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

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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

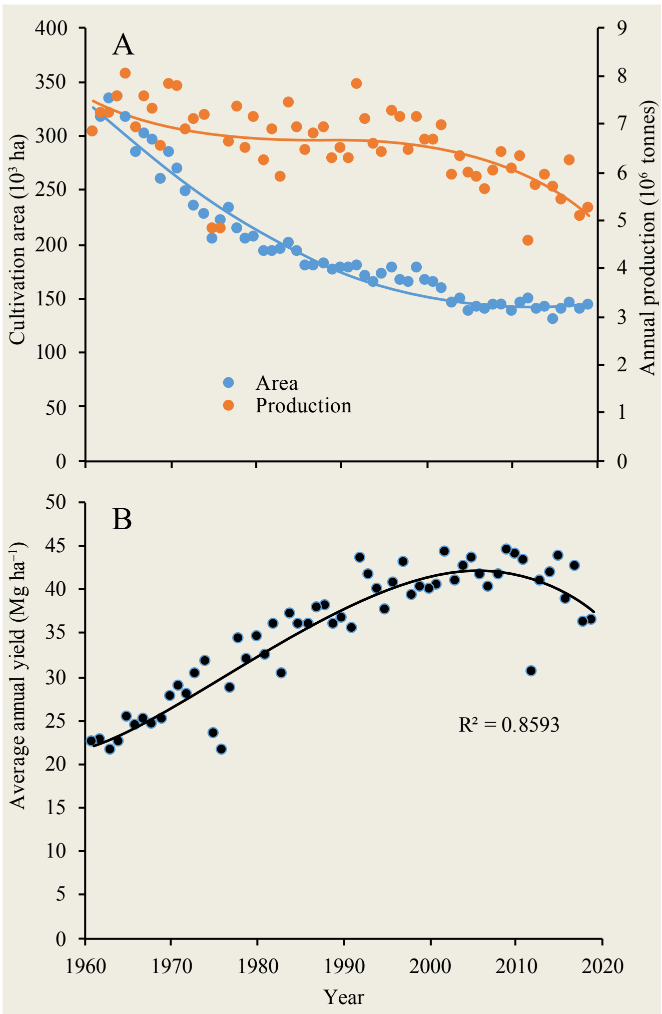


Fig. 1. Historical analysis of the potato industry in the UK during 1961-2019. Potato cultivated area and annual production (A) and, average annual potato yield (B). *Source:* FAOstat. 2021.

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,

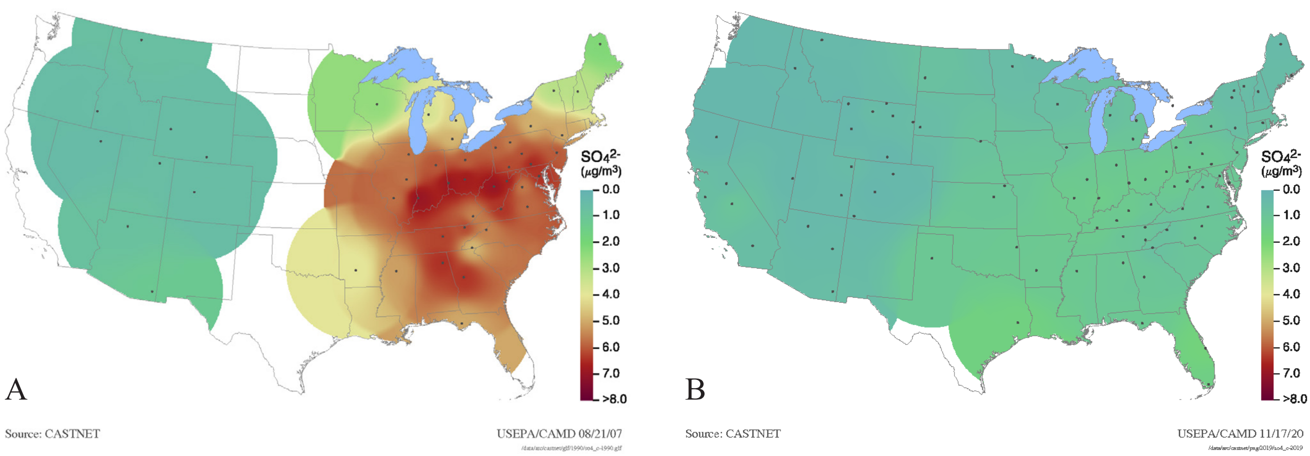


Fig. 2. The amount of annual sulfur (SO_4^{2-}) atmospheric deposition in the USA in 1990 (A), and in 2019 (B). *Source:* https://www3.epa.gov/castnet/airconc.html

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	N	P	K	Ca	Mg	S	Supplementary fertilizers		
		Nutrients								
		---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.

