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Optimizing Crop Nutrition

Editorial

Dear readers,

If the global COVID-19 pandemic is teaching us anything it is that it is so important to have the essentials right. In our professional and personal lives, we are all reminded of the everyday 'essentials' that make normal life productive and enjoyably effective.

Whilst mindful of the ongoing hardships being experienced in many parts of the world, in this latest edition of the *e-ifc*, we bring you more evidence from research teams and agronomists of the benefits of meeting crop plants' essential nutrient needs.

From Vietnam, we present a paper that investigated the nutrition of cabbages, a crop that has increased in popularity 20-fold in forty years. Cabbage commands premium prices and good incomes for the grower if the quality and yield is good enough. The researchers measured the response of cabbages to six different fertilizer treatments, with different lengths of nutrient availability in the soil, in order to help determine the optimized nutrition strategy for brassica growers to choose to use.

From France, there is a paper reporting research with rainfed alfalfa which investigated the benefits of adequate K fertilization and substitution of KCl with polyhalite. It reports the optimal fertilizer strategy it found for better yield and improved quality – no doubt appreciated by the animal consumers for who this forage crop is produced. Also, as is so important in the face of the contemporary climate crisis, it measured the carbon footprint of different fertilizer strategies.

Finally, from the UK, we share with you the series of field trials examining the role and benefits of essential nutrients in commercial crops of potatoes.

Combined, I hope this edition's selection of science provides you with some essential and enjoyable reading.

Stay safe!

Dr. Patricia Imas
IPI Scientific and Communications Coordinator

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Photo cover page: Monitoring pepper response to fertilizers in greenhouse, South Israel. Photo by N. Cohen Kadosh.

Research Findings

Photo 1. Researcher in cabbage field in Vietnam. Photo by the authors.

Effects of Polyhalite Application on Yield and Quality of Cabbage Grown on Degraded Soils in Northern Vietnam

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Abstract

Cabbage (*Brassica oleracea* var. *oleracea*) production in Vietnam recorded a 20-fold increase from 1981 to 2019. Nevertheless, a substantial yield gap exists between the current local mean yield (27 Mg ha^{-1}) and those of leading cabbage producing countries. Low soil fertility and commonly imbalanced fertilization practices were suggested among the major reasons for this yield gap. Polyhalite, a natural marine sedimentary mineral consisting of a hydrated sulfate of potassium (K), calcium (Ca), and magnesium (Mg) was examined as a potential partial substitute for muriate of potash (MOP) as the K donor. Polyhalite, as a four-in-one fertilizer, has the advantage of providing more balanced mineral nutrition. An experiment was carried out in northern Vietnam, comparing cabbage crop performance under six fertilizer treatments: farmers' practice (150 kg K_2O ha^{-1}); control (no K applied); 60 kg K_2O ha^{-1}, applied through MOP; and 60, 90, and 120 kg K_2O ha^{-1}, applied through combinations of polyhalite and MOP at 1:1 ratio at the K_2O level.

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All treatments received farmyard manure (FYM) at 15 tonnes ha^{-1}, 180 kg N ha^{-1} (urea) and 80 kg P_2O_5 ha^{-1} (superphosphate). The combinations of MOP and polyhalite gave rise to significantly higher cabbage yields. The optimum K_2O rate was about 100 kg K_2O ha^{-1}, much lower than at the common farmers' practice. The contribution polyhalite made to prolonged K availability, and to more balanced crop nutrition, was most clearly demonstrated when treatments with a similar K_2O rate (60 kg ha^{-1}) were compared. An economic analysis showed that under the circumstances of the present study, the polyhalite and MOP combination at a rate of 100 kg K_2O ha^{-1} was the most profitable practice, far above the output from farmers' usual practice. The economic analysis also clearly demonstrated that no K application might lead to a substantial loss on investment. In conclusion, adequate K supply is essential to profitable cabbage production under the climatic and edaphic conditions in northern Vietnam. Furthermore, combinations of polyhalite and MOP can open new horizons in enhancing cabbage and other crops' performance in Vietnam.

Keywords: Balanced plant nutrition; *Brassica oleracea* var. *oleracea*; Polysulphate; potassium; yield gap.

Introduction

The genus Brassica is known for its important agricultural crops, which include species and varieties of cole crops such as broccoli, cauliflower, and cabbage, root crops such as turnip and radish, herb crops like ruccola and choy sum, and oil and spicy seeds such as canola and mustard, respectively. World production of cole crops in 2019 was 70.1 million tonnes (FAOstat, 2021). Cabbage (*Brassica oleracea* var. *oleracea*) – a good source of vitamin K, vitamin C and dietary fiber (White and Broadley, 2005) – is consumed in many different ways: pickled, fermented, steamed, stewed, sautéed, braised, or raw. Over the last three decades, Brassicaceae crops have been the focus of intense research due to their human health benefits (Stoewsand, 1995; Björkman *et al.*, 2011; Šamec *et al.*, 2017; Ware, 2017).

Sulfur-containing secondary metabolites, such as glucosinolates, have been associated with some anti-cancer activities (Higdonm *et al.*, 2007; Cartea and Velasco, 2008; Sarıkamış, 2009) and with a reduced risk for degenerative diseases, cardiovascular diseases and diabetes (Björkman *et al.*, 2011, and references therein). Some S-containing compounds are desired as flavor components in cooked Brassica vegetable products (Schutte and Teranishi, 1974). Glucosinolates' contents largely depend on S availability and significantly varies with S fertilization (Falk *et al.*, 2007).

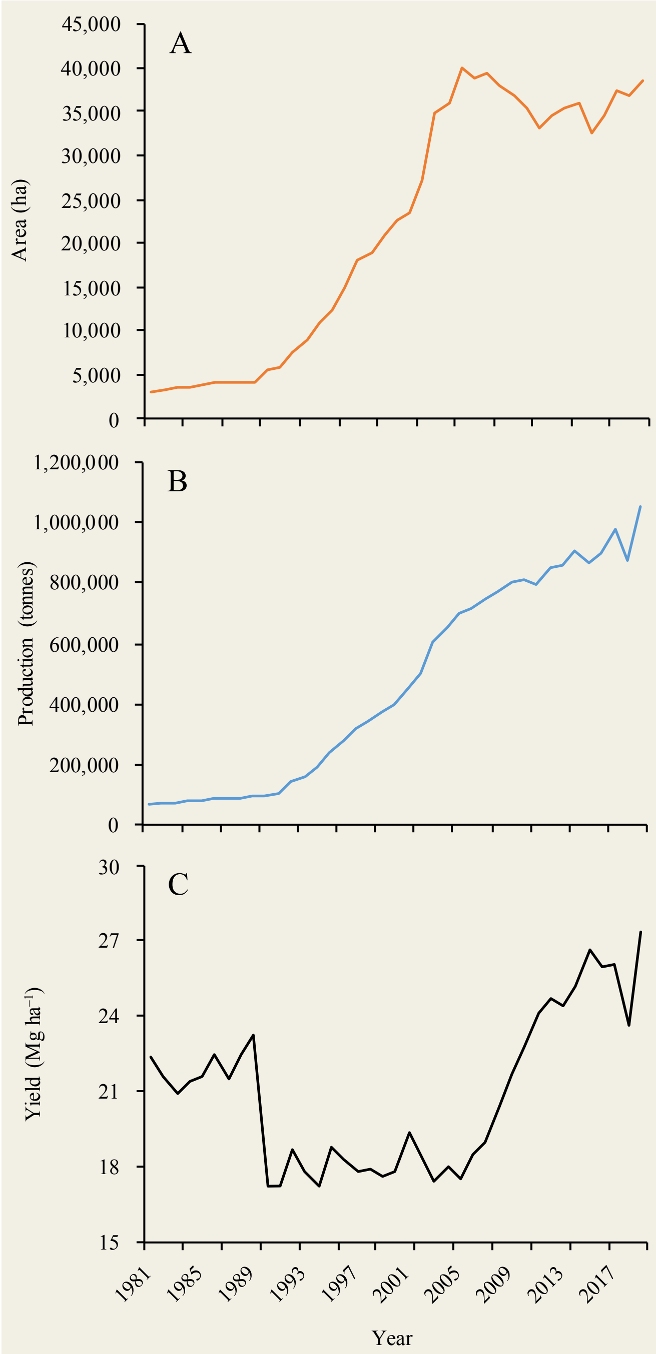


Fig. 1. Development of cabbage and other Brassica crops in Vietnam from 1981-2019. Cultivated area (A); production (B); and, calculated average annual yields (C). Source: FAOstat, 2021.

Cole crop species are highly appreciated in Vietnamese tradition and cuisine. Within less than 15 years (1991-2005), the cole crop cultivation area grew 10-fold, from 4,000 to 40,000 ha, but during the successive 15 years, it fluctuated between 30,000 and 40,000 ha (Fig. 1A). During the last 30 years, the annual cole crop production steadily rose from 100,000 to 1,050,000 tonnes (Fig. 1B). These figures make Vietnam the eighth largest producing country of cole crops. Nevertheless, with mean annual yields ranging from 17-27 Mg ha^{-1} (Fig. 1C), Vietnam lags behind 60 other cole producing countries (FAO, 2021). Obviously, the annual average yield data covers substantially different climate regions in Vietnam, most of which are less suitable for high cabbage production. Cabbage grows best in temperate climate regions, into which the subtropical northern Vietnam partially fits, more so than the central or southern regions of the country.

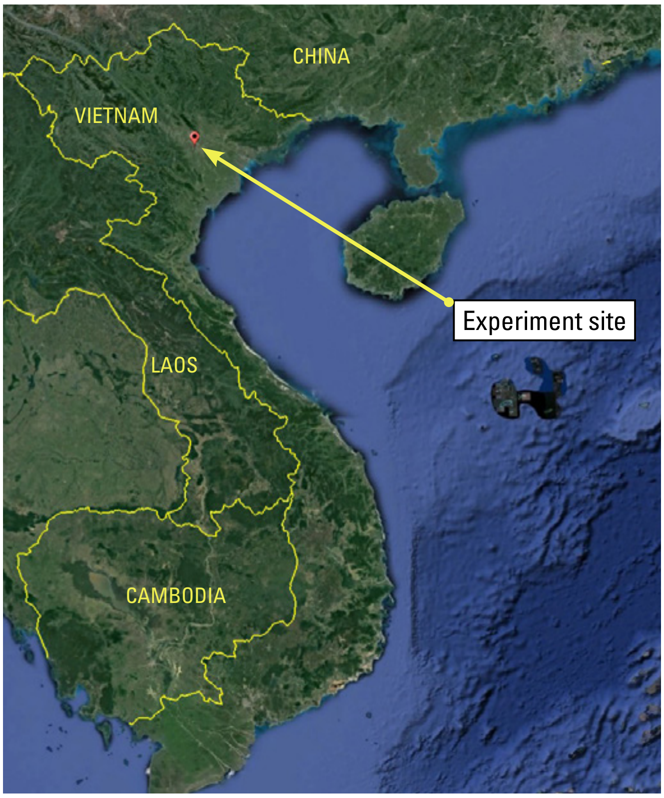
Conversion of forest to agricultural land is known to negatively affect soil fertility. According to Schweizer *et al.*, (2017), soil aggregate stability declined simultaneously with a decrease in soil organic carbon and exchangeable Ca^{2+} and Mg^{2+}, which both declined with increasing time since land use modification. The humid climate of Vietnam creates significant further challenges for soil nutrient availability. During the wet season, the liquid soil phase is prone to swap very frequently, within hours or days, depending on the precipitation regime. This liquid phase contains most of the currently available nutrients, including potassium (K), that are leached away from the rhizosphere. In addition, high precipitation rates intensify soil weathering and significantly increase soil acidity (Sanchez, 2019), which further reduces soil cation exchange capacity (CEC) and K availability (Zörb *et al.*, 2014). Cole crops prefer soil pH ranging from 6.0-6.8 (White and Broadley, 2005), considerably higher than the typical soil pH range in Vietnam (5.0-5.5). Subsequently, insufficient nutrient availability, particularly K, but also imbalanced mineral nutrition, have been consistently shown to be responsible for yield gaps in numerous crop species in Vietnam (Pandey *et al.*, 2019).

Potassium is essential for most basic processes in plants' life cycle (Zörb *et al.*, 2014). In cole crops, this nutrient is particularly important during the early stages of expansion of the outer leaves (Wien and Wurr, 1997). Potassium application practices were introduced to Vietnam much later than N and P and, therefore, were insufficiently disseminated among farmers (Pandey *et al.*, 2019). Under the climatic and edaphic constraints of Vietnam, K application must be addressed with careful attention to the problem of rapid leaching. In recent years, the practice of splitting the fertilizer dose into several application events during the growing season, thus providing better K availability whenever necessary (Joshi *et al.*, 2014), has gradually been disseminated in Vietnam. In addition less soluble fertilizers, that would last for a significantly longer period in the growing season, should be considered.

Similar to the danger of K shortage, other alkaline nutrients, Ca and Mg, are at risk of deficiency. Calcium is pivotal to numerous structural and physiological functions from the subcellular to the whole plant scale (White and Broadley, 2003). Magnesium is part of chlorophyll in all green plants and is essential for photosynthesis and carbohydrate partitioning (Cakmak and Yazici, 2010; Farhat *et al.*, 2016). Sulfur (S) is recognized as the fourth major plant nutrient after N, P, and K (Khan *et al.*, 2005), and has been associated with high productivity (Dick *et al.*, 2008), as it often interacts with N to significantly enhance protein metabolism (Jamal *et al.*, 2010).

It is clear that more balanced fertilization strategies are needed. A partial replacement of the highly soluble chemical K fertilizers, combined with supplementary essential macronutrients appears a promising solution. Polyhalite is a natural mineral which occurs in sedimentary marine evaporates and consists of a hydrated sulfate of K, Ca, and Mg with the formula: $K_2Ca_2Mg(SO_4)_4 \cdot 2(H_2O)$. The deposits found in Yorkshire, in the UK, and marketed as Polysulphate®, typically consist of K_2O: 14%, SO_3: 48%, MgO: 6% and CaO: 17%. As a fertilizer providing four key plant nutrients – S, K, Mg, and Ca – polyhalite may offer attractive solutions to crop nutrition. In addition, polyhalite is less water soluble than more conventional sources (Yermiyahu *et al.*, 2017; Yermiyahu *et al.*, 2019) and is, therefore, a suitable fertilizer to supply these four nutrients in regions with high rainfall. So far, polyhalite application has been found to enhance cole crops performance in India (Satisha and Ganeshamurthy, 2016), Turkey (Anac *et al.*, 2019), and Switzerland (Terrones *et al.*, 2020).

The objective of the present study was to evaluate the agronomic efficiency of polyhalite on yield, quality, and economic returns of cabbage crop on degraded soils in northern Vietnam. Demonstrating the advantages of using polyhalite as an alternative to a chemical K fertilizer, and as a key fertilizer for balanced crop nutrition, will encourage Vietnamese farmers to adopt this into their strategy for cabbage and other crops.



Map 1. Location of the cabbage field trial at Tien Thang commune, Me Linh district, Hanoi, Vietnam.

Table 1. Detailed description of the fertilizer treatments

Treatment		FYM	Nitrogen (N)	Phosphorus (P_2O_5)	Potassium (K_2O)	
					MOP	Polyhalite
		ton ha^{-1}	--------------	*kg ha^{-1}*	--------------	
K_{150+0}	(FP control)	15	180	80	150	0
K_0	(control)	15	180	80	0	0
K_{60+0}		15	180	80	60	0
K_{30+30}		15	180	80	30	30
K_{45+45}		15	180	80	45	45
K_{60+60}		15	180	80	60	60

Note: FYM = farmyard manure, FP = Farmers' practice.

Materials and methods

Experiment site

The field experiment was carried out at Tien Thang commune, Me Linh district, Hanoi (Map 1). The climate in this region is subtropical with a mean annual temperature of 23.5°C and a mean annual rainfall of 1,620 mm, of which more than 80% occurs between May and October. Between September to December, during the cabbage growing season, max/min temperatures steadily decline from 32/25°C to 22/16°C, while monthly precipitation decreases from 270 to 30 mm.

The soil profile of the research area was classified as Grey degraded soil or Plinthic Acrisols (FAO, 1990) or as Plinthaquults (Soil Survey Staff, 1992). The properties of the basic top-soil (0-25 cm) were 2% clay, 70% silt, 20% fine sand (20-200 µm) and 8% coarse sand (> 200 µm). Soil $pH_{(KCl\ 1M)}$ was 5.0, and the total soil carbon (C), nitrogen (N), phosphorus (P), and potassium (K) contents were 6.6, 1.2, 0.35, and 0.58 g kg^{-1}, respectively.

Experiment plan

Before sowing, a standard basic fertilizer practice was carried out throughout, which included the spreading of farmyard manure (FYM), or composted cattle dung, at 15 t ha^{-1}; 180 kg N ha^{-1}, using urea (46% N); and, 80 kg P_2O_5 ha^{-1} with superphosphate Lam Thao (16.5% P_2O_5). The experiment consisted of six treatments (Table 1) with 4 replications in a randomized complete block design, i.e. 24 plots (24 m^2 plot^{-1}).

The treatments differed in K rate (from 0-150 kg K_2O ha^{-1}) and source: muriate of potash (MOP; KCl, 60% K_2O) and polyhalite (19.2% S, 14% K_2O, 6% MgO and 17% CaO). The first control (K_{150+0} – farmers' practice, FP) included a high K rate, all of which was applied through MOP (K_{150+0}), and served to compare with the other treatments, agronomically and economically. The second control did not include any K application (K_0), providing an evaluation of K contribution to the cabbage crop performance under the experiment conditions. In treatments K_{60+0} and K_{30+30}, the K rate was reduced to 60 kg K_2O ha^{-1}, applied solely through MOP or through a combination of MOP and polyhalite, respectively. In treatments K_{45+45} and K_{60+60}, K application rates rose to 90 and 120 kg K_2O ha^{-1}, respectively, while maintaining a 1:1 ratio between MOP and polyhalite as the sources of K_2O (Table 1). Fertilizers were applied at five stages: pre-planting, and irrigated dressings at 10, 30, 40, and 50 days after planting, as shown in Table 2.

Table 2. Description of fertilizer application schedule during the cabbage crop experiment in northern Vietnam.

Fertilizer	Application time				
		Days after planting			
	Pre-plant	10	30	40	50
	------------	------------	%	------------	------------
FYM	100				
Urea		30	30	20	20
Superphosphate	50		50		
MOP/polyhalite	20		30	25	25

Crop management

A locally recommended green cabbage Japanese cultivar was used. Seeds were sown in a nursery on 9 August 2016, and seedlings were transplanted on 3 September 2016 into raised beds, 120 cm width and 30 cm height, spacing between two beds was 30 cm, with a density of 4 plants m^{-2} (40,000 plants ha^{-1}). Harvest started on 2 December 2016.

