another urgent task. Prof. Mamo leaves his beloved wife, who he always referred to as ‘Madam’, and two daughters who he always spoke of proudly. To all of his family, we extend our heart-felt condolences.

We will miss Prof. Tekalign Mamo for his great energy, his endless dedication and his vast knowledge and experience, as well as, of course, for being a dear friend, teacher and colleague.

Impressum *e-ifc*

ISSN 1662-2499 (Online); ISSN 1662-6656 (Print)

Publisher:	International Potash Institute (IPI)
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