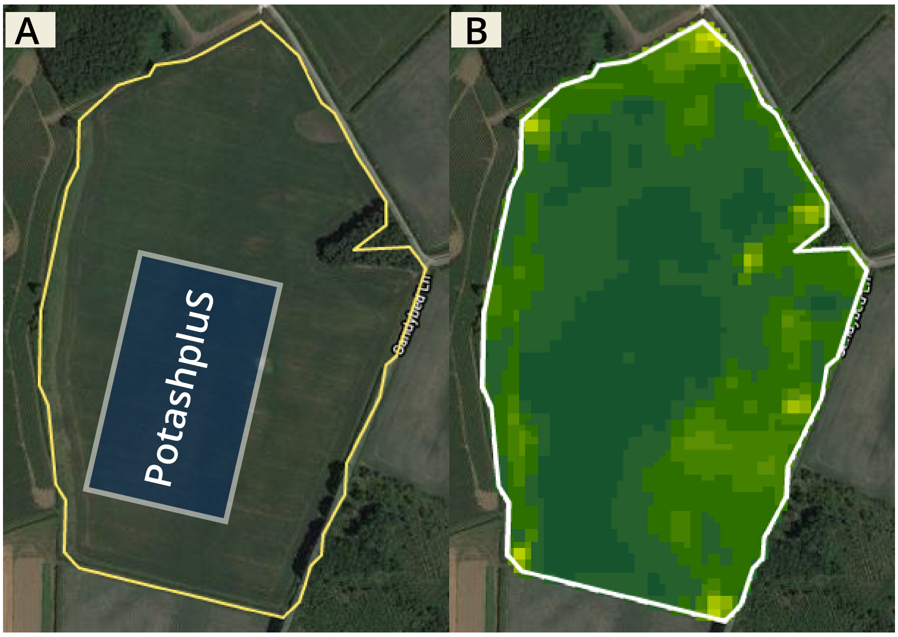


Fig. 3. Experiment 1 field. The PotashpluS-applied plot is marked with a blue border, surrounded by the MOP-applied area (A); NDVI image of the field in June (B).

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

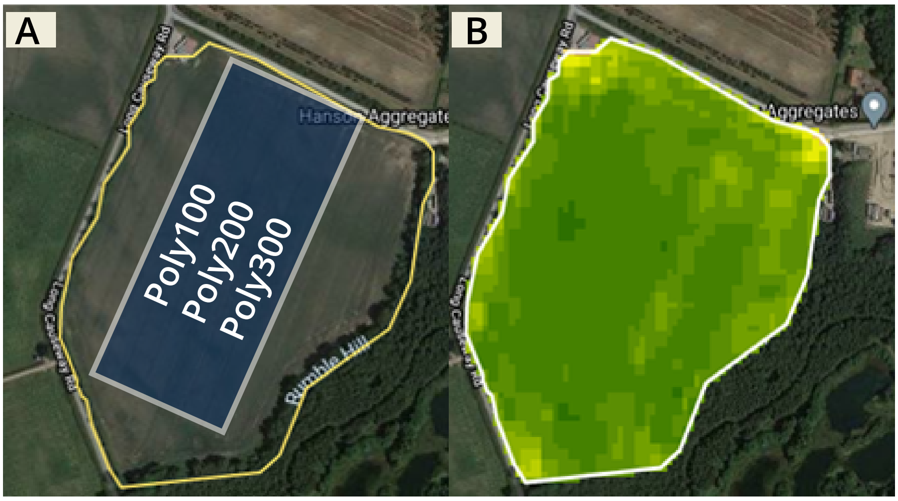
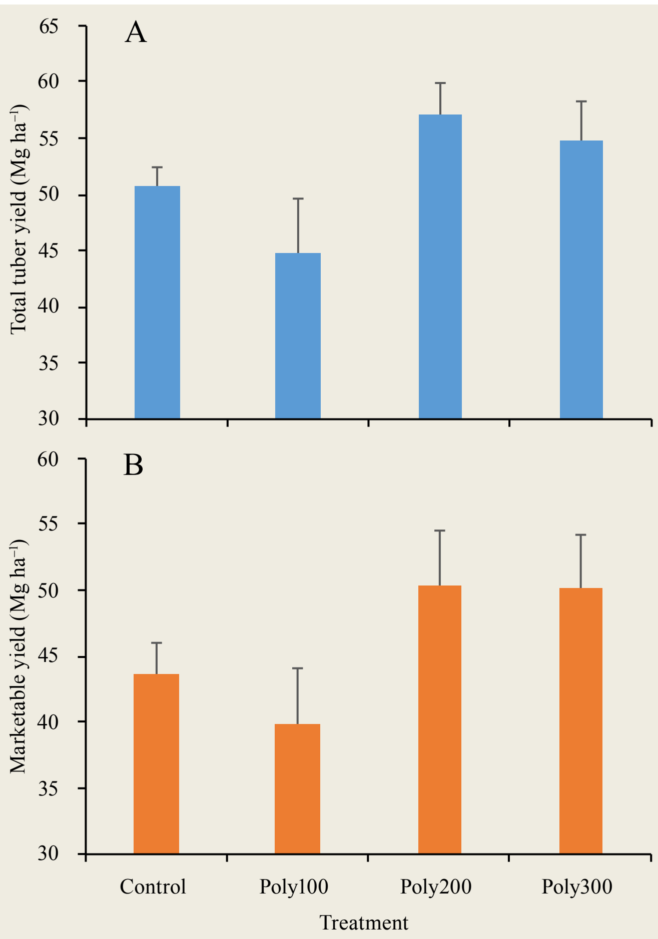