Observations and measurements

During the growing season, crop phenological development was followed. Estimates of pest and disease infection took place at 30, 45, and 60 days after planting. At harvest, cabbage heads were sampled to determine yield and quality parameters, as well as the concentrations of total soluble solids and vitamin C.

Results and discussion

In all fertilizer treatments excluding K_0, the cabbage growing season from planting to harvest lasted 115 days, indicating that polyhalite had no significant effects on cabbage phenological development. Potassium deficiency delayed cabbage development by 5 days over the growing season, from the pre-cupping and head formation in October, until harvest at 120 days after planting (DAP).

Significant effects on plant dimensions were observed as early as the pre-cupping stage, in the first week of October (Fig. 2). Plants of all treatments with combined polyhalite and MOP had significantly greater canopy diameter compared to the MOP-applied plants, and K_0 plants displayed the smallest diameter.

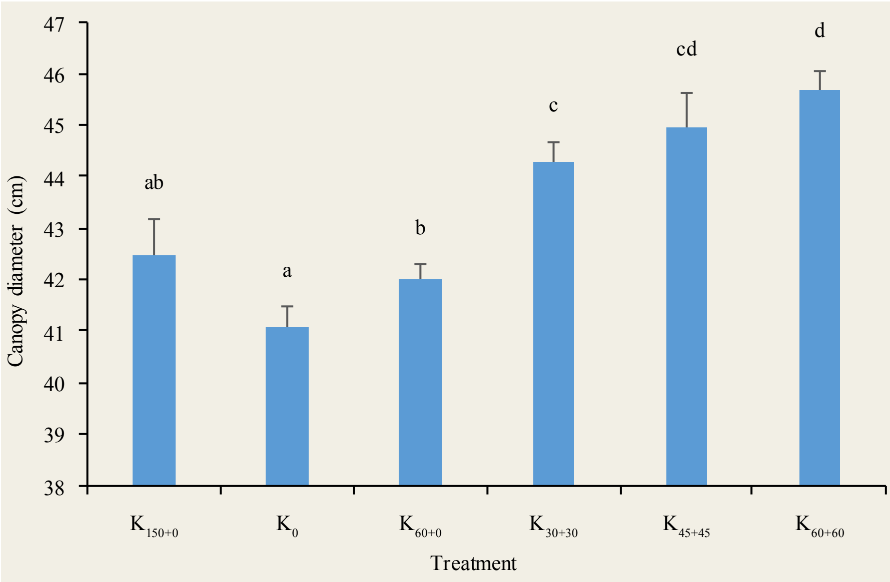


Fig. 2. Effects of fertilizer treatments on the pre-cupping canopy diameter in the first week of October. For detailed description of the fertilizer treatments refer to Table 1. Bars indicate SE. Similar letters indicate no significant differences at P<0.05.

Differences became clearer at harvest (Fig. 3). Total plant weight, which was significantly small at K_0 (2.2 kg plant^{-1}), substantially increased in response to MOP application up to 2.65 kg plant^{-1} at K_{150+0}. Nevertheless, under combined MOP and polyhalite, plant weight further increased, reaching 3.05 kg with much smaller K inputs, 90-120 vs. 150 kg K_2O ha^{-1}. Interestingly, with a similar K input of 60 kg K_2O ha^{-1}, the combined K_{30+30} treatment gave rise to significantly greater plant weight compared to K_{60+0}, 2.85 vs. 2.5 kg plant^{-1}, respectively

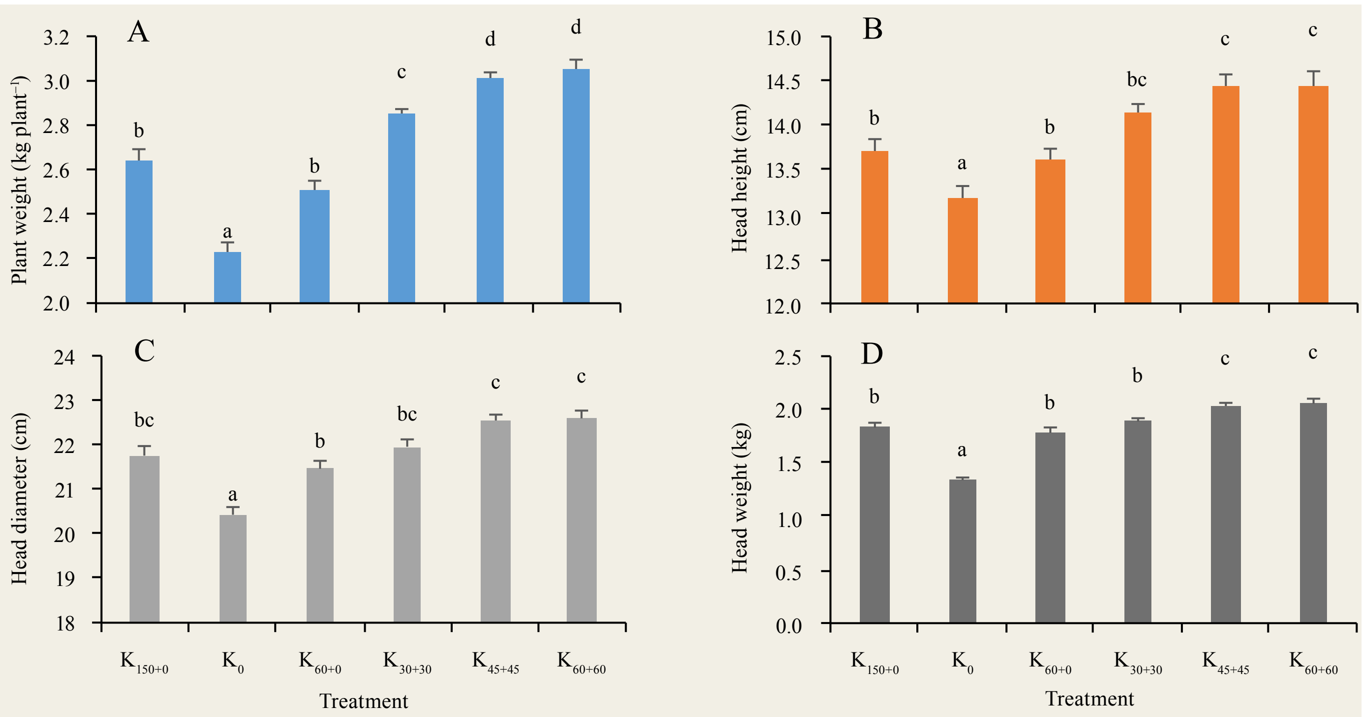


Fig. 3. Effects of fertilizer treatments on cabbage plant weight, and head dimensions at harvest. Total plant weight (A); head height (B); head diameter (C); and, head weight (D). For detailed description of the fertilizer treatments refer to Table 1. Bars indicate SE. Similar letters indicate no significant differences at P<0.05.

(Fig. 3A). Similar response patterns were observed for the cabbage head dimensions (Fig. 3B-D); while K_0 consistently exhibited the smallest head dimensions and weight, and cabbage head size increased significantly in response to K application, the differences between MOP and combined MOP and polyhalite were slightly smaller, being significant only at the higher K dose. Still, the cabbage head weight was significantly greater at the K_{45+45} and K_{60+60} than at the K_{150+0} treatment (Fig. 3D).

Consequently, the response of the total and marketable cabbage yields to the fertilizer treatments follow a similar pattern – lowest at K_0, intermediate under MOP, and significantly higher under MOP and polyhalite combinations. The marketable yield was quite similar, 65-67%, among all treatments, excluding K_0 with only 57% (Fig. 4A). Normalizing the marketable yield to that of K_0 highlights the significance of K fertilizer application to cabbage crop performance on the local degraded soil (Fig. 4B); the increase in the marketable cabbage yield ranged from 33-61%. Nevertheless, the nature of the K source appears very important; using MOP solely, the marketable yield rose by 33 and 40% in response to doses of 60 and 150 kg K_2O ha^{-1}, respectively, compared to the K_0 control. Using a 1:1 combination of MOP and polyhalite at the lower dose tested (60 kg K_2O ha^{-1}) resulted in a further rise of the relative marketable yield, from 33 to 47%. Moreover, increasing the K_2O dose using the same combined fertilizers to 90 and 120 kg K_2O ha^{-1} brought about yield increments of 59 and 61%, respectively, in comparison to the 40% yield increase by MOP alone at a much higher dose of 150 kg K_2O ha^{-1} (Fig. 4B). These results clearly indicate the significant advantage of utilizing polyhalite as a supplementary K fertilizer. This enhanced productivity stems from several advantages of the polyhalite fertilizer: 1) synergistic interactions between S, provided by polyhalite, and N uptake and protein metabolism (Jamal *et al.*, 2010); 2) slower nutrient release from polyhalite, compared to MOP (Yermiyahu *et al.*, 2017); and, 3) polyhalite supplies Ca and Mg, essential macronutrients that might have been insufficiently available in the local soils.

Normalizing the marketable yields to the farmers' practice (K_{150+0}) revealed the inefficiency of that treatment: using solely MOP at 150 kg K_2O ha^{-1} resulted in less than 5% yield increase compared to a substantially smaller dose of 60 kg K_2O ha^{-1} (Fig. 4C). Furthermore, under a similar small dose, the MOP and polyhalite combination yielded 10% more than MOP alone. It appears that the ceiling K_2O dose, above which no significant further yield increase can be reached, is about 100 kg K_2O ha^{-1}, as indicated by the tiny yield contribution of the move from K_{45+45} to K_{60+60} treatment (Fig. 4C). Thus, when applying combined MOP and polyhalite, about a third of the currently recommended K dose can be avoided, while still producing a 15% increase in the marketable yield.

Cabbage quality analyses revealed the dry matter (about 8%) and vitamin C (14-18 mg 100^{-1} g) contents showed no significant

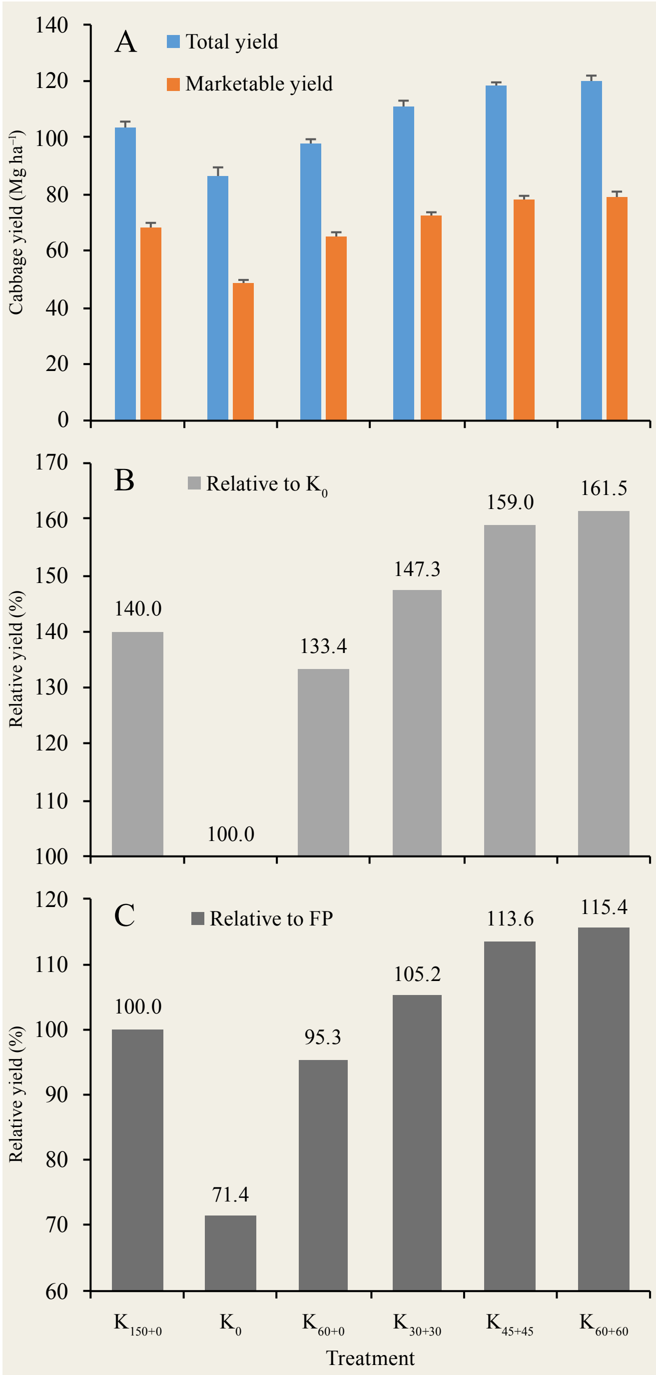


Fig. 4. Effects of fertilizer treatments on cabbage yields on degraded grey soil in northern Vietnam. Total and marketable yields (A); relative marketable yield normalized to the K_0 control (B); relative marketable yield normalized to the local farmers' practice, FP, K_{150+0} (C). For detailed description of the fertilizer treatments refer to Table 1. Bars indicate SE.

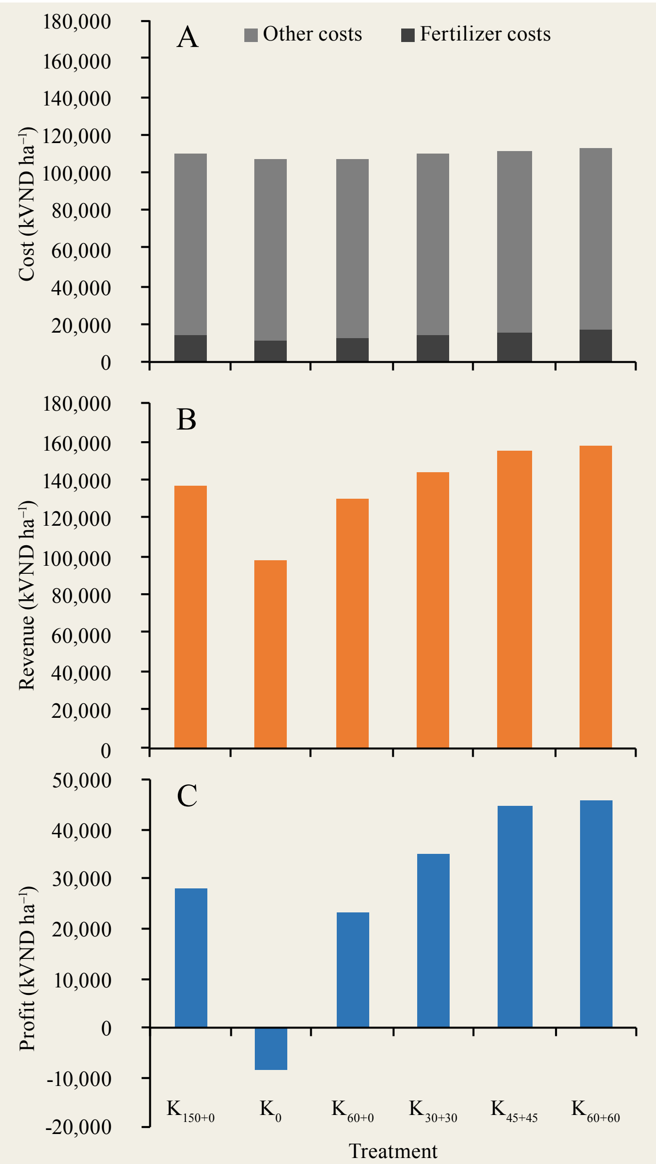


Fig. 5. Effects of fertilizer treatment on the costs (A); revenue (B); and, on the profit (C) of cabbage crop grown on degraded grey soil in northern Vietnam. For detailed description of the fertilizer treatments refer to Table 1.

differences between treatments. Significant differences did occur in the total soluble solids content of the cabbage heads that ranged from 2.8-3.7%, however, these could not be attributed to any consistent response to the fertilizer treatments (data not shown).

The incidence of pests was low and similar between treatments. There were two main insect types, Diamondback moth (*Plutella xylostella*) and cabbage white butterfly (*Pieris rapae*), the influences of which were very light during 30-45 DAP, and quite normal at 60 DAP. Two cabbage diseases, black rot of crucifers (*Xanthomonas caminsectris*) and bacterial soft rot (*Erwinia carotovora*), occurred very slightly (less than 1% leaf area damage) until 45 DAP. At 60 DAP, the bacterial soft rot severity substantially increased. Nevertheless, the diseases' influence was similar among all treatments.

Economic analyses of the influences of the various fertilizer treatments on cabbage crop at the farm gate showed a negligible increase in farmer's costs when polyhalite was combined with MOP. At the highest combination dose (K_{60+60}), the fertilizer cost was only 3,152 kVND ha^{-1} higher than that of the FP, K_{150+0}, while all other costs remained constant (Fig. 5A). In contrast, moving from the K_{150+0} approach to the K_{60+60} treatment, the farmer's revenue substantially increased from 137,300 to 158,420 kVND ha^{-1} (Fig. 5B). The profit analysis (Fig. 5C) revealed that without application of any K fertilizer (K_0), farmers would have lost about 9,000 kVND ha^{-1}, compared to an expected profit of 28,000 kVND ha^{-1} at the FP control. At a dose of 60 kg K_2O ha^{-1}, the expected profit was a bit smaller than FP when MOP was solely used (K_{60+0}), but was higher than at FP when combined with polyhalite (K_{30+30}). The expected profit continued to rise with the increasing K dose up to 90 kg K_2O ha^{-1}, and even a bit further at 120 kg K_2O ha^{-1}, demonstrating that using a 1:1 combination of polyhalite and MOP would result in a profit of 46,000 kVND ha^{-1}, almost 18,000 more than with MOP alone at 150 kg K_2O ha^{-1} (Fig. 5C). The marginal balance point between the additional fertilizer cost and the expected profit occurred at about 100 kg K_2O ha^{-1}, using the combined fertilizers. These results support earlier studies that demonstrated the advantages of utilizing polyhalite fertilizers for cabbage and other crucifer crops grown on various soil types in other countries (Satisha and Ganeshamurthy, 2016; Anac *et al.*, 2019; Terrones *et al.*, 2020).

Conclusions

Polyhalite, in 1:1 combination with MOP, was used to fertilize cabbage grown on a degraded grey soil in northern Vietnam. The combined fertilizer significantly enhanced cabbage crop performance and consequently gave rise to substantial increases in the total and marketable yields, compared to the common farmers' practice which used solely MOP. Using a combination of polyhalite and MOP, K application dose was reduced from 150 to 100 kg K_2O ha^{-1}, while the profit grew by 64%, from 28,000 to 46,000 kVND ha^{-1}. These results indicate the advantage of polyhalite as a supplemental fertilizer contributing K as well as other essential macronutrients.

Acknowledgements

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The paper "Effects of Polyhalite Application on Yield and Quality of Cabbage Grown on Degraded Soils in Northern Vietnam" also appears on the IPI website.

Research Findings

Photo 1. Alfalfa (*Medicago sativa*). Photo by the authors.

