Research Findings

Wheat response to polyhalite application, most likely due to sulfur contribution. Photo by R. Melgar.

Polyhalite for Grain in Soybean-Based Production Systems in Argentina and Paraguay

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Abstract

South American countries are huge grain producers, primarily cultivating soybean (*Glycine max*), wheat (*Triticum aestivum*), and maize (*Zea mays*). The long-term maintenance of prolific grain production systems largely depends on soil fertility. Beyond liming, which is a necessary common practice due to the low soil acidity prevailing in most of the arable lands, preserving adequate soil availability of the macronutrients nitrogen (N), phosphorus (P), potassium (K), and sulfur (S), throughout a single or successive cropping cycles, has become a considerable challenge. Starter fertilizer blends frequently fail to support the anticipated crop yield and grain quality. Polyhalite is a natural marine sediment, which consists of 14% potassium oxide (K_2O), 48% sulfur trioxide (SO_3), 6% magnesium oxide (MgO) and 17% calcium oxide (CaO). As a fertilizer, polyhalite releases nutrients

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Note: Fabio Vale has taken on the role of corresponding author as, sadly, Ricardo Melgar passed away before publication of this paper.

considerably slower than other K-containing fertilizers, thus suggesting additional means to improve soil K availability. The main objective of the trials set in Argentina and Paraguay was to compare, under field conditions, the agronomic efficiency of bulk fertilizer blends that include polyhalite with other formulations currently in use.

Three field trials were conducted in Argentina - one experiment at Nueve de Julio with wheat and two at Mercedes with soybean and maize - and were designed to evaluate the direct effects on a single crop. The treatments included mono-ammonium phosphate (MAP) alone (control), single super phosphate (SSP), MAP + gypsum (34/66%), and MAP + polyhalite at three different ratios 37/63%, 22/78%, and 16/84% that provided increasing levels of K, magnesium (Mg), and S. The crop responses to S were obvious at all growth stages and the average yield increases were 1,371, 1,303 and 754 kg ha^{-1}, (29%, 24% and 39%) for wheat, maize and soybean, respectively. Among the three crops, only soybean yield increased significantly in response to elevated polyhalite rates.

In Paraguay, a single trial was carried out at Itapúa with soybean as the initial crop grown using the starter fertilizer blend, and maize as the succeeding crop testing the residual soil effects. Treatments included MAP (control), compared with two common fertilizer blends which differed in their phosphorus pentoxide and potassium oxide ratio (P_2O_5:K_2O) - 3:1 vs. 2:1 - comprising MAP, SSP, and a K donor (KCl or polyhalite). Both crops demonstrated significant yield increases in response to the higher K dose applied with the 2:1 P:K ratio. The use of polyhalite also gave rise to a slight but significant soybean yield increase at the 3:1 P:K ratio.

In conclusion, polyhalite is an effective S source on S-deficient soils. In addition, it can successfully replace KCl fertilizers on K-deficient soils. However, the long-term impact of polyhalite is quite limited and cannot be accounted for under successive cropping cycles. Moreover, the advantages of supplemented S, K, or MgO are observable only where the requirements of other essential macronutrients, such as N and P, are adequately met. Otherwise, polyhalite or other corresponding nutrient donors are prone to fail in supporting grain production systems in South America.

Keywords: Glycine max; potassium; starter fertilizers; sulfur; *Triticum aestivum; Zea mays.*

Introduction

Soybean is the most important crop in large grain production systems of southern South America. In this region, fertilization practices differ significantly in quantity, source, methodology and timing, mainly due to considerable ecological divergence arising from different climates and soils. While phosphorus (P) and sulfur (S) are usually applied in all regions, other nutrients are applied less consistently; for instance, potassium (K) is commonly used in Brazil and Paraguay, but is applied to a lesser extent in Uruguay, and almost not at all in Argentina. Magnesium (Mg) is also included in some fertilizing formulas, but only in Brazil and Paraguay.