Fig. 4. Experiment 2 field. The polyhalite-applied plots are marked with blue borders, while the surrounding area was farmers' usual practice, MOP-applied control (A); NDVI image of the field in June (B).

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.



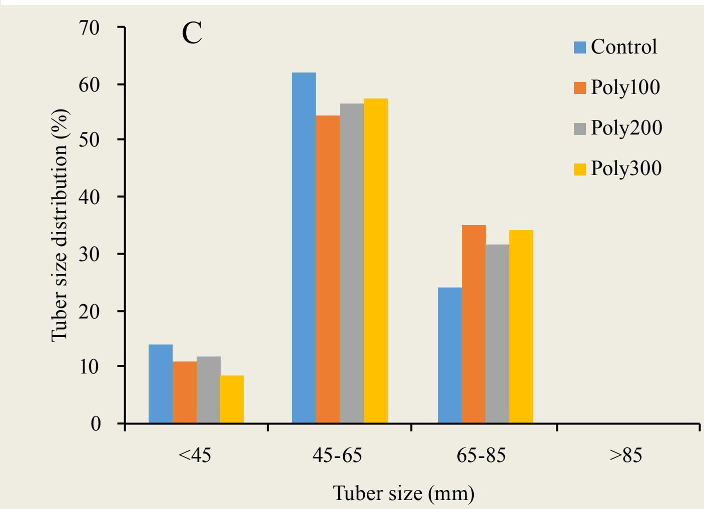


Fig. 5. Effects of increasing polyhalite application rates on potato tuber yield and quality, compared to farmer's usual practice or MOP-applied control. Total (A), and marketable (B) tuber yields, and tuber size distribution (C). Bars indicate SE.

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).

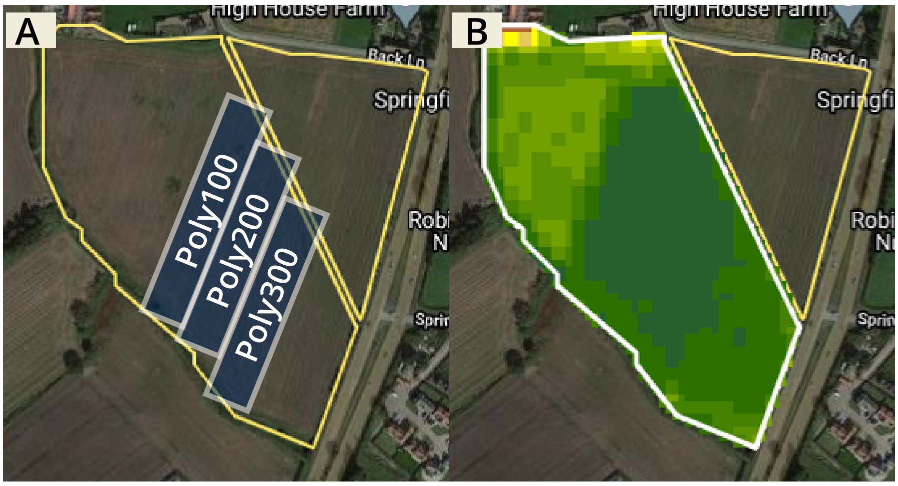


Fig. 6. Experiment 3 field. The polyhalite-applied plots are marked with blue borders, while the surrounding area was applied with PotashpluS (A); NDVI image of the field in June (B).