Polyhalite Enhances Alfalfa Production, Quality, and Environmental Footprints, Reims, France

Morell, F.J.[(1)*], M. de Villenaut[(2)], and F. Carnec[(3)]

Abstract

Similar to most rainfed crops, alfalfa (*Medicago sativa*) is assumed to benefit from a balanced macronutrient supply. Polyhalite is a natural mineral fertilizer consisting of a hydrated sulfate of potassium (K), calcium (Ca), and magnesium (Mg) with the formula: $K_2Ca_2Mg(SO_4)_4 \cdot 2(H_2O)$. Polyhalite is less water soluble than conventional nutrient sources and is, therefore, suitable as a supply of these four nutrients during rainy growing seasons. Due to its relatively low K content (14%), fortification of polyhalite application with alternative K sources, such as KCl (potassium chloride) should be considered. The objectives of the present study were to examine the response of alfalfa yield and quality to increasing proportions of polyhalite, and to estimate the crop's carbon footprint, compared to KCl alone and to an unfertilized control. A field trial was established at Vésigneul-sur-Marne, France, during the second and third years (2019-2020) of a perennial alfalfa field. An annual dose of 300 kg K_2O ha^{-1} was supplied to four treatments through 0, 200, 405, or 800 kg polyhalite ha^{-1} and 500, 450, 405, and 310 kg KCl,

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respectively, and compared with a K_0 control. Over the two-year experiment period, the treatments with polyhalite yielded 1.6 Mg ha^{-1} more the crop applied only with KCl, and 3.1 Mg ha^{-1} more than the K_0 control, differences that were particularly pronounced in the second, drier, 2020 season. Feed value parameters tended to increase under the polyhalite treatments, however, differences were not significant and require further investigation. Carbon footprints, calculated on the basis of dry matter production, were slightly lower in the polyhalite-applied crop, however, due to the higher production rates, carbon footprints per hectare were much higher in all fertilized treatments, compared to the control. An extended three to five year research period of alfalfa production would be necessary to finally assess these findings.

Keywords: Carbon footprint; feed value; *Medicago sativa*; Lucerne; MOP; Polysulphate; potassium; sulfur

Introduction

Alfalfa or Lucerne (*Medicago sativa*) is a deep-rooted, temperate, perennial pasture legume, which is a high protein feed for livestock. Global consumption of alfalfa hay was 197.8 million metric ton in 2018. Alfalfa consumption is expected to register a compound annual growth rate (CAGR) of 6.9% during 2019-2024. North America is the largest market for alfalfa hay, whereas China, UAE, and Saudi Arabia are major importers, mostly from the USA (Research and Markets, 2020). The USA and Europe are among the largest alfalfa producers in the world, accounting for around 7 million ha. In Europe, Spain and France are leading producers that also export dry alfalfa hay to countries not able to meet their own demand. In France, around 80% of the alfalfa is grown in the area east of Paris as a rainfed crop, producing three or four cuts each year, over a three-year period, and rotated with wheat. A steadily increasing part of the alfalfa production in France is shifting to organic farming systems.

Alfalfa produces high quality green feed for livestock. It has high energy – digestibility of 65-72% with a metabolisable energy of 8-11 MJ kg^{-1} DM – and a high protein content (12-24%). Alfalfa grows in areas receiving as little as 325 mm annual rainfall but also provides good summer production in areas with up to 700 mm rainfall. While the crop can quickly respond to significant summer rainfall (>10 mm), it requires 20-25 mm to produce substantial growth. Where suitable environmental conditions prevail, a rain-fed alfalfa pasture can produce 4-8 Mg DM ha^{-1} a year (Revell and Dolling, 2018). However, yields are highly sensitive to the current precipitation regime.

Alfalfa crops can fix 10-20 kg ha^{-1} of nitrogen (N) per tonne of dry matter produced, increasing soil N levels for subsequent crops. However, N fixation, and consequently, protein production and content, strongly depend on soil fertility. Alfalfa has a recommended pH range of 5.2-8.0, and is sensitive to soil acidity below pH ($CaCl_2$) of 4.8. On soils with low pH, the crop would benefit calcium-rich fertilizers. Phosphorus (P) is the nutrient most often required by alfalfa even though the uptake of other nutrients by the crop is much greater. Phosphorus is tied up in high pH soils, where it forms insoluble minerals with calcium. Transported to the roots by diffusion, a process that slows down in cool soils, P application is of particular importance during the cooler months of the year (Ottman, 2010).

Potassium (K) fertilization is an important, though controversial, management aspect to consider in alfalfa. In rainfed production, the recommended soil K status is 100-200 mg kg^{-1}; an application dose of 20-40 kg K ha^{-1} is recommended for lower K status soils (Revell and Dolling, 2018). However, even on non-limiting K soils, K application may still have a positive effect on yield (Macolino *et al.*, 2013). For highly productive alfalfa (about 15 Mg ha^{-1}), a much higher dose of 300 kg ha^{-1} $year^{-1}$ is often recommended. However, luxury consumption, with possible negative effects on forage nutritive value, have been found when K supply is too high (Lloveras *et al.*, 2012; Jungers *et al.*, 2019).

Alfalfa has high sulfur (S) requirement, estimated from 45-70 kg ha^{-1}. Sulfur is an important nutrient for alfalfa as a component of specific amino acids, lysine and cysteine, that are essential for protein metabolism. Therefore, S influences yield, protein content, stand density, and stand life of alfalfa. Sulfur supply is often missing or inadequate, leading to unbalanced nutrient supply to the crop. Yield and quality responses can be clearly observed in response to S fertilizer applications, when soil S levels are low (Michigan State University Extension, 2016). In addition, soil deficiency of secondary macronutrients, such as calcium (Ca) and magnesium (Mg), might significantly impair crop production and quality, in alfalfa, as well as in other crops (Kumar, 2011; Marschner, 2012). Thus, a balance between crop nutrient requirements and fertilizer supply should be reached to ensure high yield and quality.

The awareness of the environmental consequences of food production is steadily growing (Brankatschk and Finkbeiner, 2017; Peter *et al.*, 2017; Flachowsky *et al.*, 2018; Balogh and Jámbor, 2020; Panchasara *et al.*, 2021), focusing on the water and carbon footprints of various crops and products. While rainfed alfalfa displays a minor water footprints, the carbon footprint of this crop is more complex and is the subject of recent research (Druille *et al.*, 2017; Bacenetti *et al.*, 2018; Wagle *et al.*, 2019). Where fertilizer application is required, the nature and sources of the fertilizers used might significantly affect the crop's overall environmental impact (Chojnacka *et al.*, 2019). In this respect, natural fertilizers seem advantageous compared to chemically manufactured ones.

Polyhalite is a natural mineral which occurs in sedimentary marine evaporates and consists of a hydrated sulfate of K, Ca, and Mg with the formula: $K_2Ca_2Mg(SO_4)_4{\cdot}2(H_2O)$. The deposits found in Yorkshire, in the UK, typically consist of K_2O: 14%, SO_3: 48%, MgO: 6%, CaO: 17%. As a fertilizer providing four key plant nutrients – S, K, Mg, and Ca – polyhalite offers attractive solutions to crop nutrition. In addition, polyhalite is less water soluble than more conventional sources (Yermiyahu *et al.*, 2017; Yermiyahu *et al.*, 2019) and is, therefore, a suitable fertilizer to supply these four nutrients during rainy growing seasons. Polyhalite is available in its natural form as Polysulphate® and has been approved as an input for organic production systems in many countries. Due to its relatively low K content, fortification of polyhalite application with additional K sources, such as KCl (potassium chloride, also known as muriate of potash – MOP) should be considered according the K demands of the crop.

The objectives of the present study were to evaluate polyhalite, in combinations with KCl, as a K source for alfalfa, and to examine the response of both yield and quality to increasing proportions of polyhalite. Additionally, the carbon footprint of alfalfa was calculated, comparing the polyhalite and KCl treatments.

Map 1. Location of the experiment site in France. Sources: https://www.map-france.com/ and Google Earth.

Materials and methods

A field trial was established on second year alfalfa, in winter 2019 (GPS, latitude 48.884, longitude 4.476), Vésigneul-sur-Marne, France. Soil at the trial location was a calcareous soil (52% calcium carbonate), pH 8.2, with 2.2% soil organic carbon. Soil texture was silt loam, with 12% clay and 27% sand.

According to local guidelines, soil P content was low (61 mg P_2O_5 kg^{-1}), and K content high (431 mg K_2O kg^{-1}). Fertilization rates were established to supply 300 units of K_2O, following general potassium fertilization recommendations in the region (Circulaire 156, Coop de France Déshydratation, www.culture-luzerne.org/).

Four different treatments were established with combinations of 2 different sources of potassium, potassium chloride (potash), and polyhalite (as a powder and a granular product, 14% K_2O). The polyhalite also added magnesium, calcium and sulphur (Table 1). A control was established which received no additional nutrient supply.

The trial consisted of 3 replications, on a randomized complete block design. Individual plot size was 11.25 m by 2.5 m. Alfalfa productivity was assessed by harvesting the plot with a 1.5 m wide mower across the central part of the plots. Moisture content was assessed in each plot by oven drying under control conditions, and productivity referred to dry matter at 9% moisture content.

Precipitation has a significant influence on alfalfa productivity. The precipitation data was retrieved from NASA gridded weather data (https://power.larc.nasa.gov/data-access-viewer/).

Feed quality parameters were assessed from a mixture of samples from the 3 replicates. The nitrogen content and all other quality parameters were obtained using NIRS technology (Near Infra-Red Spectroscopy). The protein digestible in the intestine

Table 1. Fertilizer application and nutrient additions.

Treatment	Fertilizer rate		Nutrient rate			
	MOP (KCl)	Polyhalite	K_2O	MgO	SO_3	CaO
	kg ha^{-1}					
Control	0	0	0	0	0	0
KCl	500	0	300	0	0	0
200p	450	200 (granular)	300	12	96	32
405p	405	405 (granular)	300	24	194	65
800p	310	800 (powder)	300	48	384	128

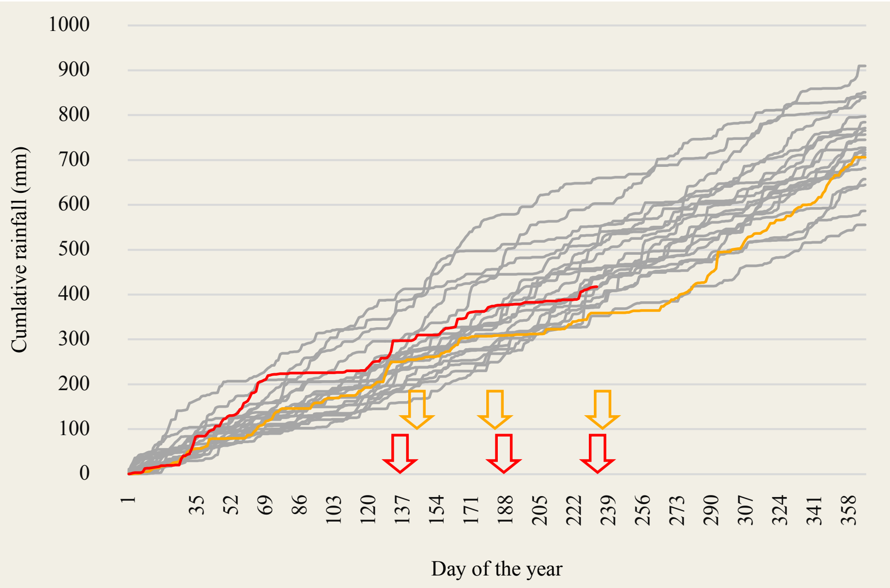

Fig. 1. Cumulative rainfall at the trial location (gridded data from POWER Data, NASA). Gray lines indicate cumulative rainfall in various years; Orange line indicates cumulative precipitation in 2019; red line indicates cumulative rainfall in 2020, until DOY 233, 20th of August (third and last cut). Arrows indicate the days the alfalfa was cut during the experiment (orange arrows for 2019, and red arrows for 2020).

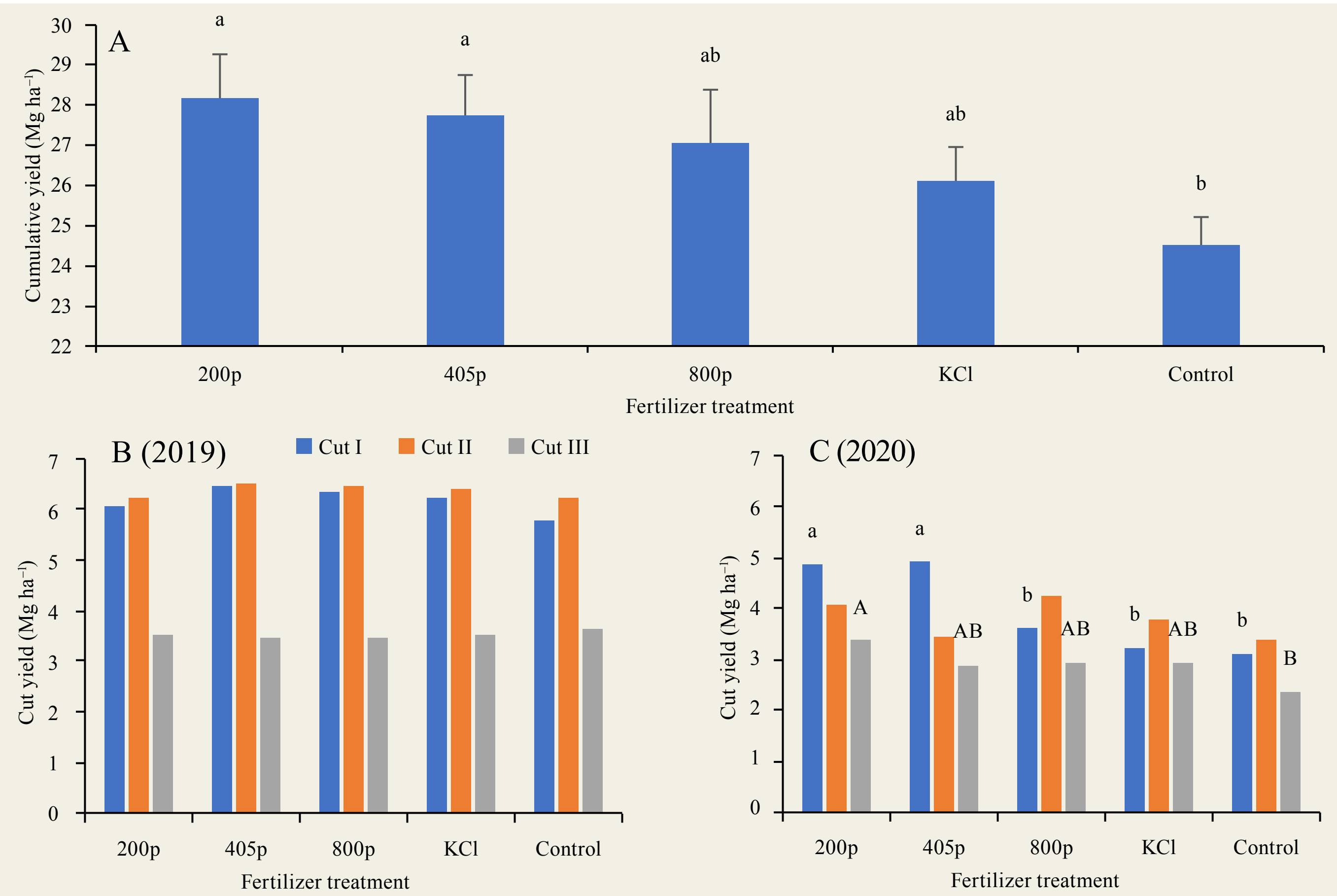

Fig. 2. Effects of the fertilizer treatments on the cumulative yield over the two successive growing seasons, 2019 and 2020 (A), and separately, on the yield of each cut during 2019 (B), and 2020 (C). For detailed treatment description refer to Table 1. Similar letters indicate no statistical differences between treatments at P>0.05.

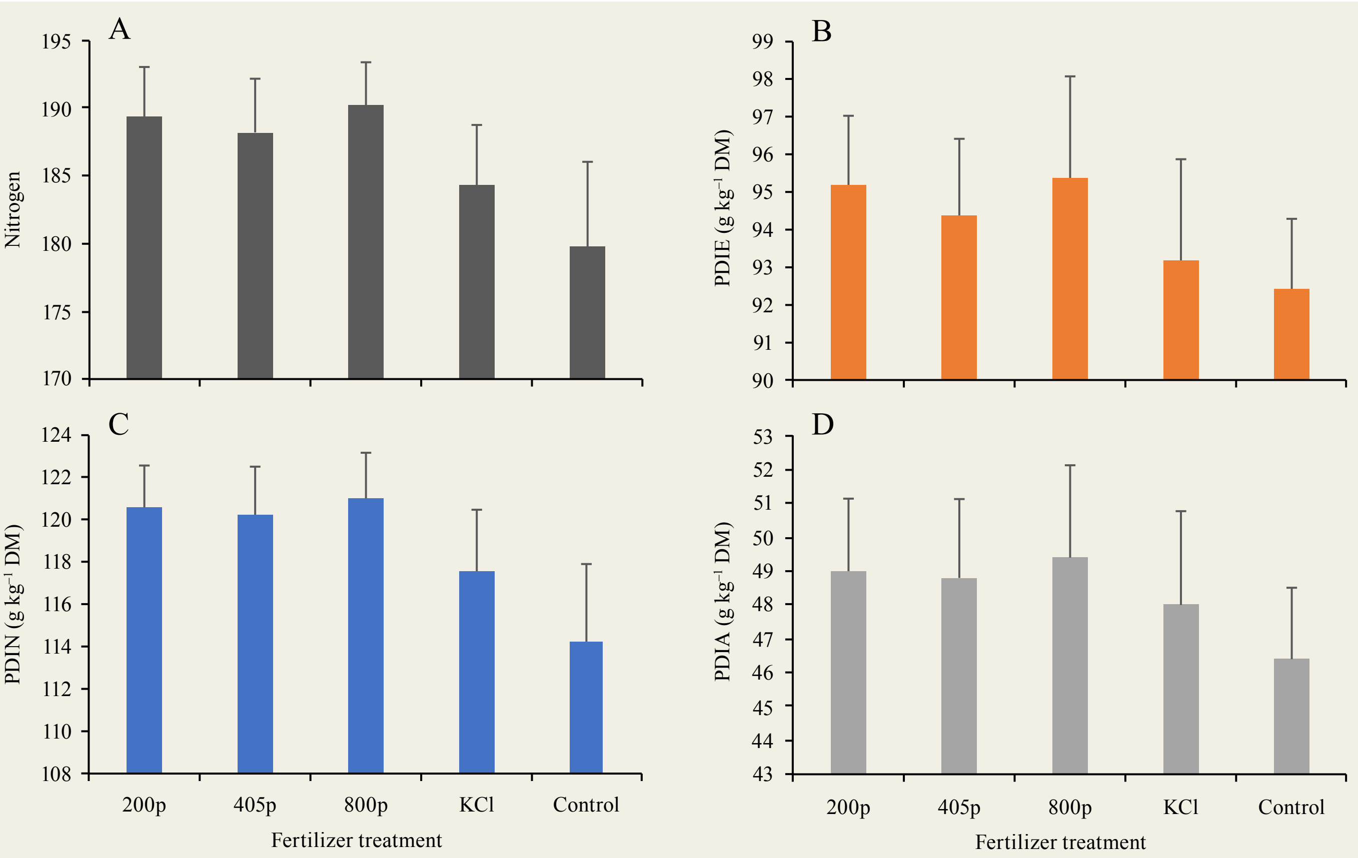

Fig. 3. Effects of the fertilizer treatments on the alfalfa quality parameters. Total protein content (A); PDIA – dietary protein undegraded in the rumen but actually digestible in the small intestine (B); PDIN – digestible protein in the intestine limited by nitrogen (C); PDIE – digestible protein in the intestine limited by energy (D). For detailed treatment description refer to Table 1.

system (PDI, after Vérité *et al.*, 1979; INRA, 2010) estimates the quantity of amino-N × 6.25 absorbed in the small intestine from the dietary protein which has escaped fermentation in the rumen, and the microbial protein arising from that fermentation. Two PDI values are ascribed to each feed: PDIN is calculated from both the degradable and non-degradable N contents; PDIE is calculated from both the rumen available energy and non-degradable N contents. Calculating the PDI value of a given diet, the PDIN and PDIE values of the different ingredients are summed separately, and the final PDI is the lower of the two values. Both PDIN and PDIE depend on PDIA, which expresses the non-degradable dietary protein in the rumen but truly digestible in the small intestine, as follows:

$$PDIN = PDIA + PDIMN$$
$$PDIE = PDIA + PDIME$$

Where PDIM is the microbial factual protein digestible in the small intestine. Each feed contributes to microbial protein synthesis both by the degradable N (PDIMN), and the available energy that it supplies to the rumen micro-organisms (PDIME).