Current fertilization practices in Argentina only just supply sufficient P and S for the grain crops commonly grown on typical Pampean soils, which usually contain enough K and Mg to avoid supplementation (Garcia and González-Sanjuan, 2013; Grasso and González-Sanjuan, 2018). Nevertheless, recent surveys have revealed the occurrence of K and Mg depletion symptoms in many areas (Sainz Rozas *et al.*, 2013; Herrrera and Rotondaro, 2017). This is particularly evident where soil texture is more sandy than loamy, indicating that K reserves might be low. Crops grown in regions known as ‘sandy pampas’ and in the Eastern provinces of Corrientes and Entre Rios are expected to respond to K and Mg application, especially under conditions of heavy yields.

Typically, soybean is the most important crop, functioning as the base of a crop rotation system, complemented with wheat and maize. Often, when wheat precedes soybean, only the former receives fertilization. Depending on the region, median fertilization for soybean in Argentina usually includes 40 kg phosphorus pentoxide (P_2O_5) ha^{-1} and 10 kg S ha^{-1} of varying sources, with no potassium oxide (K_2O) or magnesium oxide (MgO). The nutrients are all applied at sowing and within the seed line. Maize usually receives a higher volume of inputs, i.e., about 60 kg P_2O_5 and 20 kg S ha^{-1}, plus variable amounts of nitrogen (N), ranging from 90 to 120 kg ha^{-1} under different application modes (Grasso and González-Sanjuan, 2018; Fertilizar AC, 2018).

In contrast, fertilization practices for soybean cultivation in Paraguay, along with the neighboring states of Parana and Santa Catarina in Brazil, originated from the traditional approach of extensive and generous P and K application. Median soybean fertilization in Paraguay includes 200 kg ha^{-1} of 4-30-10-4 N-P-K-S, (comprising of 60, 20, and 8 kg ha^{-1} of P_2O_5, K_2O, and S, respectively), and formulation of 5-30-10 N-P-K. A typical rotation is soybean followed by maize as the second crop (Cubilla, 2005; Wendling, 2005).

While P tends to accumulate in most of the local soils, K is frequently depleted. This phenomenon may be explained by the nature of the soils, which are highly weathered with poor cation exchange capacity, deep, and well drained. Potassium is usually applied at sowing through soluble NPK formulations, resulting in an extremely high K concentration at germination, followed by a rapid exhaustion of this soluble nutrient, as it is leached away from the rhizosphere during the rainy season.

In both countries, soil K status has become a critical crop nutrition challenge. In sandy as well as highly weathered soils, the development and maintenance of sufficient K availability throughout the crop cycle requires a stable source of the nutrient. Frequent fertilizer applications are impractical or too expensive in large grain production systems. So far, there have been no perceptible alternatives to the pre-plant fertilizer application. However, at least in the case of K, the fertilizer should be much less soluble than in the currently used complex formulations.

In addition to the problem of insufficient K throughout the crop cycle, there are several other crop nutrition aspects requiring better solutions. High soil acidity endangers many arable lands in South America, a problem encountered by extensive calcium (Ca) application through liming (Caires *et al.*, 2015; dos Santos *et al.*, 2018). Crops also require more S fertilizer since the recent significant reductions in the world's atmospheric S pollutants (Haneklaus *et al.*, 2016). While S is recognized as the fifth most important plant macronutrient, responsible for protein metabolism and many other vital processes in the plant biology (Hawkesford, 2000), the decreasing availability of this nutrient in most arable soils necessitates more active fertilization approaches. Gypsum ($CaSO_4$) application is quite common, contributing both S and Ca, however, it lacks K and Mg. Other S fertilizers are combined with N – a nutrient for which crop requirements are easily met using affordable fertilizers.

Polysulphate™ (produced by Cleveland Potash Ltd., UK) is the trade mark of the natural mineral polyhalite, 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 14% K_2O, 48% SO_3, 6%, MgO and 17% CaO. As a fertilizer providing four key plant nutrients - S, K, Mg, and Ca - polyhalite may offer attractive solutions to crop nutrition. In addition, polyhalite releases the nutrients considerably slower than other K-containing fertilizers, which may also be significant for extended soil K availability. Once an optimum application rate is established, polyhalite may not only provide a significant part of crop K requirements, but also supply secondary macronutrients that are essential for the grain production systems in Argentina and Paraguay.