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

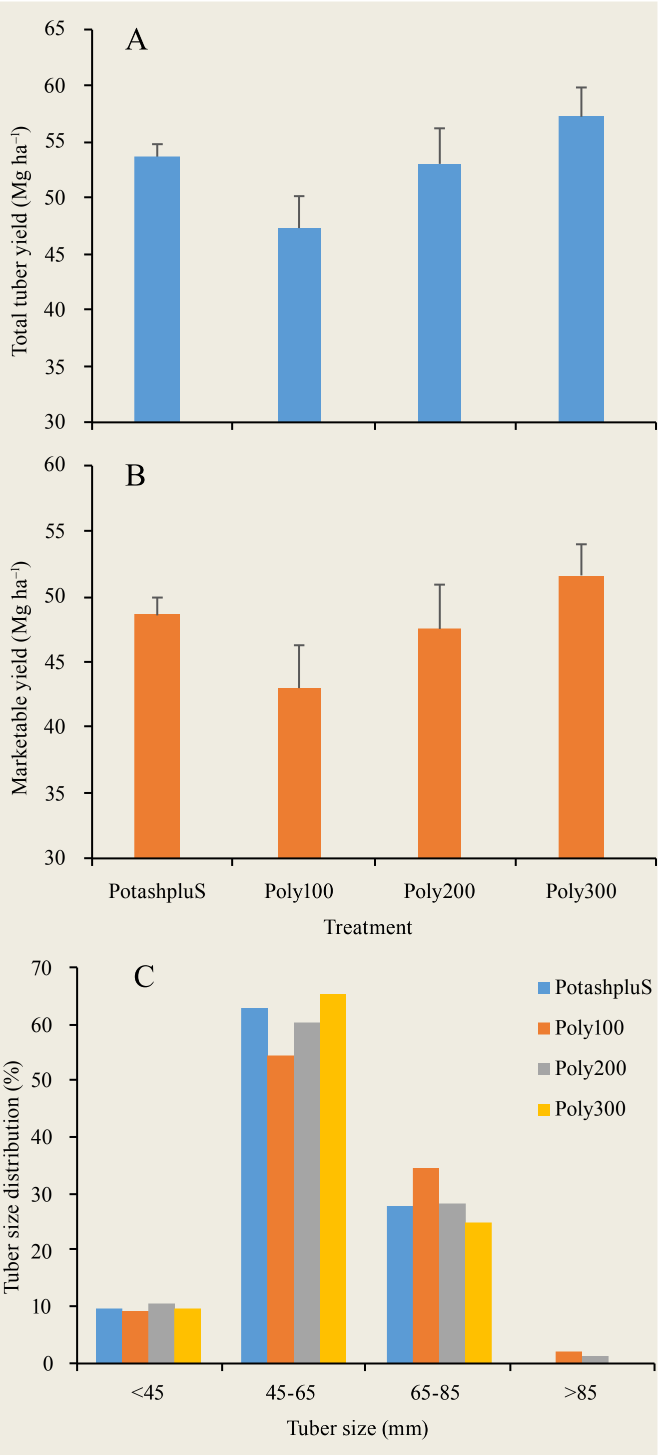


Fig. 7. Effects of increasing polyhalite application rates on potato tuber yield and quality, compared to a PotashpluS-applied control. Total yield (A), and marketable (B) tuber yields, and tuber size distribution (C). Bars indicate SE.

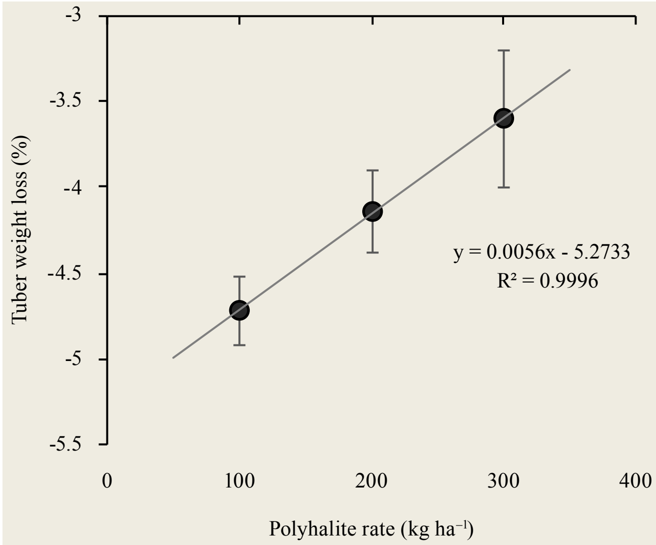


Fig. 8. Water loss from tubers during storage from June to September as a function of polyhalite application rate in the field. Bars indicate SE.

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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