Statistical analyses of yield were performed on a single factor analyses of variance for each of the six cuts. Statistical analyses of quality parameters were assessed comparing all 5 samples, as a sample of values for each treatment, on a single factor (Treatment) analysis of variance.

Finally, an assessment of the C footprint of each treatment was obtained with the Cool Farm Tool (https://coolfarmtool.org/), to assess the environmental impact of each strategy. The assessment of the carbon footprint of each of the strategies took into account the energy costs of the alfalfa drilling (1 operation), spraying (twice a year), baling (six operations, one for each cut), and where applicable, the energy cost of the fertilizer manufacturing and spreading (two applications).

Results and discussion

The mean cumulative production in 2019 was 16.12 Mg ha^{-1}, compared to 10.62 Mg ha^{-1} in 2020. The substantial difference between the two years may be attributed to differences in the precipitation regimes rather than to the cumulative precipitation, which was similar in 2019 and 2020, with a dry spell in both years from mid-July to the end of

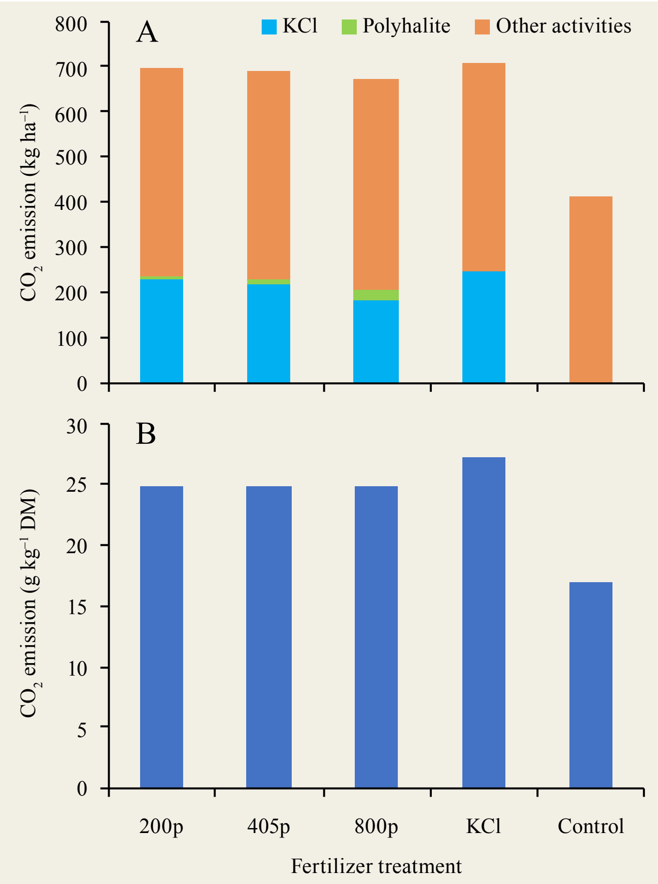

Fig. 4. Effects of fertilizer treatments on CO_2 emission rates associated with rainfed alfalfa production. Distribution of CO_2 emission due to KCl, polyhalite, and other operation activities, expressed as kg CO_2 ha^{-1} (A); Specific CO_2 emission (g CO_2e kg^{-1} DM), as affected by the fertilizer treatments (B). For detailed treatment description refer to Table 1.

August (Fig. 1). The lower productivity in 2020 can be associated to a dry spell during March and April (DOY, 62 to 120, Fig. 1), which negatively affected the productivity of the first cut.

In the first season, dry matter production was similar, with no significant differences between the treatments. The unfertilized control tended to have the lowest cumulative production, on average 0.5 Mg ha^{-1} lower than the fertilized alfalfa (Fig. 2B). In the second season, however, the differences among treatments were more pronounced, with significant differences in 2 out of the 3 cuts (Fig. 2C). Over the whole experiment period, the alfalfa fertilized with polyhalite yielded 1.6 Mg ha^{-1} more than the crop fertilized with MOP, and 3.1 Mg ha^{-1} more than the K_0 control (Fig. 2A).

Quality assessment was performed on a composite sample from each cut, without replicates, in order to identify trends. A clear trend was observed in all cuts – especially in the second year – with improvments in all the quality parameters of the polyhalite-applied (Fig. 3). Nevertheless, this consistent tendency over two successive years was not statistically significant. Alfalfa sensitivity to other limiting factors, such as drought, might have overridden some of the fertilizer effects. With a crop cycle duration of three to five years, these trends may become more significant through further examinations.

In the present study, the calculated CO_2 emissions (CO_2e) associated with alfalfa production were 416 and 710 kg ha^{-1} (Fig. 4A), or 17 and 27 g kg^{-1} DM (Fig. 4B), for the control and the MOP-applied treatments, respectively. The significantly higher yields of all fertilized treatments, compared to the unfertilized control, imposed higher CO_2e rates, 460-463 vs. 416 kg ha^{-1}, respectively (comparing only the emissions associated with the activities related to alfalfa production, and excluding emissions associatied with fertilizer production) (Fig. 4A). Of the alfalfa production activities, the major contribution to CO_2e was attributed to the baling operations, with a total of about 300 kg CO_2 ha^{-1}. When compared to other farming systems (e.g., irrigated alfalfa), or to other crops, these C footprints are considered low, largely due to the very low input intensity and energy cost of rainfed alfalfa field operations. Fertilizer manufacturing and transport were the second largest CO_2e contributor, ranging from 208–250 kg CO_2 ha^{-1} (Fig. 4A). In this sense, the low C footprint of polyhalite in contrast to KCl, 0.034 vs. 0.250 g CO_2 kg^{-1} product, respectively, may explain the slight increase in the estimated specific CO_2e of the KCl treatment compared to combined treatments (Fig. 4B).

Conclusions

Rainfed alfalfa production productivity and quality improved with K fertilizer application. Polyhalite, a natural mineral fertilizer containing K, Ca, Mg, and S, was used to partially replace KCl in supplying alfalfa K requirements, with the advantage of providing secondary macronutrients. Consequently, combined polyhalite and KCl application gave rise to significantly higher yields, and a tendency to improve hay quality parameters. In addition, being a natural mineral fertilizer, polyhalite slightly reduces the C footprint of the crop. An extended research period examining alfalfa production over three to five years would be necessary to fully assess the yield and quality over the whole crop cycle.

Acknowledgements

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The paper "Polyhalite Enhances Alfalfa Production, Quality, and Environmental Footprints – Short News from Reims, France" also appears on the IPI website.

Research Findings

Photo 1. Potato experiment field. Photo by the author.

Potential of Polyhalite Fertilizers to Enhance Potato Yield and Quality in the United Kingdom

Garnett, S.[(1)*]

Abstract

Following three decades (1961-1990) of consistent increases, average potato yields in the UK have plateaued at 36-44 Mg ha^{-1}. Coincidentally, worldwide atmospheric sulfur (S) deposits have substantially declined, resulting in an emerging occurrence of S deficiencies in many crop species. It was hypothesized that S donor fertilizers might restart the trend of increasing potato yield in the UK. Polyhalite, available as a new commercial fertilizer marketed as Polysulphate® by ICL, is a natural hydrated sulphate of K, Ca, and Mg with the formula: $K_2Ca_2Mg(SO_4)_4{\cdot}2H_2O$. Polyhalite is comprised of 48% sulfur trioxide (SO_3), 14% potassium oxide (K_2O), 6% magnesium oxide (MgO), and 17% calcium oxide (CaO). Nevertheless, and due to the very high K requirements of potato crops, the relatively low proportion of this nutrient in polyhalite does not permit the use of this fertilizer as a sole K source. ICL PotashpluS® (ICL UK) is a new granular fertilizer formulated using a combination of potash (MOP, KCl) and polyhalite, in the formula: 37% K_2O, 24% SO_3, 3% MgO and 8% CaO. Both fertilizers contain traces of boron.

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The objective of the present preliminary study was to evaluate the influences of various polyhalite rates and combinations with MOP on tuber yield and quality. A set of three separate experiments was carried out, in which MOP was compared to PotashpluS (Exp. 1), MOP was progressively replaced by polyhalite (Exp. 2), and PotashpluS was progressively replaced by polyhalite (Exp. 3). In all three experiments, the application doses of nitrogen (N), phosphorus (P), and potassium (K) were kept equal throughout treatments, whereas the application doses of calcium (Ca), magnesium (Mg), and S were modified by the polyhalite rates (100, 200, and 300 kg ha^{-1}, in Exp. 2 and 3). While the differences in crop performance between MOP and PotashpluS-applied plots were small, replacing MOP or PotashpluS by polyhalite resulted in significantly enhanced yields at the higher polyhalite rates. It appears that the combination of high application doses of all three nutrients, Ca, Mg, and S together promotes higher yields than when each nutrient applied alone. In addition, high Ca rates increased tuber Ca concentration at harvest, and reduced tuber weight loss during storage. In conclusion, the set of experiments carried out in the present study demonstrates the potential of polyhalite fertilizers to enhance potato crop performance and tuber yield and quality through a more balanced mineral nutrition. However, further research is necessary to elucidate the contribution of Ca, Mg, or S to this enhancement, and to establish precise fertilization strategies for various edaphic conditions.

Keywords: Calcium; magnesium; polyhalite; Polysulphate; *Solanum tuberosum* L.; sulfur; tuber quality.

Introduction

Potato (*Solanum tuberosum* L.) is among the five most important staple crop species cultivated worldwide. With 144,000 ha cultivated with potatoes, and production of 5.25 million tonnes in 2019 (FAO, 2021), the United Kingdom is among the 15 leading potato producing countries in the world.

Historical analysis of the UK potato industry from 1961 to 2019 shows a consistent decline in the potato cultivated area until year 2000, when it stabilized at about 140,000 ha (Fig. 1A). Annual production slightly decreased, exhibiting substantial fluctuations until year 2000, from when it consistently dropped from 6.6 to the present levels of 5.2 million tonnes (Fig. 1A). The average annual potato yield doubled from 22-44 Mg ha^{-1} during the years 1961-2000 but since then it remained stable or even decreased (Fig. 1B).

The consistent climb in the UK potato yield during 1960-1990 may be attributed to the impacts of the 'Green Revolution' era, in which genetic improvements, chemical fertilizers and pesticides were intensively introduced and disseminated, resulting in significant increases in the performance of many crop species (Evenson and Gollin, 2003; Fuglie *et al.*, 2019). The cessation of this process during the recent decades, which has occurred despite continuing efforts to enhance agricultural practices, requires explanation. While climate change may provide an ultimate explanation for the recent fluctuations in the potato yield in the UK (Adesina and Thomas, 2020), slowly emerging problems of plant nutrition should not be excluded. Whereas routine examinations of soil nitrogen (N), phosphorus (P), and potassium (K) status are carried out in most commercial potato producing farms, the availability of secondary macronutrients, such as calcium (Ca), magnesium (Mg), and sulfur (S), is less addressed.

Sulfur is an essential element for all organisms and has a wide variety of functions. Methionine, a fundamental brick in protein biosynthesis, and cysteine, are both sulfur-containing amino acids, hence the availability of S is essential for normal plant growth and development. Furthermore, since plants are the primary source of the essential amino acid methionine in the human diet, crops' S nutrition is particularly important. Several studies have established regulatory interactions between N and S assimilation in plants (Kopriva

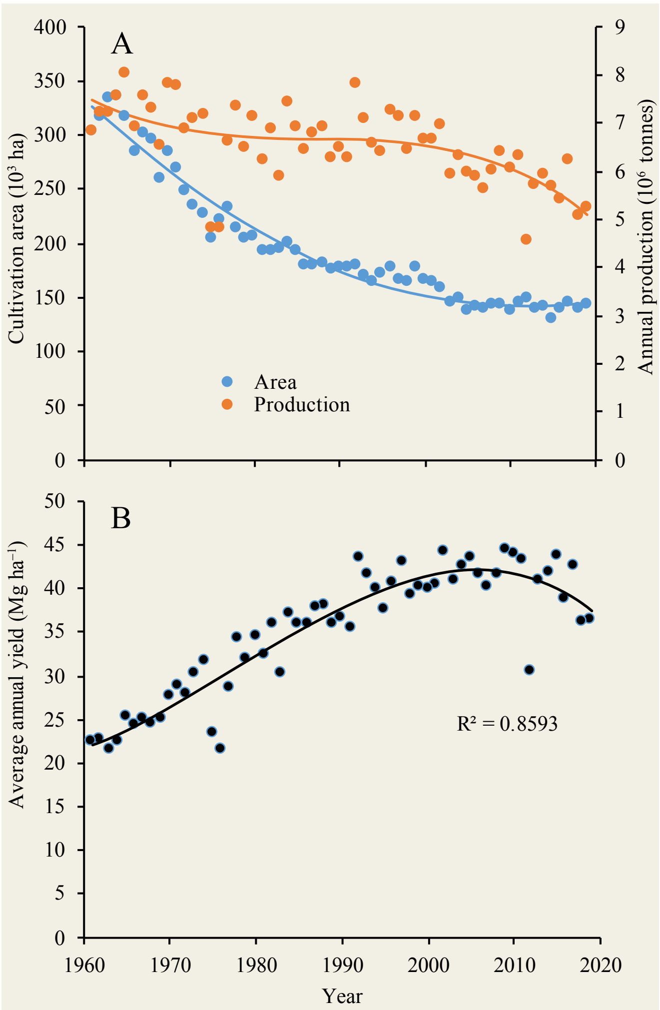


Fig. 1. Historical analysis of the potato industry in the UK during 1961-2019. Potato cultivated area and annual production (A) and, average annual potato yield (B). *Source:* FAOstat. 2021.

Photo 2. Potato root system from polyhalite trial. Photo by the author.

et al., 2002). Sulfur availability regulates N utilization efficiency in plants, and thus affects primary production of crops. Recent studies have found that interactions between S and other mineral nutrients may be crucial to normal plant development (Courbet *et al.*, 2019). In addition, it appears that S-metabolites have essential regulatory roles in plant cell physiology and, moreover, in plant responses to stress (Chan *et al.*, 2019; Huang *et al.*, 2019; Kaufmann and Sauter, 2019). Consequently, S deficiency affects the growth, development, disease resistance, and performance of plants and has a great impact on the nutritional quality of crops (Kopriva *et al.*, 2019).

Generally, sulfur deficiency problems began occurring in many crop species in the 1990's and became increasingly widespread over countries and continents during the last three decades. The major reason for this change was the introduction of strict regulation aiming to diminish the acid rain phenomenon that substantially reduced the industrial S (and N) emission to the atmosphere. This regulation resulted in a significant decline in the atmospheric S (SO_4^{2-}) deposition in the USA over the last three decades (Fig. 2). Similar regulations were also introduced in Europe and other regions, giving rise to comparable environmental impacts.

During the 20th century, industrially-generated atmospheric S deposition could meet agricultural requirements. Nevertheless, this situation changed remarkably with the declining S depositions during the beginning of the 21st century. In Indiana USA, for example, soil enrichment by S pollution was cut by 45% from 2001 to 2015 (Camberato and Casteel, 2017). Similar processes were reported in Iowa, USA (Sawyer *et al.*, 2015), as well as in Western Europe (Engardt *et al.*, 2017) and in China (Chen *et al.*, 2019).

Optimum management of crop nutrition supports high tuber yield (Koch *et al.*, 2019a), however, it is also significant to primary tuber quality traits including dry matter and starch contents; skin integrity; and tolerance to various diseases (Zhang *et al.*, 2018; Koch *et al.*, 2019b; Naumann *et al.*, 2020). While efficient potato crop nutrition management is well established in the UK with regard to N, P, and K, less attention has been paid to other essential macronutrients such as Ca, Mg, and S.