Given the differences in fertilization practices between the two countries, the main common objective of the trials was to compare, under field conditions, the agronomic efficiency of bulk fertilizer blends that include polyhalite with other current formulations applied to soybean. A more specific objective in Argentina was to determine crops' responses to K and Mg on areas with coarse-textured soils. In Paraguay, crop responses to Mg, and the residual effects of fertilizer application to soybean on the succeeding maize crop, were also studied.

Materials and methods

In Argentina, two locations were chosen on mollisols soils, one in the center (Nueve de Julio) and the other in the northern (Mercedes) Pampean region (Fig. 1). One field experiment with wheat was set in Nueve de Julio, and two trials with maize and soybean in neighboring plots in Mercedes. The three trials were carried out during the 2016-2017 season.

In Paraguay, the field experiment was carried out with soybean followed by maize in two consecutive seasons (2017-2018) on ultisol of Itapúa Dept. (Fig. 1). The soil at each location was sampled before sowing and characterized (Table 1).

Due to significant differences in the common fertilization practices employed in each country, the treatments varied between the two countries. In Argentina, all treatments were based on different sources of S that were applied at sowing and with a single rate of P (30 kg P_2O_5 ha^{-1}), in addition to other fertilizer combinations, including a control with no sulfur. Gypsum and single super phosphate (SSP) treatments were included, since they were the

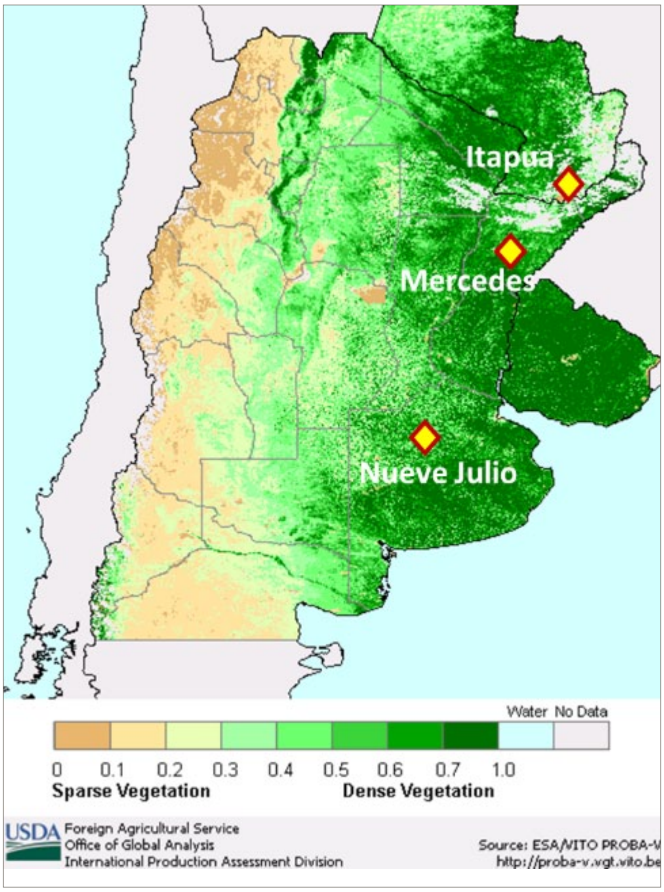

Fig. 1. Map of the study area with locations of field trials.

Table 1. Soil chemical and textural attributes of the top layer (0.0-0.2 m).