The significance of Ca nutrition to the development and yield of potatoes has been investigated in the last two decades, and the number of studies demonstrating Ca effects on tuber number and size is steadily increasing (Ozgen *et al.*, 2003; Palta, 2010; Seifu and Deneke, 2017; Singh, 2018; Potarzycki and Grzebisz, 2020). In addition, Ca is pivotal to the process of tuber skin development and maturation, being a key element in periderm cell wall integrity (Ginzberg *et al.*, 2012), which explains the contribution of Ca to the generally enhanced postharvest tuber quality (Palta, 2010; Murayama *et al.*, 2016; Keren-Keiserman *et al.*, 2019; Koch *et al.*, 2019b; Naumann *et al.*, 2020). Magnesium is part of chlorophyll in all green plants and is essential for photosynthesis and carbohydrate partitioning (Cakmak and Yazici,

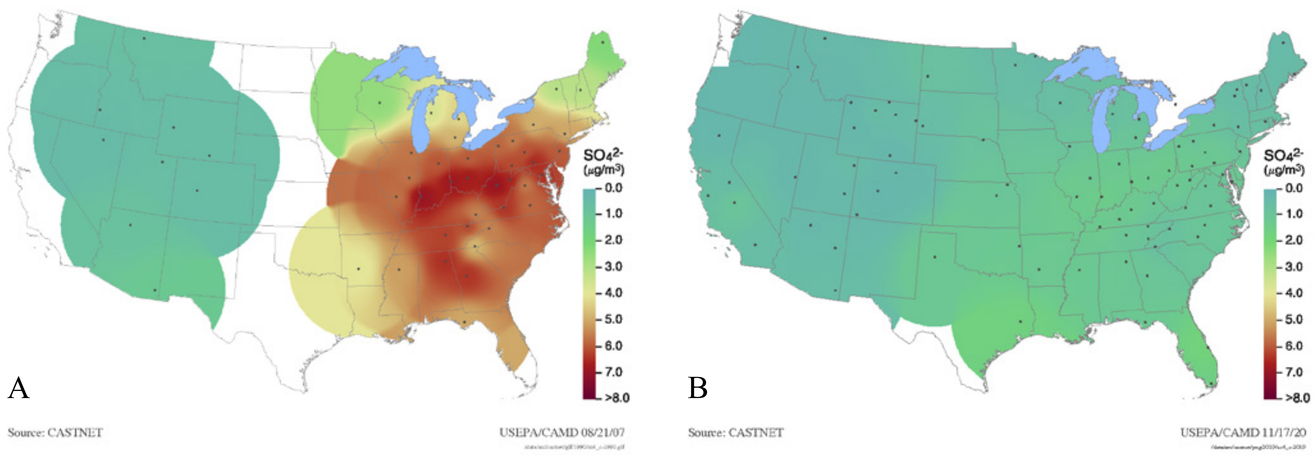


Fig. 2. The amount of annual sulfur (SO_4^{2-}) atmospheric deposition in the USA in 1990 (A), and in 2019 (B). *Source:* https://www3.epa.gov/castnet/airconc.html

2010; Farhat *et al.*, 2016). The importance of adequate Mg nutrition for potato plant development, carbohydrate partitioning (Koch *et al.*, 2019a), as well as tuber yield and disease tolerance (Singh, 2018) has recently been demonstrated. Potato crops exhibit no special S requirement compared to other crop species. Typically, 1 tonne of potato tubers will remove 4.5 kg of S (Burke, 2016). However, S-deficient plants develop short and spindly stems, smaller size, pale yellow foliage, and bright yellow young leaves. As a result, tuber yield and quality may decline, resembling N deficiency consequences (Burke, 2016).

Table 1. Soil properties at the three different experiment sites.

	Exp. 1	Exp. 2	Exp. 3
pH	6.9	6.8	6.2
Phosphorus (ppm)	14	10	88
Potassium (ppm)	94	58	89
Magnesium (ppm)	57	87	75
Calcium (ppm)	2013	2432	1293
Sulfur (ppm)	2	1	3
Manganese (ppm)	33	28	30
Copper (ppm)	4.3	5.0	21.3
Boron (ppm)	1.3	1.48	0.76
Zinc (ppm)	2.8	4.8	17.5
Molybdenum (ppm)	0.01	0.02	<0.01
Iron (ppm)	693	830	1249
Sodium (ppm)	27	34	29
C.E.C. (meq 100 g^{-1})	12.6	15.7	8.5

Polyhalite, a new commercial fertilizer marketed as Polysulphate® by ICL, is a natural hydrated sulphate of K, Ca, and Mg with the formula: $K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$. The purity of the product is very high (95% polyhalite) with <5% sodium chloride (NaCl) and traces of boron (B) and iron (Fe) at 300 and 100 ppm, respectively. Polyhalite is comprised of 48% sulfur trioxide (SO_3), 14% potassium oxide (K_2O), 6% magnesium oxide (MgO), and 17% calcium oxide (CaO). Calcium, the least soluble nutrient in polyhalite (Yermiyahu *et al.*, 2019), can provide available Ca at rates equivalent to those of gypsum. Polyhalite fertilizer, tested as an alternative source of Ca in potato, had a positive effect on tuber skin appearance and skin-related gene expression (Keren-Keiserman *et al.*, 2019). When examined as a substitute K donor fertilizer in Brazil, polyhalite enhanced potato yield with a positive influence on various quality traits (da Costa Mello *et al.*, 2018).

Nevertheless, and due to the very high K requirements of potato crops, the relatively low proportion of this nutrient in polyhalite does not permit the use of this fertilizer as a sole K source. ICL PotashpluS® is a new granular fertilizer formulated using a combination of potash (MOP, KCl) and polyhalite. While primarily a potash and sulphate fertilizer, PotashpluS also contains essential Mg and Ca, and supplies all K and S crop requirements in a single application. The formula is 37% K_2O, 9% S (24% SO_3), 3% MgO and 8% CaO. In addition, PotashpluS contains boron.

In the context of the diminishing atmospheric S deposits and the recently expanding occurrence of S deficiency in various crop species, it was hypothesized that S donor fertilizers would restart the trend of the increasing potato yield in the UK. The objective of this preliminary study was to evaluate the influences of various polyhalite rates and combinations with MOP on tuber yield and quality.

Materials and methods

Three preliminary experiments were carried out at three locations in the UK. The soil properties of the experiment sites are detailed in Table 1.

The first experiment (Exp. 1) aimed to compare the effects of the fertilizer

Table 2. Detailed description of the fertilizer treatments that were evaluated in the three different experiments carried out in the present study.

	Treatment	Nutrients N	P	K	Ca	Mg	S	Supplementary fertilizers		
		---kg ha^{-1}---								
Exp. 1 (cv. Brooke)	Farmers' practice	180	170	330	-	30	60	MOP, $MgSO_4$		
	PotashpluS	180	170	333	72	25	207			
Exp. 2 (cv. Brooke)	Farmers' practice	180	170	330	-	30	60	MOP, $MgSO_4$		
	Poly100	180	170	330	17	36	108	MOP, polyhalite		
	Poly200	180	170	330	34	42	154	MOP, polyhalite		
	Poly300	180	170	330	51	48	204	MOP, polyhalite		
								PotashpluS	Polyhalite	Composite NPK
								---kg ha^{-1}---		
Exp. 3 (cv. Shelford)	PotashpluS	222	185	333	32	11	199	400	0	1235
	Poly100	222	185	334	46	16	239	365	100	1235
	Poly200	222	185	335	60	21	279	330	200	1235
	Poly300	222	185	341	76	26	322	310	300	1235

PotashpluS vs. MOP (usual farmers' practice) with regard to crop performance, yield, and tuber size. The second experiment (Exp. 2) tested polyhalite at three different rates (100, 200, and 300 kg ha^{-1}) as a partial replacement of MOP as the K source, compared to the farmers' practice of 100% MOP. In the third experiment (Exp. 3), three polyhalite rates were tested in combination with declining PotashpluS rates, from 400 to 310 kg ha^{-1}. About half of the K application dose in Exp. 3, 185 kg ha^{-1}, was applied through a composite NPK fertilizer. In each experiment, the rates of N, P, and K application were equal in all treatments, while the differences were focused on the K source, and on the rates of Ca, Mg, and S application, as described in details in Table 2.

Seed tubers were sown in April in all three experiments. Aerial NDVI screening of the fields was conducted in June, when the crop reached full coverage. At harvest, sample 2 m digs were taken from each treatment (5 replicates) for the determination of plant and stem counts, tuber yield, and tuber size distribution.

In Exp. 1 and 2, tubers were sampled for the determination of N, K, Ca, Mg, and B concentration. In Exp. 3, tuber samples of 10 kg from each polyhalite treatment (5 replicates) were stored under commercial conditions for 4 months, and weight loss was determined.

Statistical analyses were made separately for each experiment using ANOVA and JMP software.

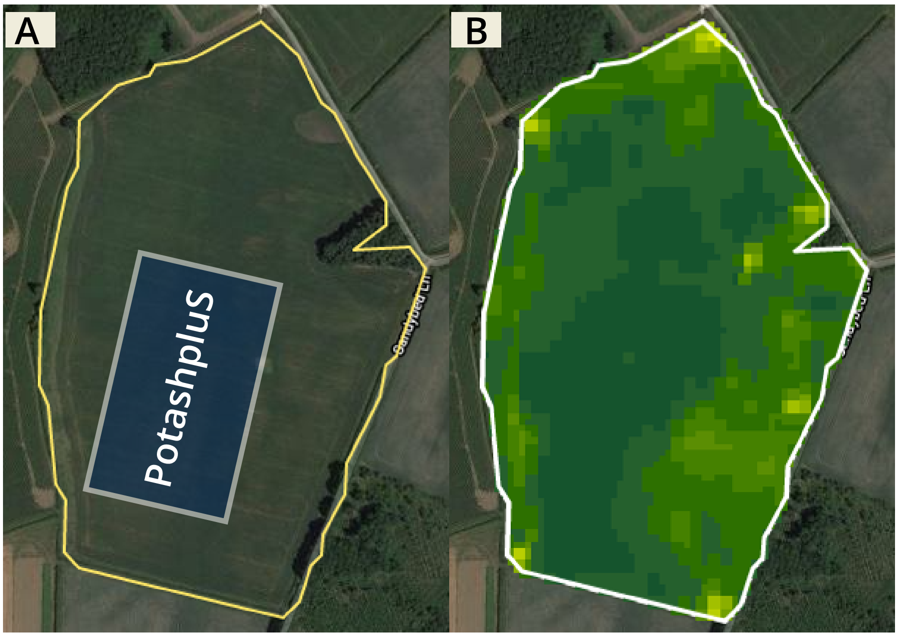


Fig. 3. Experiment 1 field. The PotashpluS-applied plot is marked with a blue border, surrounded by the MOP-applied area (A); NDVI image of the field in June (B).

Results

Experiment 1 – PotashpluS vs. MOP

In Exp. 1, the area treated with PotashpluS showed a darker color in NDVI images recorded in June (Fig. 3), which is usually associated with a better status of crop nutrition. However, no differences could be observed from visual assessments at ground level between the two treatments during site visits.

No significant differences between the fertilizer treatments were detected in the plants and stems counts at harvest (Table 3). Total and marketable tuber yields were slightly but not significantly higher under the PotashpluS treatment. The proportion of larger size (65-85 mm) tubers was significantly greater under the PotashpluS treatment. Tuber nutrient concentrations were unaffected by the fertilizer treatments in this experiment (Table 3).

Experiment 2 – polyhalite vs. MOP

In Experiment 2, the plots treated with polyhalite showed slightly darker colors in NDVI images made in June (Fig. 4). The polyhalite-applied strips looked greener throughout the season.

Table 3. Effects of PotashpluS application on potato crop performance, yield, tuber size distribution, and on tuber N, K, Ca, Mg, and B concentration, compared to MOP-applied control plants, in Exp. 1.

							Tuber size (mm)				Tuber concentration				
Treatment	Plant count	Stem count	Total yield	Field loss[1]	Marketable yield		< 45	45-65	65-85	> 85	N	K	Ca	Mg	B
	Plants m^{-2}	*Stems m^{-2}*	-------*Mg ha^{-1}*-------		*Mg ha^{-1}*	*%*	----------------%----------------				--------------*mg 100 g^{-1}*--------------				
PotashpluS	4.03	11.77	48.4	7.1	41.3	85.4	14.6	46.8	38.5	0	320.4	426.6	21.61	23.49	0.12
MOP	3.6	11.88	45.2	6.3	38.9	86.0	14.0	58.1*	27.9*	0	320.5	427.7	21.41	21.54	0.11

* Significant difference at 0.05%.

[1] Field loss: small tubers

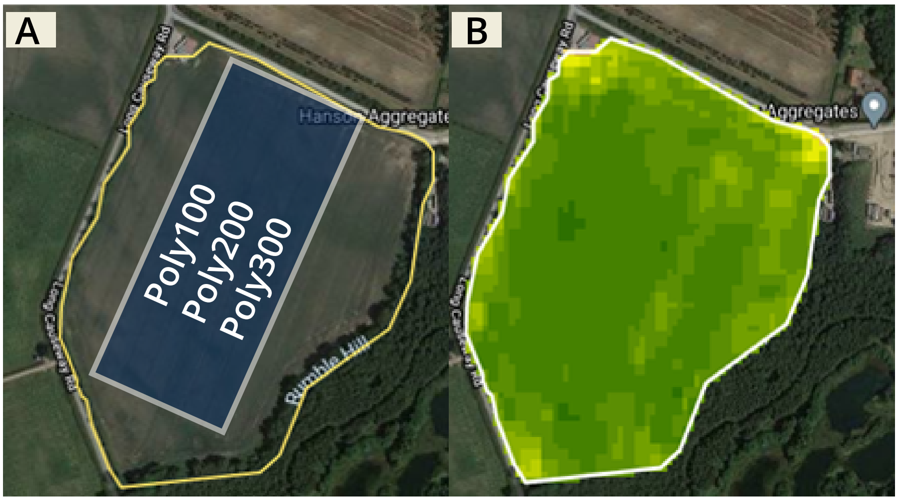
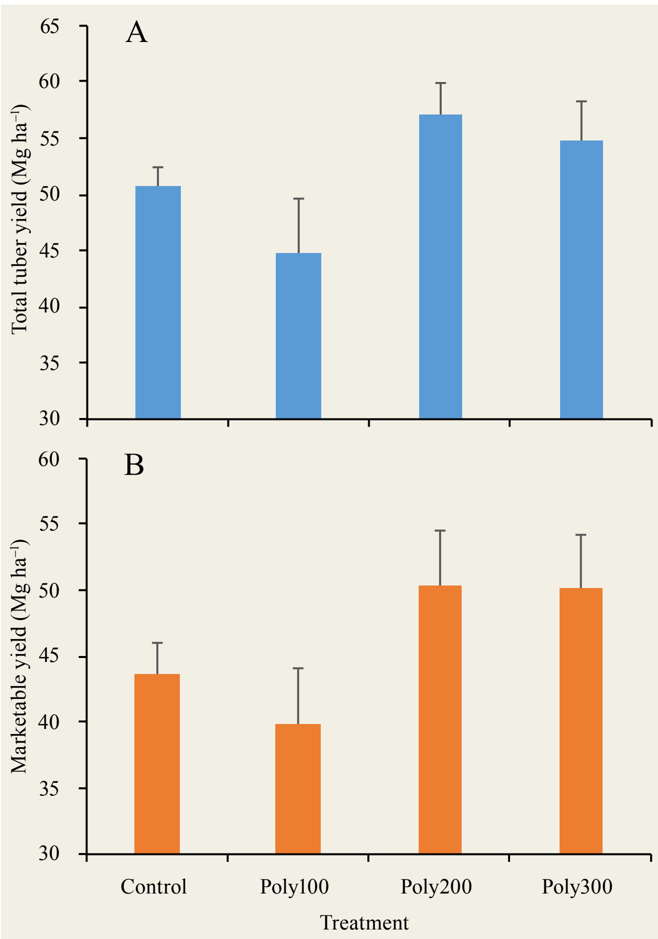


Fig. 4. Experiment 2 field. The polyhalite-applied plots are marked with blue borders, while the surrounding area was farmers' usual practice, MOP-applied control (A); NDVI image of the field in June (B).

Crop establishment was unaffected by the fertilizer treatments. Plant and stem counts ranged from 6.4-6.6 m^{-2} and 12.4-13.3 m^{-2}, respectively, excluding the Poly300 treatment, which was somewhat lower, with 6.0 plants m^{-2} and 12.2 stems m^{-2}.

The total tuber yield of the Poly200 treatment, 57.2 Mg ha^{-1}, was significantly higher than those of the MOP-applied control and the Poly100 treatment, with 50.8 and 44.9 Mg ha^{-1}, respectively, and slightly but insignificantly higher than that of the Poly300 treatment (Fig. 5A). Interestingly, the polyhalite treatments increased the rate of the marketable yield from 86% to 88-92%, mainly through significant reduction of field losses due to too small tubers. Although the response pattern of the marketable yield to the fertilizer treatment remained similar to that of the total yield (Fig. 5B), the polyhalite treatments displayed remarkable effects on the tuber size distribution, with a clear reduction in the proportions of small and medium size tubers, and a consequent increase in that of the large tubers (Fig. 5C).

Polyhalite treatments resulted in progressive increases of tuber N, Ca, Mg, and B concentrations that also were significantly higher than under MOP (Table 4). Similarly, tuber K concentration was significantly lower under MOP application compared to the polyhalite-applied plants, however no differences occurred between the treatments with different polyhalite rates.



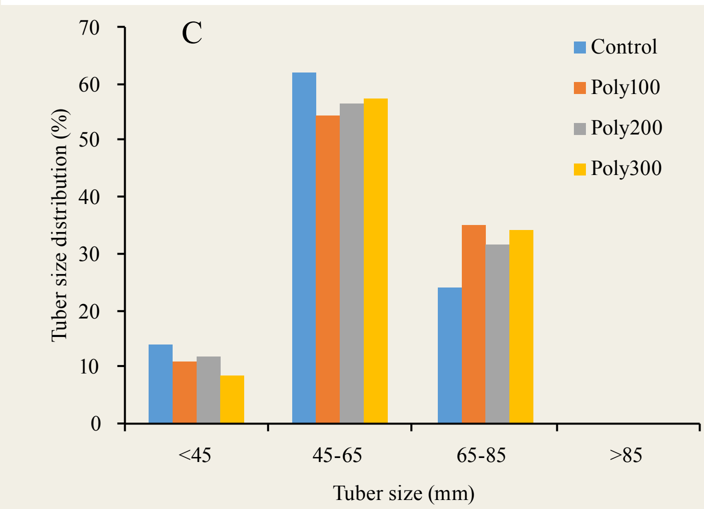


Fig. 5. Effects of increasing polyhalite application rates on potato tuber yield and quality, compared to farmer's usual practice or MOP-applied control. Total (A), and marketable (B) tuber yields, and tuber size distribution (C). Bars indicate SE.

Table 4. Effects of polyhalite application rate on the nutrient concentrations in potato tubers at harvest, compared to MOP-applied control.

Treatment	Nutrient				
	N	K	Ca	Mg	B
	-----	-----	*mg 100g^{-1}*	-----	-----
MOP	320.5	427.7	21.41	21.54	0.11
Poly100	346.3	456.6	26.17	23.19	0.14
Poly200	355.7	448.4	30.81	24.78	0.16
Poly300	374.7*	445.7*	33.10*	24.16*	0.16*

* Indicates significant differences at 0.05%

Experiment 3 – PotashpluS vs. polyhalite

In experiment 3, the polyhalite-applied plots were much darker than the PotashpluS-applied area in the NDVI image made in June (Fig. 6), and exhibited a slightly greener color during most of the season.

Crop establishment was similar under the higher polyhalite rates as well as under PotashpluS, with counts ranging at 3.8-4.0 plants m^{-2} and 23.5-24.9 stems m^{-2}, respectively. At the lower polyhalite rate, counts were smaller, with 3.6 plants m^{-2} and 19.7 stems m^{-2}.

In this experiment, both total and marketable tuber yields displayed a significant positive response to increasing polyhalite application rates. While Poly100 treatment gave rise to significantly lower yields than Poly300, Poly200 and PotashpluS obtained intermediate, comparable yields (Fig. 7A and B). No influence on the marketable yield rate, which was very close to 90% in all treatments, could be observed in this experiment. In addition, the proportion of small tubers (<45 mm) was similar, about 10% in all treatments. The proportion of medium-size tubers (45-65 mm) increased from 55 to 65% with the rising polyhalite application rate, which was probably at the expense of the large-size tubers (65-85 mm). Under the Poly100 treatment, about 2% of the tubers were too large, bigger than 85 mm (Fig. 7C).

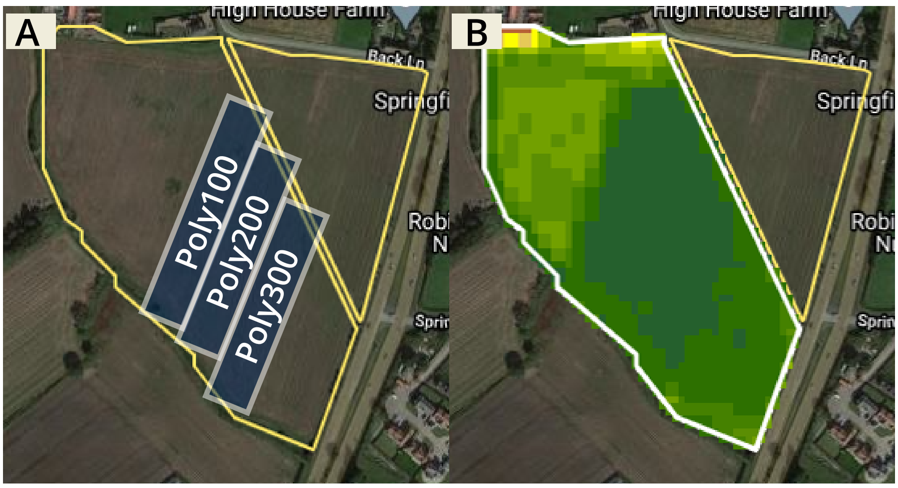


Fig. 6. Experiment 3 field. The polyhalite-applied plots are marked with blue borders, while the surrounding area was applied with PotashpluS (A); NDVI image of the field in June (B).

Table 5. Relationships between the ascending marketable yield and the input of secondary macronutrients Ca, Mg, and S across the three experiments.

Marketable yield	Nutrient application dose		
	Ca	Mg	S
Mg ha^{-1}		----------*kg ha^{-1}*----------	
38.9	0	30	60
39.9	17	36	108
41.3	72	25	207
43.0	46	16	239
43.7	0	30	60
47.5	60	21	279
48.6	32	11	199
50.2	51	48	204
50.3	34	42	154
51.6	76	26	322

A four-month storage test revealed a consistent reduction of tuber weight loss along with the rising polyhalite application rate in the field (Fig. 8). Unfortunately, there was no data available on weight loss of tubers from the PotashpluS treatment.

Discussion

In the light of plateaued potato yields during the last two decades, the impact of various polyhalite fertilizers that enrich the crop rhizosphere with four essential macronutrients (K, Ca, Mg, and predominantly S) was preliminarily evaluated. The diminishing atmospheric S deposits since the 1990's have led to an increasing occurrence of S deficiency symptoms in numerous crop species (Camberato and Casteel, 2017). Accordingly, awareness of crop S requirements is steadily rising (Engardt *et al.*, 2017; Chan *et al.*, 2019; Chen *et al.*, 2019; Courbet *et al.*, 2019; Huang *et al.*, 2019). The synergistic relationships between N and S in plant metabolism gave rise to the assumption that soils with poor available S might restrict N uptake and subsequently, inhibit potato crop establishment. No significant differences in the number of plants or stems were observed that could be related to the fertilizer

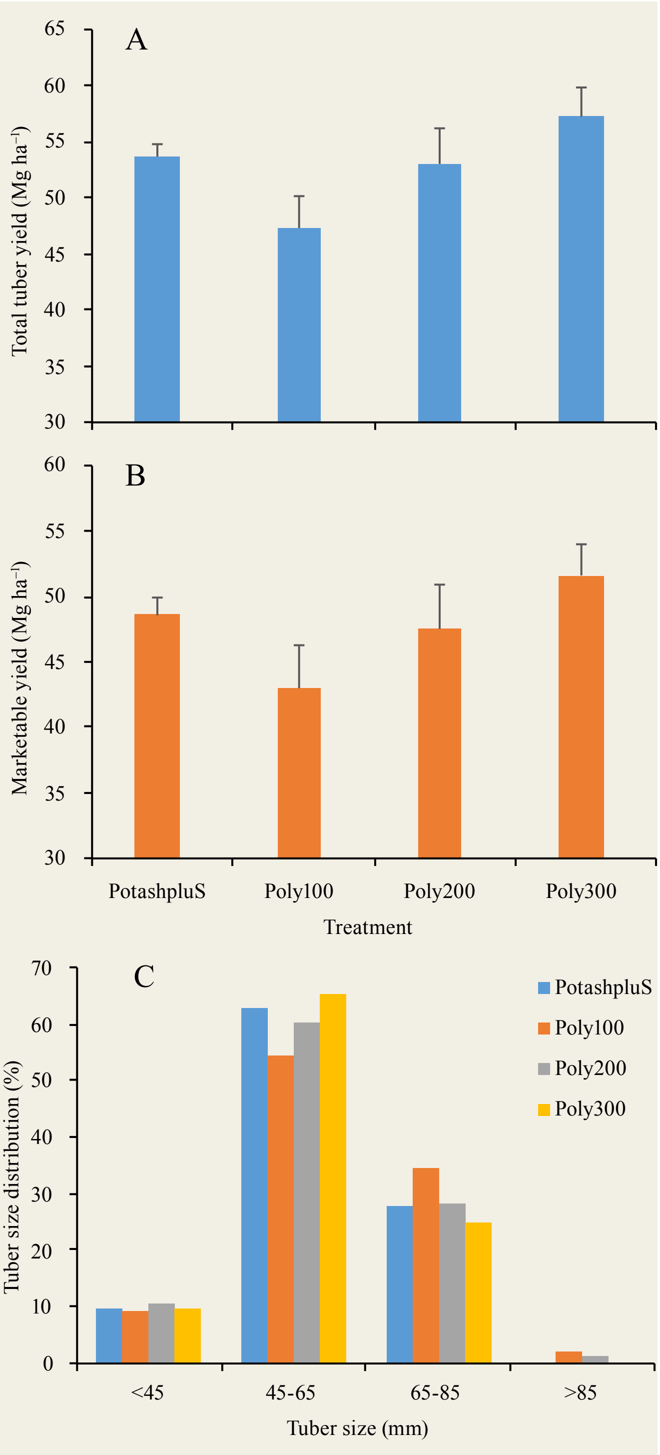


Fig. 7. Effects of increasing polyhalite application rates on potato tuber yield and quality, compared to a PotashpluS-applied control. Total yield (A), and marketable (B) tuber yields, and tuber size distribution (C). Bars indicate SE.

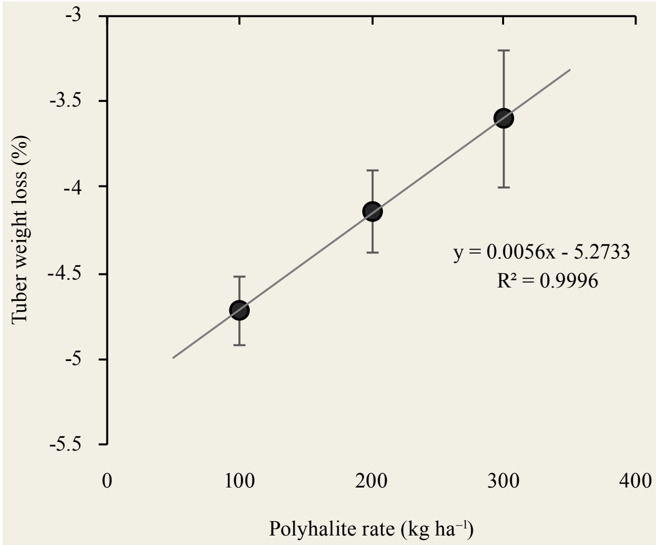


Fig. 8. Water loss from tubers during storage from June to September as a function of polyhalite application rate in the field. Bars indicate SE.

type – MOP, PotashpluS, or polyhalite. Establishment differences observed in response to polyhalite application rate were inconsistent.

Tuber yield was positively influenced by the polyhalite fertilizers commensurate with rate of application. While the advantage of PotashpluS comparing to MOP with regard to tuber yield was small and insignificant statistically (Table 3), the progressive replacement of MOP by polyhalite was responded to by a clear increase of the tuber yield under the higher polyhalite rates (Fig. 5). In a similar way, the higher the polyhalite rate the higher tuber yield under a progressive replacement of PotashpluS by polyhalite (Fig. 7). In each experiment, the rates of N, P, and K application were kept equal between treatments and hence, the differences in crop performance could be attributed solely to the rates of the secondary macronutrients – Ca, Mg, and S. At this early stage of the present study, it would be difficult to elucidate the precise nutrient responsible. Nevertheless, a rough analysis of the results indicates a minimum threshold for Ca input of about 30 kg ha^{-1}, which would be required for achieving marketable yield levels higher than 50 Mg ha^{-1} (Table 5), compared with the current 10-year range of marketable tuber yields in the UK of 36-44 Mg ha^{-1} (Fig. 1C).

Increasing Ca input resulted in greater Ca concentration in the tubers (Tables 1 and 3). Recent studies have pointed to the key role Ca plays in the tuber development (Ozgen *et al.*, 2003; Palta, 2010; Seifu and Deneke, 2017; Singh, 2018; Potarzycki and Grzebisz, 2020), and particularly in the periderm maturation and integrity (Ginzberg *et al.*, 2012; Keren-Keiserman *et al.*, 2019), and its subsequent positive effects on the duration and safety of potato tuber storage (Murayama *et al.*, 2016; Koch *et al.*, 2019b; Naumann *et al.*, 2020). An indication for these positive influences is the clear reduction of water loss from tubers during long storage (Fig. 8).

However, high Ca inputs do not guarantee high marketable yields. High yields also coincided with high S inputs, but not always, and Mg inputs displayed no correlation with tuber yield at all. It appears that the combination of high application doses of all three nutrients together promotes higher yields rather than each nutrient alone (Table 5). Such combinations are made easily available to the crop using various polyhalite fertilizers and application rates that should be thoroughly adjusted to the properties of the local soil and to crop rotation.

In conclusion, the set of experiments carried out in the present study demonstrates, in agreement with several recent studies (da Costa Mello *et al.*, 2018; Keren-Keiserman et al., 2019), the potential of polyhalite fertilizers to enhance potato crop performance and tuber yield and quality through a more balanced mineral nutrition. However, further research is necessary to elucidate the contribution of Ca, Mg, or S to this enhancement, and to establish precise fertilization strategies for various edaphic conditions.

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Photo 3. Comparing root system and potato tuber yield from polyhalite potato trial. Photo by the author.

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The paper "Potential of Polyhalite Fertilizers to Enhance Potato Yield and Quality in the United Kingdom" also appears on the IPI website.

Publications

Publications by the PDA

Nutrient Use Efficiency
POTASH News, March 2021


PDA POTASH NEWS 2021

As governments consider ways to help reduce the environmental impact of agriculture, attention is turning to nutrient use efficiency. More efficient nutrient management will reduce greenhouse gas emissions, through better fertilizer application and management of manures.

Nitrogen is generally considered to have the greatest influence on crop yield however, it is also one of the biggest contributors to greenhouse gas emissions from agricultural cropping. It is therefore critical that while it is given prime consideration, nitrogen cannot be managed in isolation, as its efficiency of use is linked to the availability of all essential nutrients, both in terms of uptake and utilization. Read more on the PDA website.

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

Scientific Abstracts

K in the Literature

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Raman Spectroscopy Enables Non-invasive and Confirmatory Diagnostics of Salinity Stresses, Nitrogen, Phosphorus, and Potassium Deficiencies in Rice

Sanchez L., A. Ermolenkov, S. Biswas, E.M. Septiningsih, and D. Kurouski. 2020. Front. Plant Sci. 11:1620. DOI: 10.3389/fpls.2020.573321.

Abstract: Proper management of nutrients in agricultural systems is critically important for maximizing crop yields while simultaneously minimizing the health and environmental impacts of pollution from fertilizers. These goals can be achieved by timely confirmatory diagnostics of nutrient deficiencies in plants, which enable precise administration of fertilizers and other supplementation in fields. Traditionally, nutrient diagnostics are performed by wet-laboratory analyses, which are both time- and labor-consuming. Unmanned aerial vehicle (UAV) and satellite imaging have offered a non-invasive alternative. However, these imaging approaches do not have sufficient specificity, and they are only capable of detecting symptomatic stages of nutrient deficiencies. Raman spectroscopy (RS) is a non-invasive and non-destructive technique that can be used for confirmatory detection and identification of both biotic and abiotic stresses on plants. Herein, we show the use of a hand-held Raman spectrometer for highly accurate pre-symptomatic diagnostics of nitrogen, phosphorus, and potassium deficiencies in rice (*Oryza sativa*). Moreover, we demonstrate that RS can also be used for pre symptomatic diagnostics of medium and high salinity stresses. A Raman-based analysis is fast (1 s required for spectral acquisition), portable (measurements can be taken directly in the field), and label-free (no chemicals are needed). These advantages will allow RS to transform agricultural practices, enabling precision agriculture in the near future.

Genetic Architecture Underpinning Yield Components and Seed Mineral–Nutrients in Sesame

Teboul N., Y. Gadri, Z. Berkovich, R. Reifen, and Z. Peleg. 2020. Genes 11(10):1221. DOI: 10.3390/genes11101221.

Abstract: Genetic dissection of yield components and seed mineral-nutrient is crucial for understanding plant physiological and biochemical processes and alleviate nutrient malnutrition. Sesame (*Sesamum indicum* L.) is an orphan crop that harbors rich allelic repertoire for seed mineral-nutrients. Here, we harness this wide diversity to study the genetic architecture of yield components and seed mineral–nutrients using a core-collection of worldwide genotypes and segregating mapping population. We also tested the association between these traits and the effect of seed nutrients concentration on their bio-accessibility. Wide genetic diversity for yield components and seed mineral-nutrients was found among the core-collection. A high-density linkage map consisting of 19,309 markers was constructed and used for genetic mapping of 84 QTL associated with yield components and 50 QTL for seed minerals. To the best of our knowledge, this is the first report on mineral–nutrients QTL in sesame. Genomic regions with a cluster of overlapping QTL for several morphological and nutritional traits were identified and considered as genomic hotspots. Candidate gene analysis revealed potential functional associations between QTL and corresponding genes, which offers unique opportunities for synchronous

improvement of mineral-nutrients. Our findings shed-light on the genetic architecture of yield components, seed mineral–nutrients and their inter- and intra- relationships, which may facilitate future breeding efforts to develop bio-fortified sesame cultivars.

Influence of Potassium on the Productivity and Quality of Potato: A Review

Singh A., H.S. Chahal, G.S. Chinna, and S. Ranvir. 2020. Environment Conservation Journal, 21 (3):79-88. DOI: 10.36953/ECJ.2020.21309.

Abstract: Potato ranks one of the most important food crops after rice, wheat, and other field crops. A healthy potato crop removes about 1.7 to 2.3 quintals of potassium ha^{-1}, illustrating that the potassium requirement for potatoes is much higher than that of grains. Being a shallow root crop, the effectiveness of using potassium fertilizers on potatoes varies from 50 to 60 percent. Potassium nutrition plays an important role in increasing the potato yield, either due to the formation of large tubers or the increase in the number of tubers per plant. Among the integrated nutrient management in potatoes, farmyard manure improves the absorption and availability of potassium for potato plants. Potassium protects against frost and drought stress in plants and reduces the incidence of diseases or pests. Potassium availability also decreases the concentration of reducing sugar and improves the colour and quality of potato chips. Potassium sulfate improves potato quality better than sources of potassium chloride.

Determination of the Best Controlled-Release Potassium Chloride and Fulvic Acid Rates for an Optimum Cotton Yield and Soil Available Potassium

Geng J., X. Yang, X. Huo, J. Chen, S. Lei, H. Li, Y. Lang, and Q. Liu. 2020. Front. Plant Sci. 11:562335. DOI: 10.3389/fpls.2020.562335.

Abstract: Potassium and fulvic acid (FA) fertilizer applications are two important measures for improving cotton growth. However, there are few studies on the application interactive effects of controlled-release potassium chloride (CRK) in combination with FA on cotton production. To explore the effects of CRK combined with FA on cotton, field experiments were conducted in 2018 and 2019 using a split-plot design. The main plots were assigned to two types of potassium fertilizer – controlled-release potassium chloride (CRK) and potassium sulfate (KS) – while low, moderate, and high FA application rates (90, 180, and 270 kg ha^{-1}) were assigned to the subplots. The cotton yield, fiber quality, net profit, soil available potassium concentration, potassium use efficiency, and leaf photosynthesis were markedly affected by potassium fertilizer and FA. The cotton boll number and boll weight in the 2 years and the yield in 2019 were all affected by the interaction between potassium fertilizer and FA. Compared to the other potassium treatments, the CRK × FA180 treatment increased the seed yield and net profit by 4.29-14.92% and 13.72-62.30%, respectively, over the 2 years. The potassium agronomy efficiency and potassium recovery efficiency (KRE) of the CRK × FA180 treatment were also improved by 6.25-30.77% and 3.82-12.78% compared to those of the other potassium treatments. Overall, the FA180 treatment resulted in better cotton growth than that in the FA90 and FA270 treatments. The release period of CRK in the field during the growth period of cotton was longer than that detected by 25°C static water extraction, which increased the soil available potassium content and met the potassium demands over the whole cotton growth period. Therefore, the application of CRK in combination with 180 kg ha^{-1} FA is the best choice for cotton fertilization.

Response of Cassava, Huay Bong 80 Variety, Grown in an Ustic Quartzipsamment, to Chicken Manure and Potassium Fertilizer

Chaem-Ngern C., S. Anusontpornperm, S. Thanachit, and I. Kheoruenromne. 2020. Communications in Soil Science and Plant Analysis 51:(22)2765-2777. DOI: 10.1080/00103624.2020.1849260.

Abstract: An Ustic Quartzipsamment was the soil that had light texture and very low fertility status with intense leaching. A field experiment was conducted in a farmer field, northeast Thailand. Experimental design was arranged in split plot. Main plot comprised four rates of chicken manure (CM) and subplot consisted of six rates of K_2O. Soil leaching column was also studied in laboratory. Amending the soil with 3.125, 6.25 and 12.5 t/ha of CM highly significantly promoted greater respective fresh tuber yield of 14.9%, 24.2% and 31.6% over the control with no CM addition. Cassava responded best to 100 kg/ha of K_2O. The manure evidently induced greater uptake of N, P and K in all plant parts while potassium (K) fertilizer increasing N, P and K uptakes in almost all plant parts. Soil properties at 0-30 cm depth were affected by the addition of 6.25 and 12.5 t/ha of CM as soil pH and cation exchange capacity, and quantities of total N, available P and K, and extractable Ca and Mg increased significantly and K fertilizer significantly affected a decrease of soil pH. In the leaching column study, greater K leached from soil column as well as the improvement of soil properties with increasing rates of CM addition was observed.