Site/crop	Soil taxonomy	Texture class	pH	Ca	Mg	K	S	P	O.M.
			Water 1:2.5	---------------*cmol$_c$ kg^{-1}*		----------------	---------*mg kg^{-1}*	---------	*g kg^{-1}*
Nueve de Julio/wheat	Entic Hapludoll	Loamy sand	5.9	6.5	1.36	1.23	7.1	9.8	29
Mercedes/maize	Typic Argiudoll	Sandy loam	5.4	7.4	2.10	0.50	3.1	5.8	32
Mercedes/soybean			5.2	7.8	2.20	0.20	3.1	4.7	28
Itapúa/soybean	Typic Rhodudult	Clayey	5.9	8.0	0.83	0.60	5.4	2.1	32
Itapúa/maize			5.9	8.0	0.81	0.61	4.8	2.3	31

Note: O.M. = 1.72 * Organic carbon ($K_2Cr_2O_7$); Ca, Mg and K (NH4 Ac 1 mol L^{-1}); P (Bray 1); S (Ca_2PO_4 1M extraction).

common sources of S with comparable rates of S to polyhalite (Table 2A).

In Paraguay, where bulk blends of NPK with potassium chloride (KCl) are commonly used but S supply is still ignored, two formulations at different grades were evaluated - each with a partial replacement of K from KCl with polyhalite (Table 2B). The five treatments consisted of two grades (5-20-10 and 5-30-15) having different proportions of P_2O_5 to K_2O (2:1 and 3:1). These two formulations, typically used within the region's soybean production, were in turn, prepared with different proportions of K_2O originating from KCl and polyhalite. This resulted in the development of formulations with and without MgO. The four grades were compared with mono-ammonium-phosphate (MAP) as a control lacking S, K and Mg. All five treatments received the same rate of 70 kg P_2O_5 ha^{-1}. The treatments described, including the amount of nutrients applied and the proportion of the compounds are shown in Table 2B.

The treatments for both countries were allocated in a randomized complete block design with four replications. Fertilizers were applied at sowing of the soybean and maize in Argentina, and only to the soybean in Paraguay. The wheat crop in Nueve de Julio received 75 kg N ha^{-1}, applied prior to crop emergence in the form of urea. The maize crops at both sites received a broadcast fertilization with N as urea at V4-V6 stage in addition to the N applied through the MAP starter, thus providing 100 and 45 kg N ha^{-1} in Argentina and Paraguay, respectively.

At Nueve de Julio, Argentina, the wheat variety Klein was sown at a density of 278 seeds m^{-2} under no-till, on 16 June 2016. At Mercedes, Argentina, soybean variety DM 8277 I pro was sown on 1 December 2016, at a density of 45 seeds m^{-2} and with a distance of 0.35 m between rows. At an adjacent plot at Mercedes, a maize hybrid (Syngenta 126 VT 3pro) was sown on 5 January 2017, at a density of 5 plants m^{-2} and with 0.52 m spacing between rows.

Table 2. Bulk fertilizer starter treatments used within the experiments in Argentina (A) and Paraguay (B), listing the nutrient source, ratios and quantities. Supplement N fertilizer was evenly applied through urea, as detailed in the text.

A) Argentina

Treatment - blends (w/w)	Fertilizer rate	N	P_2O_5	K_2O	MgO	S
	------------*kg ha^{-1}*					------------
Control - MAP	58	6	30	-	-	-
SSP	158	0	30	-	-	19
MAP + gypsum (34%/66%)	167	6	30	-	-	19
MAP + polyhalite (37%/63%)	158	6	30	14	6	19
MAP + polyhalite (22%/78%)	258	6	30	28	12	38
MAP + polyhalite (16%/84%)	358	6	30	42	18	57

Note: MAP: 11-52-0-0S; SSP: 0-19-0-12S. Treatments 3-5 are bulk blends of MAP, granular gypsum (0-0-0-17S) and polyhalite (0-0-14-19S-3.6 Mg).