Potassium Application to the Cover Crop Prior to Cotton Planting as a Fertilization Strategy in Sandy Soils

Echer F.R., V.J.S. Peres, and C.A. Rosolem. 2020. Sci Rep 10:20404. DOI: 10.1038/s41598-020-77354-x.

Abstract: *Urochloa* grasses are used as cover crops in tropical cropping systems under no-till to improve nutrient cycling. We hypothesized that potassium (K) applied to ruzigrass (*Urochloa ruziziensis*) grown before cotton in a sandy soil could be timely

cycled and ensure nutrition, yield and quality of cotton cultivars with no need to split K application. Field experiments were performed with different K managements, applied to ruzigrass, to cotton grown after grass and without grass, or split as it is done conventionally. No yield differences were observed on K fertilized treatments. At 0 K, cotton yields were low, but they increased by 16% when ruzigrass was grown before, and short fiber content was lower when there was more K available. Ruzigrass grown before cotton increased micronaire as much as the application of 116 kg ha^{-1} of K without the grass. Fiber maturity was higher when K was applied to the grass or split in the grass and sidedressed in cotton. Growing ruzigrass before cotton allows for early K fertilization, i.e., application of all the fertilizer to de grass, since the nutrient is recycled, and cotton K nutrition is not harmed. Eventually K rates could be reduced as a result of higher efficiency of the systems.

Effect of Water Stress, Nitrogen and Potassium Fertilizers on Maize Yield Productivity

El-Saeed M. M. El-Gedwy, Haroun M. M. El-Naggar, Nasser Kh. B. El-Gizawy, and Haitham S. A. Mansour. 2020. Annals of Agric. Sci., Moshtohor 58(3):515-534. DOI: 10.21608/ASSJM.2020.122030.

Abstract: Two field experiments were carried out at the Farm of Agric. Res. and Exp. Center of Fac. of Agric. Moshtohor, Benha University, Toukh Directorate, Qalyubia Governorate, Egypt, during two successive summer growing seasons of 2015 and 2016 to study the effect of three water stress, i.e. normal irrigation, skipping the second irrigation (skipping one irrigation during vegetative growth stage) and skipping the fifth irrigation (skipping one irrigation during kernels filling stage) and four nitrogen fertilizer rates, i.e. 0, 50, 100 and 150 kg N/fed as well as three potassium fertilizer rates, i.e. 0, 24 and 48 kg K_2O/fed on growth, yield and its components as well as some kernels chemical properties of maize (white single cross hybrid 2031 for Misr hytech Seed Int.,). Results of combined analysis of the two seasons showed that kernels filling stage was the most sensitive to water deficit stress and preventing irrigation at this stage (skipping the 5th irrigation) caused marked decrease in mean values of allmost maize yield and its components, while, full irrigation treatment appeared to be the best irrigation treatment sine it enhanced all maize traits under study. Planting maize under water stress by skipping the 2nd irrigation and skipping the 5th irrigation significantly decreased mean values of grain yield/fed (kg) by 25.49 and 41.04% respectively, compared to mean values of grain yield/fed (kg) of maize under normal irrigation. Planting maize when received 150 kg N/fed caused significant increase in all mean values of maize traits under study such as plant height (cm), ear height (cm), No. of ears/fed, ear diameter (cm), ear length (cm), No. of rows/ear, No. of kernels/row, No. of kernels/ear, ear weight (g), kernels weight/ear (g), kernels shelling (%), 100-kernel weight (g), ear yield/fed (kg), grain yield/fed (kg), stover yield/fed (kg), biological yield/fed (kg), harvest index (%), kernels nitrogen content (%), kernels crude protein (%), nitrogen uptake/fed (kg) and protein yield/fed (kg) Meanwhile, the highest mean values of potassium use efficiency (KUE) which were recorded from growing maize when received 100 kg N/fed. Growing maize under the higher potassium rate (48 kg K_2O/fed) was produced the maximum mean values of plant height (cm), No. of ears/fed, ear length (cm), No. of kernels/row, No. of kernels/ear, ear weight (g), kernels weight/ear (g), 100-kernel weight (g), kernels shelling (%), ear yield/fed (kg), grain yield/fed (kg), stover yield/fed (kg), biological yield/fed (kg), harvest index (%), kernels potassium content (%), nitrogen uptake/fed (kg) and protein yield/fed (kg) while, the highest mean values of KUE which were recorded from growing maize when received 24 kg K_2O/fed. The first order interactions between (normal irrigation X 150 Kg N/fed), (normal irrigation X 48 kg K_2O/fed) and (150 kg N/fed X 48 kg K_2O/fed) as well as the second order interaction between normal irrigation X 150 kg N/fed X 48 kg K_2O/fed) were significantly recorded the greatest mean values of maize yield and its components as compared with the others interactions. It could be summarized that grown maize under full irrigation and fertilization by 150 kg N + 48 kg K_2O/fed in order to maximizing its productivity.

Deficiency of Essential Elements in Crop Plants

Tiwari S., A. Patel, N. Pandey, A. Raju, M. Singh, and S.M. Prasad. 2020. *In:* Mishra K., P.K. Tandon, S. Srivastava (eds) Sustainable Solutions for Elemental Deficiency and Excess in Crop Plants p. 19-52. DOI: 10.1007/978-981-15-8636-1_2.

Abstract: Plants are the eminent source of essential elements which are constructing blocks of living organism in the form of protein, carbohydrate, fats and fibres. Living organism, including plants, requires nutrients for their better growth and developmental processes. Based upon the necessity, nutrients are categorized as macro- and micronutrients. Carbon, hydrogen, oxygen, phosphorus, potassium, nitrogen, sulphur, calcium, iron and magnesium are the various plant macronutrients, while micronutrients include manganese, copper, boron, molybdenum and chlorine. Plants are able to draw these mineral nutrients in a balanced way either from soil organic matter or by the use of organic or inorganic fertilizers. Mineral nutrition is acquired by a complex network of root transporters that regulate import of minerals from the soil solution to plants. The requirement of these nutrients varies from plant to plant, and scarcity of these nutrient elements intervenes the metabolic processes. However excessive uptake induces toxicity and causes poor growth associated with reduction in crop production. Hence, balanced nutrient approach is important for proper crop yield. This chapter describes the essential nutrients, the chemical forms in which they are available to plants, their function in plants, their deficiency system, and recommended nutrient levels in plant tissues of selected crops and future prospective of nutrient management approach.

Identification and Quantification of Potassium (K^+) Deficiency in Maize Plants using an Unmanned Aerial Vehicle and Visible/Near-Infrared Semi-Professional Digital Camera

Furlanetto R.H., M.R. Nanni, L.G.T. Crusiol, G.F.C. Silva, A. de Oliveira Junior, and R.N.R. Sibaldelli. 2021. International Journal of Remote Sensing, Jan 2021. DOI: 10.1080/01431161.2020.1871091.

Abstract: Brazil is one of the largest producers of maize worldwide. However, this production is threatened due to low soil fertility, especially low levels of potassium (K^+). K^+ is one of the most important nutrients in plant metabolism, acting on enzymatic activation and also on photosynthetic processes. The identification of its deficiency by using traditional methods is difficult with regard to timely restoration of the nutrient to adequate levels. Therefore, the use of low-cost modified cameras attached to Unmanned Aerial Vehicles (UAVs) are important tools for agricultural monitoring. Nevertheless, there are no reports of studies with the purpose of evaluating the monitoring of K^+ deficiency in maize crops using multispectral images captured from UAVs. Therefore, this study aimed at exploring the possibility of identifying K^+ deficiency and quantifying the nutrient leaf content by using a Vegetation Index (VI). The experiment was carried out at the National Soybean Research Centre (Embrapa Soja, a branch of the Brazilian Agricultural Research Corporation). The experimental plots were constantly managed in order to obtain different conditions of K^+ availability to plants, achieving levels that ranged from severe deficiency to an adequate nutrient level. The following treatments were established: severe potassium deficiency (SPD), moderate potassium deficiency (MPD) and adequate supply of potassium (ASP). The evaluations were performed in the Brazilian maize crop referred to as '*safrinha*, at the V7, V12 and R3 developmental stages, with image capture covering the visible and near-infrared region, using two Fujifilm IS PRO digital cameras attached to an UAV. In these development stages, leaves were collected to determine tissue K^+ concentration. The images were radiometrically corrected with the support of calibration targets and reference values, using an Fieldspec 3 Jr. spectroradiometer. The VIs comprised the ratio among the red, green and infrared spectral bands, that is, green normalized difference vegetation index (GNDVI), normalized difference vegetation index (NDVI), ratio between infrared and green (GRVI), ratio between green and infrared (GNIR), ratio between red and infrared (RNIR) and ratio between infrared and red (RVI). Regarding all the treatments assessed, the results showed that foliar K^+ was statistically different. The VIs were efficient only in differentiating SPD and ASP treatments at all development stages evaluated. However, none were statistically significant for MPD. The linear regressions showed a high coefficient of determination (R^2) and low root mean square error (RMSE) value; the best prediction of K^+ concentration obtained was at V12 for regressions with these VIs: GRVI ($R^2 = 0.79$, RMSE 4.50 g kg^{-1}) and RVI ($R^2 = 0.71$, RMSE 4.39 g kg^{-1}). The grain yield values showed that SPD caused an average reduction of 5,645.90 kg ha^{-1} in relation to the ASP. Considering MPD, the grain yield was 1,242.00 kg ha^{-1} lower in comparison with ASP. In conclusion, estimating foliar K^+ content and identifying its deficiency in maize crops based on the VIs of multispectral images from cameras attached to UAVs is possible, which ensures agility to these evaluations in a non-destructive manner, improving efficiency of K^+ fertilization and providing farmers with a new tool.

Effects of Foliar Fertilization with Potassium and Micronutrients on Potato Yield and Quality

Gaj R., and J. Borowski-Beszta. 2020. Eur. J. Hortic. Sci. 85(6):394-400. DOI: 10.17660/eJHS.2020/85.6.3.

Abstract: The research was carried out over the period 2014-2016, on light soils, at a farm located in western Poland. The aim of the study was to determine the effect of foliar fertilization with potassium sulfate (SOP) and micronutrients (Zn, Cu, Mn, B) on potato yields and selected quality parameters of tubers (protein, starch, dry matter). The subject of the study were potato varieties Hermes and Zorba, cultivated for the production of crisps and French fries, respectively. Consistent with the adopted experimental set-up (randomized block design, 4 replications for each variety), the following treatments were analyzed: (i) SOP foliar application (twice, in total: 8.6 kg K ha^{-1}); (ii) micronutrient foliar application (twice, in total: 12 g Zn ha^{-1}, 12 g Cu ha^{-1}, 300 g Mn ha^{-1}, 500 g B ha^{-1}); (iii) SOP plus micronutrient foliar application (i)+(ii) and the control (no foliar treatment). Regardless of the analyzed experimental variant, higher tuber yields were obtained in 'Hermes' variety, and these ranged from 45 t ha^{-1} to 71 t ha^{-1}, depending on the study year. When compared to the control, the largest increases in 'Hermes' yields and tuber protein contents (24% and 6%, respectively) were observed in 2014 – as a result of foliar fertilization with SOP (i). In the whole observation period, 'Zorba' yields ranged from 32 t ha^{-1} to 65 t ha^{-1}. In 2016, this variety showed a positive response to foliar fertilization with micronutrients (ii). In comparison to control, 'Zorba' yields and tuber protein contents increased by 15% and 21%, respectively.

Improved Prediction of Potassium and Nitrogen in Dried Bell Pepper Leaves with Visible and Near-Infrared Spectroscopy Utilising Wavelength Selection Techniques

Mishra P., I. Herrmann, and M. Angiler. 2021. Talanta 225:121971. DOI: 10.1016/j.talanta.2020.121971.

Abstract: Wet chemistry analysis of agricultural plant materials such as leaves is widely performed to quantify key chemical components to understand plant physiological status. Visible and near-infrared (Vis-NIR) spectroscopy is an interesting tool to replace the wet chemistry analysis, often labour intensive and time-consuming. Hence, this study accesses the potential of Vis-NIR spectroscopy to predict nitrogen (N) and potassium (K) concentration in bell pepper leaves. In the chemometrics perspective, the study aims to identify key Vis-NIR wavelengths that are most correlated to the N and K,

and hence, improves the predictive performance for N and K in bell pepper leaves. For wavelengths selection, six different wavelength selection techniques were used. The performances of several wavelength selection techniques were compared to identify the best technique. As a baseline comparison, the partial least-square (PLS) regression analysis was used. The results showed that the Vis-NIR spectroscopy has the potential to predict N and K in pepper leaves with root mean squared error of prediction (RMSEP) of 0.28 and 0.44%, respectively. The wavelength selection in general improved the predictive performance of models for both K and N compared to the PLS regression. With wavelength selection, the RMSEP's were decreased by 19% and 15% for N and K, respectively, compared to the PLS regression. The results from the study can support the development of protocols for non-destructive prediction of key plant chemical components such as K and N without wet chemistry analysis.

Potassium Management Effects on Quantity/Intensity Relationship of Soil Potassium under Rice-Oilseed Rape Rotation System

Dandan Zhu, Jianwei Lu, Rihuan Cong, Tao Ren, Wenjun Zhang, and Xiaokun Li. 2019. Archives of Agronomy and Soil Science 66(9):1274-1287. DOI: 10.1080/03650340.2019.1663830.

Abstract: Quantity–intensity curves were used to evaluate the dynamics of soil potassium (K) at different soil depths under different K management. The equilibrium concentration ratio of K (CR_0) increased with increasing K concentration. K fertilization and straw return increased soil K supplying capacity by increasing CR_0, non-specific available K ($-\Delta K_0$) and equilibrium K (CK_0). The CR_0 increase 107%, 392% and 577% at the 0-20 cm layer and 55%, 102% and 131% at the 20-40 cm layer, respectively, under K fertilization, straw return and the interaction of them. The CK_0 and $-\Delta K_0$ at the 0-20 cm layer significantly increased after K fertilization and straw return. The labile K varied from 0.11 to 0.19 cmol kg^{-1}, contributed 85.3% to 107.6% of NH_4OAc extracted K. Soil K potential buffering capacity showed significant differences in soil depths, while little difference was observed under different K management. Th e exchangeable K was meaningless for guiding K application when minimum exchangeable K took up 85.9% to 99.0% of equilibrium exchangeable K. Our results showed K fertilization and straw return was the optimal management to enhance soil K supplying capacity, especially at the 0-20 cm layer.

Profit-Maximizing Potassium Fertilizer Recommendations for Soybean

Popp M.P., N.A. Slaton, and T.L. Roberts. 2020. Agronomy Journal 112(6):5081-5095. DOI: 10.1002/agj2.20424.

Abstract: Potassium (K) fertilizer has important yield and cost ramifications in soybean [*Glycine max* (L.) Merr.] production. Rate recommendations are often based on expected yield response as predicted by a soil test. To that end, soybean response to K application rate studies were analyzed using 86 site-years from 2004 to 2019. We estimated a generic yield response curve across soybean cultivar and soil texture to allow calculation of profit-maximizing K rates for producers in the mid-southern United States that also consider crop value and fertilizer cost. Further, we compared profit-maximizing fertilizer-K rates with those currently recommended. Using a spreadsheet-based decision aid, soybean prices and yields, fertilizer-K cost, and a range of initial soil-test K (STK) values, as observed over the last 10 yr, we find that current uniform fertilizer-K rate recommendations were greater than the predicted profit-maximizing rates. Profit-maximizing rates added profit ranging from US$2.32 ha^{-1} at initial Mehlich-3 K availability values of 110 mg K kg^{-1} to US$29.35 ha^{-1} at 60 mg K kg^{-1} on average. The corresponding fertilizer-K rate reductions were 11 and 48 kg K ha^{-1}, respectively, resulting in attendant yield penalties of only 28 and 52 kg ha^{-1}. Furthermore, K fertilization was not economically justifiable beyond STK of 128 mg K kg^{-1} on average. Hence, performing soil tests and calculating profit-maximizing fertilizer-K rates showed promising returns to producers at lesser fertilizer-K use by sacrificing a minimal amount of yield. Also, variable-rate applied K fertilizer in comparison to uniform rate application was rarely cost effective within the tested assumptions.

Combined Application of Nitrogen and Potassium Reduces Seed Yield Loss of Oilseed Rape Caused by Sclerotinia Stem Rot Disease

Jianglin Zhang, Jing Li, Guotao Geng, Wenshi Hu, Tao Ren, Rihuan Cong, Xiaokun Li, and Jianwei Lu. 2020. Agronomy Journal 112(6):5143-5157. DOI: 10.1002/agj2.20410.

Abstract: Sclerotinia stem rot (SSR) is a major fungal disease of oilseed rape (*Brassica napus* L.) that causes severe yield losses. Nutrient management is crucial for protecting crops against SSR. Two-yr field trials combined four levels of N application (0, 90, 180, and 270 kg N ha^{-1}) and four levels of K application (0, 60, 120, and 180 kg ha^{-1} K_2O) to investigate their interaction effects on SSR disease incidence and seed yield loss caused by SSR. Compared to the sole application of N, the combined application of N and K decreased the SSR disease incidence by 9.9-24.4 and 17.4-37.9% in 2016-2017 and 2018-2019, respectively. N application increased the severity of SSR only at lower K application rates (0 and 60 kg ha^{-1} K_2O). Additionally, compared to the sole application of N, the co-application of N and K dramatically decreased the total yield loss rate (TYLR), by 31.1-60.9 and 19.2-60.3% in 2016-2017 and 2018-2019, respectively. The seed yield response to N uptake was dependent on the level of K application. However, SSR disease dramatically decreased the nutrients use efficiency. Nitrogen and K supply showed synergistic interaction effects on N and K recovery efficiency. These results emphasized the importance of N and K co-application on reducing the yield loss caused by SSR infection. For

a stabilized seed yield, an adequate N (180 kg ha^{-1}) application rate combined with a slightly high K application rate (120-180 kg ha^{-1}) represents a feasible nutrient management strategy for oilseed rape against SSR disease.

Potassium Transformation in Clay Soil with Contrasting K Budgets in Long-Term Experiment

Damar H., N. Ziadi, J. Lafond, and L.E. Parent. 2020. Agronomy Journal 112(6):5180-5192. DOI: 10.1002/agj2.20379.

Abstract: Canadian Shield clay soils are high in potassium (K) reserves. The differential contribution of soil K fractions to crop nutrition is an important issue for ley farming systems of Eastern Canada where nitrogen (N)-based manure application rate leads to K surplus and redistribution. Our objective was to assess the long-term change in K offtake, K budget, and K forms under a 3-yr-cycle ley farming system (barley [*Hordeum vulgare*]–mixed forage–mixed forage) initiated in 1989 and ended in 2016. The liquid dairy manure (LDM) supplied higher amounts of K than mineral fertilization (MIN) and led to larger K offtake across crop cycles. The cumulative K budgets averaged −579 kg K ha^{-1} $cycle^{-1}$ for MIN and +69 kg K ha^{-1} $cycle^{-1}$ for LDM. Despite cyclic variations, topsoil showed a surplus of exchangeable K (>100 kg K ha^{-1}) at the end of experimentation under MIN and LDM compared to the initial state in 1989. Exchangeable and non-exchangeable K fractions increased between 2001 and 2016 in 0- to 30-cm depth even under K deficit (MIN), due to K release from slowly available forms and recycling from lower layers. There were no significant relationships between K budget and exchangeable K down to 90 cm. The approach relating soil exchangeable K and K budgets to support buildup and maintenance of soil fertility proved to be inappropriate in clay soils high in illite-like minerals. Potassium dynamics in clay soils under ley farming highlighted the importance of considering non-exchangeable and subsoil K in K fertilization recommendations.

Detection of Potassium Deficiency and Momentary Transpiration Rate Estimation at Early Growth Stages Using Proximal Hyperspectral Imaging and Extreme Gradient Boosting

Weksler S., O. Rozenstein, N. Haish, M. Moshelion, R. Wallach, and E. Ben-Dor. 2021. Sensors 21(3):958. DOI: 10.3390/s21030958.

Abstract: Potassium is a macro element in plants that is typically supplied to crops in excess throughout the season to avoid a deficit leading to reduced crop yield. Transpiration rate is a momentary physiological attribute that is indicative of soil water content, the plant's water requirements, and abiotic stress factors. In this study, two systems were combined to create a hyperspectral–physiological plant database for classification of potassium treatments (low, medium, and high) and estimation of momentary transpiration rate from hyperspectral images. PlantArray 3.0 was used to control fertigation, log ambient conditions, and calculate transpiration rates. In addition, a semi-automated platform carrying a hyperspectral camera was triggered every hour to capture images of a large array of pepper plants. The combined attributes and spectral information on an hourly basis were used to classify plants into their given potassium treatments (average accuracy = 80%) and to estimate transpiration rate (RMSE = 0.025 g/min, R^2 = 0.75) using the advanced ensemble learning algorithm XGBoost (extreme gradient boosting algorithm). Although potassium has no direct spectral absorption features, the classification results demonstrated the ability to label plants according to potassium treatments based on a remotely measured hyperspectral signal. The ability to estimate transpiration rates for different potassium applications using spectral information can aid in irrigation management and crop yield optimization. These combined results are important for decision-making during the growing season, and particularly at the early stages when potassium levels can still be corrected to prevent yield loss.

Potassium is a Potential Toxicant for *Arabidopsis thaliana* under Saline Conditions

Zhao W., F. Faust, and S. Schubert. 2020. J. Plant Nutr. Soil Sci. 183(4):455-467. DOI: 10.1002/jpln.201900491.

Background and aims: Most physiological and biochemical studies on salt stress are NaCl-based. However, other ions (e.g., K^+, Ca^{2+}, Mg^{2+}, and SO_4^{2-}) also contribute to salt stress in special circumstances. In this study, salt stress induced by various salts was investigated for a better understanding of salinity. **Methods:** Arabidopsis thaliana plants were stepwise acclimated to five iso-osmotic salts as follows: NaCl, KCl, Na_2SO_4, K_2SO_4, and $CaCl_2$. **Results and Conclusions:** Exposure to KCl and K_2SO_4 led to more severe toxicity symptoms, smaller biomass, and lower level of chlorophyll than exposure to NaCl and Na_2SO_4, indicating that Arabidopsis plants are more sensitive to potassium salts. The strongly reduced growth was negatively correlated with the accumulation of soluble sugars observed in KCl- and K_2SO_4-treated plants, suggesting a blockage in the utilization of sugars for growth. We found that exposure to KCl and K_2SO_4 suppressed or even blocked sucrose degradation, thus leading to strong accumulation of sucrose in shoots, which then probably inhibited photosynthesis via feedback inhibition. Moreover, K^+ was more accumulated in shoots than Na^+ after corresponding potassium or sodium salt treatments, thus resulting in decreased Ca^{2+} and Mg^{2+} concentrations in response to KCl and K_2SO_4. However, K_2SO_4 caused more severe toxicity symptoms than iso-osmotic KCl, even when the K^+ level was lower in K_2SO_4-treated plants. We found that Na_2SO_4 and K_2SO_4 induced strong accumulation of tricarboxylic acid intermediates, especially fumarate and succinate which might induce oxidative stress. Thus, the severe toxicity symptoms found in K_2SO_4-treated plants were also attributed to SO_4^{2-} in addition to the massive accumulation of K^+.

Potassium Fertilization for White Oat and Maize in Integrated Crop-Livestock System Under No-Tillage

Flavia Biassio Riferte, Adriel Ferreira da Fonseca, and Laíse da Silveira Pontes. 2020. Grassland Science, Dec 2020. DOI: 10.1111/grs.12312.

Abstract: Integrated crop-livestock systems (ICLS) are diversified agroecosystems characterized by the rotation, succession or mixtures of agricultural, livestock or forestry activities, in no-tillage systems. In ICLS with trees, the tree modifies the light and water availability, and might generate root competition for nutrients, like potassium (K). The study aims to evaluate dry matter (DM) and macronutrients accumulation in white oat, DM and grain yield of maize, and the K use efficiency (KUE) by these crops cultivated in an ICLS with eucalyptus. The experimental design was a randomized block in a split-plot design with three replications. Plots consisted of four cultivation positions (CP) between the tree rows, where CP1 (0 to 4 m distance) refers to a position close to the trees; CP2 (4 to 8 m distance) and CP4 (12 to 16 m distance) corresponds to two intermediate positions between rows; and CP3 (8 to 12 m distance) corresponds to a central position between rows. In subplots, four potassium oxide (K_2O) annual doses were assigned, with potassium chloride being applied on the surface, where each rate was half the rate applied at sowing of each crop. DM and macronutrients accumulation in white oat shoot decreased due to eucalyptus shadow (64.5% light restriction). Responses of maize DM and grain yield to K_2O addition were different among CPs, possibly owing to different light patterns. No changes in the maize yield were observed with K_2O application in CP1 and CP2. However, for other positions, quadratic responses in grain yield were observed. In ICLS with eucalyptus in a subtropical region of Brazil, the reduction of K fertilization led to lower yields in white oat and maize. As KUE was high in plots with low K rate, the production cost in ICLS with trees may be decreased if massive production is not required.

Soil-Based, Field-Specific Fertilizer Recommendations are a Pipe-Dream

Schut A.G.T., and K.E. Giller. 2020. Geoderma 380:114680. DOI: 10.1016/j.geoderma.2020.114680.

Abstract: Fertilizer recommendations are key for farmers: the investment is relatively large for smallholders and risky with unknown yield responses and variable fertilizer prices. Are agronomists able to provide useful site-specific fertilizer recommendations that reduce these uncertainties? We evaluated the influence of errors introduced due to soil sampling and chemical analysis procedures both within- and among laboratories on fertilizer recommendations. Using what we consider to be conservative estimates of the uncertainty in estimating soil supply of N, P and K in a single composite soil sample, the resulting 90% confidence interval of fertilizer recommendations ranged from 86 to 186, 0-58 and 38-114 kg N, P and K ha^{-1} respectively. The numerous laboratory services and digital applications providing field-specific recommendations appear to promise more accuracy than soil analysis can realistically deliver. We conclude that a field-specific fertilizer recommendation based on a single composite soil sample is indeed a pipe-dream.

Silicon Alleviates Salt Stress-Induced Potassium Deficiency by Promoting Potassium Uptake and Translocation in Rice (*Oryza sativa* L.)

Yan G., X. Fan, W. Zheng, Z. Gao, C. Yin, T. Li, and Y. Liang. 2021. Journal of Plant Physiology 258-259:153379. DOI: 10.1016/j.jplph.2021.153379.

Abstract: Under salt stress, plants suffer from potassium (K) deficiency caused by excess salts in growth substrate. Silicon (Si) can promote K status in many plant species under salt stress, however, the underlying mechanisms remain unclear. In this study, we assessed the effects of Si on K homeostasis in rice under salt stress and investigated the mechanisms behind using two low-Si rice mutants (*lsi1* and *lsi2*) and their wild types (WTs). After five days' treatment with Si, plant growth was improved and salt stress-induced K deficiency was alleviated in WTs but not in mutants. Simultaneously, Si significantly enhanced K accumulation content, K uptake index and shoot K distribution rate in WTs but not in mutants. Besides, Si enhanced K concentration in xylem sap in WTs but not in mutants. Scanning ion-selected electrode technique (SIET) analysis showed net K influx rate was raised by Si addition under salt stress in WTs but not in mutants. Moreover, Si up-regulated the expression of genes responsible for K uptake (*OsAKT1* and *OsHAK1*) and xylem loading (*OsSKOR*) in WTs but not in mutants. Overall, our results strongly indicate that Si can improve K uptake and translocation by up-regulating the expression of relevant genes, thereby promoting K status and alleviating salt stress in rice.

Rice Yield Response to Potassium: An Economic Analysis

Popp M.P., N.A. Slaton, J.S. Norsworthy, and B. Dixon. 2021. Agronomy Journal 113(1):287-297. DOI: 10.1002/agj2.20471.

Abstract: Potassium fertilizer represents a non-trivial input cost in rice (*Oryza sativa* L.) production and its rate recommendation is often based on yield and K deficiency observations alone. However, profit-maximizing fertilizer-K rate not only hinges on the yield response to both initial available soil K and applied fertilizer K, but also the crop value and fertilizer cost. To that end, K application rate studies for rice, performed across 91 site-years from 2001 to 2018, allowed estimation of a generic yield response curve to calculate profit-maximizing K rates for producers in the mid-southern United States. To determine whether those calculation efforts are justified, we compared profit-maximizing fertilizer-K rates to those currently recommended. Using rice prices and yields, fertilizer-K cost, and a

range of initial soil-test K values, as observed over the last 10 yr, we find that current fertilizer-K rate recommendations are too high. Profit-maximizing rates added from US$0.88 ha^{-1} at initial Mehlich-3 K availability values of 75 mg K kg^{-1} to $28.19 ha^{-1} at 105 mg K kg^{-1} on average. The corresponding fertilizer-K reductions were 0.35 and 56 kg K ha^{-1}, respectively, resulting in attendant yield penalties of only 4 kg ha^{-1} and 105 kg ha^{-1}. Hence, performing soil tests and using decision support software to obtain profit-maximizing fertilizer-K rates is expected to enhance producer profit at rice yield penalties that are smaller than fertilizer cost savings. While profit-maximizing rate recommendations do vary in a field with varying available soil K, using the mid-range estimate rather than variable-rate technology was deemed most feasible.

Potassium Management Over 60 Crops: A Long-Term Study on an Oxisol Under No-Till

Firmano R.F., A. de Oliveira Junior, C. de Castro, and L.R.F. Alleoni. 2021. Agronomy Journal 113:478-489. DOI: 10.1002/agj2.20456.

Abstract: Potassium (K) is a typical yield-limiting nutrient for soybeans [*Glycine max* (L.) Merr.] in humid tropical regions. The effect of fertilization on K balance over 32 yr of continuous cropping was investigated in a highly weathered Rhodic Hapludox under no-till. The nutrient balance was calculated based on the amounts of K added via fertilization and on the amounts removed by the crops. Potassium rates interfered with yields over time and modified the final balance of K in the system. Depending on K rates, the balance tended to be positive or negative, and the range of K rates evaluated allowed us to establish conditions of either continuous K depletion, resulting from K removals by harvests, or the accumulation in soil under high rates. In this range, indicators of the efficiency of K fertilizer also varied and made it clear that K fertilizer is not the only source of K for plants.

Irrigated Grain Sorghum Response to 55 years of Nitrogen, Phosphorus, and Potassium Fertilization

Schlegel A.J., and J.L. Havlin. 2020. Agronomy Journal 113(1):464-477. DOI: 10.1002/agj2.20453.

Abstract: Although long-term field experiments provide a valuable resource to assess crop yield response to climate and fertilizer, few studies have included grain sorghum (*Sorghum bicolor* L.). The objectives of this study were to quantify the effects of 55 yr of annual nitrogen (N), phosphorus (P), and potassium (K) application on irrigated continuous sorghum grain yield, grain nutrient uptake, and economic optimum N rates. Six N rates (0, 45, 90, 134, 179, and 224 kg N ha^{-1}) and three combinations of P and K (0 P with 0 K, 20 kg P ha^{-1} with 0 K, and 20 kg P ha^{-1} with 37 kg K ha^{-1}) were applied annually from 1961 to 2015 to a Ulysses silt loam near Tribune, KS. Average maximum grain yield with N was 53% greater than with no N applied; however, application of 20 kg P ha^{-1} with N resulted in a 70% increase in average maximum grain yield. Potassium fertilization had no effect on grain yield. The N rate required for maximum profit at 20 kg P ha^{-1} averaged 137 kg N ha^{-1}. At the economic optimum N rate, apparent fertilizer N recovery in grain was 25% with no P and increased to 42% with P. Apparent fertilizer P recovery at the economic optimum N rate was 51% with 20 kg P ha^{-1}. Fifty-five yr of irrigated sorghum response to N and P fertilization demonstrated a strong positive interaction between N and P on grain yield, apparent N and P recovery, and profitability.

Effects of Foliar Fertilization with Potassium and Micronutrients on Potato Yield and Quality

Gaj R., and J. Borowski-Beszta. 2020. Eur. J. Hortic. Sci. 85(6):394-400. DOI: 10.17660/eJHS.2020/85.6.3.

Abstract: The research was carried out over the period 2014-2016, on light soils, at a farm located in western Poland. The aim of the study was to determine the effect of foliar fertilization with potassium sulfate (SOP) and micronutrients (Zn, Cu, Mn, B) on potato yields and selected quality parameters of tubers (protein, starch, dry matter). The subject of the study were potato varieties Hermes and Zorba, cultivated for the production of crisps and French fries, respectively. Consistent with the adopted experimental set-up (randomized block design, 4 replications for each variety), the following treatments were analyzed: (i) SOP foliar application (twice, in total: 8.6 kg K ha^{-1}); (ii) micronutrient foliar application (twice, in total: 12 g Zn ha^{-1}, 12 g Cu ha^{-1}, 300 g Mn ha^{-1}, 500 g B ha^{-1}); (iii) SOP plus micronutrient foliar application (i)+(ii) and the control (no foliar treatment). Regardless of the analyzed experimental variant, higher tuber yields were obtained in 'Hermes' variety, and these ranged from 45 t ha^{-1} to 71 t ha^{-1}, depending on the study year. When compared to the control, the largest increases in 'Hermes' yields and tuber protein contents (24% and 6%, respectively) were observed in 2014 – as a result of foliar fertilization with SOP (i). In the whole observation period, 'Zorba' yields ranged from 32 t ha^{-1} to 65 t ha^{-1}. In 2016, this variety showed a positive response to foliar fertilization with micronutrients (ii). In comparison to control, 'Zorba' yields and tuber protein contents increased by 15% and 21%, respectively.

The results of the IPI Photo Contest 2020: Nutrient Deficiencies in Crops

After judging the record number of photographic entries showing plant symptoms of nutrient deficiencies submitted from all over the world, we are delighted to announce the runner-up and winner of the IPI Photo Contest 2020.

Record number of entries

No-one would have been happier at the popularity of this year's contest than the man in whose memory the competition is held, Ricardo Melgar. Our dear colleague strongly believed in the power of people to promote crop stories through, for example, a photo of a crop showing signs of a nutrient deficiency.

You took your smartphones and cameras out and about in fields, orchards and plantations all over the world. As the entries came in, it was fascinating to set the counter going and eventually reach a total of over forty crops from more than twenty countries.

Thanks to all of you who saw, snapped and sent your evidence of crop nutrition deficiencies in leaves, fruits and buds. Having studied each entry for clarity and composition we came up with a shortlist of potential prize-winners.

And the winner is...

Our warmest congratulations and first prize of 500 USD go to our winner of the IPI Photo Contest 2020, Bhushan P. Phadnis.

His winning photo shows manganese deficiency in cotton in Rajasthan, India. "Cotton being an Indicator crop as well as oil-seed crop commonly shows manganese deficiency symptoms", he reports. "The reasons are that this cotton crop is mainly cultivated as a rainfed crop in arid dry climatic conditions. The sandy soils inherently having low CEC cannot hold cations including manganese. In addition to these constraints, the soils have high alkaline pH."

Winner: Bhushan P. Phadnis

Being selected as the winner of the IPI Photo Contest 2020 is a lifetime achievement for me. My happiness is beyond words and has no bounds. Thank you all.

Through nutrient deficiencies the crop tries to communicate about quantitative and qualitative decrease in its yields well in advance. Crop damage resulting from insect, pest and disease attack is apparent because it is predominantly external. On the contrary, the crop damage caused due to the deficient nutrient(s) often gets unnoticed since it is physiological or internal.

To get optimum yields of any crop do not overlook its nutrient deficiency symptoms. Please remember, 'A Stitch in Time Saves Nine!'

First place: Manganese deficiency symptoms in cotton crop in Nagaur, Rajasthan. Photo by Bhushan P. Phadnis.

Our runner-up is...

The runner-up prize of 250 USD was awarded to this photo by Jesús Arévalo Zarco, submitted by his wife Janet Cabrera Meza, of a tomato plant showing symptoms of magnesium deficiency.

Runner-up: Magnesium deficiency in Tomato crop, in Aguascalientes, México. Photo by Jesús Arévalo Zarco.

We offer our thanks again to all the entrants in the competition and we look forward to inviting entries for the next IPI Photo Contest. In the meantime, let's continue to capture the evidence of nutrient deficiencies so that we can help show and share the nutrition solutions for optimized crop productivity with farmers and growers everywhere.

Runner-up: Janet Cabrera Meza

I am a regular reader of IPI's publications so I could hardly believe it when I heard my picture had been selected.

While it is desirable to not see nutrient deficiencies in a crop, when it is a new advised crop or when the conditions are complicated, they come to appear. It is then time to document them. A nutrient deficiency picture must be used to learn, to teach and to have it for later consultation.

Frequently people see some chlorosis with certain characteristics in a crop and ask for the cause. If we have some key photographs, they can be used as a reference making it easier to identify the problem.

These photographs are very educational, they clearly show the loss in photosynthesis due to the nutrient deficiency, and in this way growers get an idea of the reduction in the crop yield.

I want to congratulate the IPI for organizing this event and thank all the participants for collaborating with their contributions, which are useful to readers.

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