B) Paraguay

Treatment (fertilizer blend)	P_2O_5:K_2O	Grade NPKS	Fertilizer rate	N	P_2O_5	K_2O	MgO	S
			------------*kg ha^{-1}*					------------
Control - MAP	-	10-52-0-0 S	135	15	70	-	-	-
MAP, SSP, KCl	3:1	5-30-10-5 S	233	11	70	23	-	11
MAP, SSP, polyhalite	3:1	6-30-10-6 S	233	15	70	23	5	15
MAP, SSP, KCl	2:1	5-30-15-3 S	233	12	70	35	-	8
MAP, SSP, polyhalite	2:1	6-30-15-4 S	233	15	70	35	3	10

Note: Treatments 2-5 are bulk blends of MAP (11-52-0-0S), SSP (0-19-0-12S), KCl (0-0-60) and polyhalite (0-0-14-19S-3.6 Mg).

In Paraguay, 45 kg seeds ha^{-1} of the soybean variety Nidera 5959 was sown using farmers' machinery on 18 October 2017, with 0.45 m spaced rows under no tillage. After harvesting the soybean, a maize hybrid (Pioneer 4285 YHR) was sown on 9 March 2018 under no-till, at a density of 6.1 plants m^{-2}, and with row spacing of 0.45 m. The maize crop was applied with 115 kg NPK fertilizer ha^{-1} (11-15-15), adding 14 kg K_2O ha^{-1} to all treatments.

Weed, pest, and disease control were performed with the best information available at each site using farmer's machinery and practices. When the crops reached physiological maturity, a selected central zone of each plot at every site was harvested with an experiment-scale combine. Grains were weighted and sampled for their humidity content. Wheat samples were also analyzed for quality parameters, such as protein and gluten contents and grain size (test weight). Grain yields were adjusted to the commercial humidity standard of 13.5% and expressed as Mg ha^{-1} (ton ha^{-1}).

Results were analyzed statistically using the SAS package and general linear model procedure.

Results and discussion

Argentina

Wheat (Nueve de Julio, Argentina)

The experiment was conducted in a field typical of the region, presenting very low soil nutritional values (Table 1). Soil S was particularly low and close to being deficient. Since all treatments were applied with similar doses of N and P, the differences in results could be attributed to the levels of S, K or Mg (Table 2A).

Yield response to S application was significant, unequivocal (Table 3), and even visible in the field (Fig. 2). The S-applied wheat obtained on average 1,371 kg grain ha^{-1} more than the control, which is a 29% increase. These results support previous studies that demonstrated wheat S requirements (Shah *et al.*, 2018; Yu

Fig. 2. A wheat field in Nueve de Julio, Argentina with the control treatment (without S) left vs. the highest S-applied treatment (57 kg S ha^{-1}, 84% polyhalite), at the vegetative stage (above) and near harvest (below). Photos by R. Melgar.

et al., 2018). Among the polyhalite-applied treatments, yield tended to increase with the higher polyhalite rate in the fertilizer blend; however, these differences were not statistically significant.

Grain protein levels ranged from 9-11%, which is below the minimum industry standards of 11% (Delwiche and Miskelly, 2017). The highest wheat protein content, 11%, was obtained by the control, which also had the lowest grain yield, while the protein content of wheat applied with S was quite stable at 9.1-9.3% (Table 3). Consequently, the calculated protein yield ranged from 520-581 kg ha^{-1} with no significant differences between treatments. Thus, in contrast to the significant relative increase in the grain yield in response to S application, the corresponding protein yield increment was small and similar to the control (Fig. 3 and Table 3). Interestingly, grain test weights were much greater than the commercial set for the best grade (above 79). However, any significant differences found among treatments could not be ascribed to any specific nutrient rate (Table 3). Gluten contents corresponded with the protein pattern.

Table 3. Mean grain yield and quality parameters of wheat as affected by different fertilizer treatments at Nueve de Julio experiment.

Treatment	Grain yield	Protein		Test weight	Gluten
	Mg ha⁻¹	----%----	---*kg ha⁻¹*---	*g 1,000⁻¹ seeds*	*% of protein*
Control - no S	4.719b	11.0a	520	84.5ab	26.7a
SSP	5.934a	9.1c	537	82.4b	22.0c
MAP + gypsum	6.165a	9.3b	572	86.6a	22.9b
MAP + polyhalite 37/63	5.919a	9.3b	549	86.4a	22.9b
MAP + polyhalite 22/78	6.089a	9.2b	562	85.8ab	22.5bc
MAP + polyhalite 16/84	6.345a	9.2bc	581	87.6ab	22.1c
$P_{Treatment}$	<0.001	<0.001		0.08	<0.001
$LSD_{5\%}$	474	0.15		3.58	0.73
CV %	5.4	1.1		2.8	2.1

Note: Data followed by equal letters are not statistically different within a column.

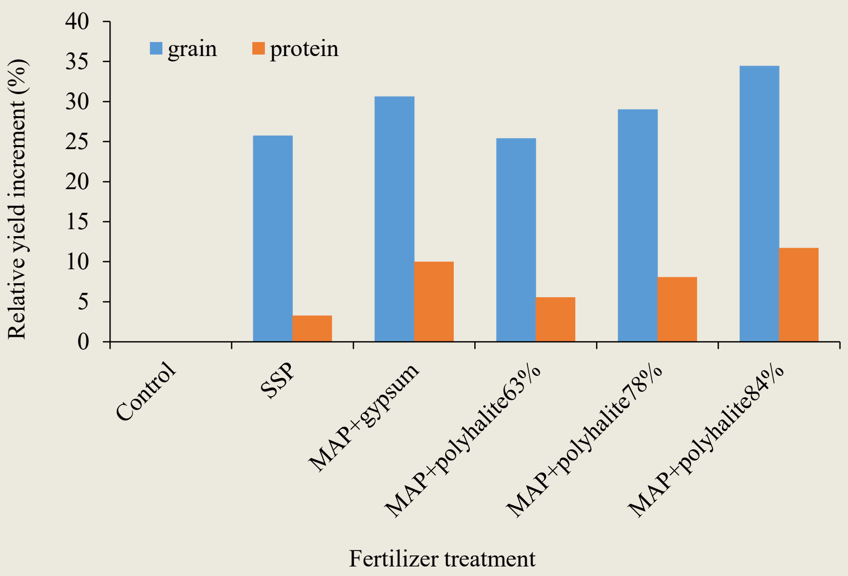

Fig. 3. Effects of fertilizer treatments on the relative increment in wheat grain and protein yields. For a detailed description of fertilizer treatments refer to Table 2.

While the improved S, K, and Mg availability in some of the treatments gave rise to a much higher grain yield, it may be speculated that the soil status of another macronutrient, probably N, was too poor during the wheat-cropping season to support higher grain protein contents. Nitrogen, although generously applied through urea prior to wheat emergence, is essential to protein metabolism (Hawkesford, 2014). However, urea is a temporal N source, as it rapidly breaks down and disappears from the rhizosphere. Therefore, a single urea application at sowing, or even additional but sporadic broadcasts of an N fertilizer during the season, might support plant growth and even normal grain development, but would fail to provide the high protein content expected (Geng *et al*., 2016; Thierry and Larby, 2018).

Maize (Mercedes, Argentina)

Under a similar fertilization program at Mercedes, Argentina, the maize response was a bit different. SSP fertilizer, contributing 19 kg S ha^{-1} but no K, Ca, and Mg, brought about a slight grain yield increase, about 10% above control, which was insignificant statistically (Fig. 4). MAP + gypsum, which added S and Ca, gave rise to a much more significant yield increase of 1.7 Mg ha^{-1}, 32% above control. The three MAP + polyhalite blends also obtained high yields, however, these did not differ from that of MAP + gypsum (Fig. 4).

These results demonstrate the importance of meeting Ca and S requirements for improved crop yield (Sirikare *et al*., 2015; Ahmad *et al*., 2016). On the other hand, in this maize experiment, the higher doses of K, Mg and S provided by the polyhalite did not have any significant effects on crop development or yield. It should also be said that maize potential yields in this region normally reach 10 Mg ha^{-1}, much higher than the level obtained in the present study. These facts may indicate other yield limiting factors, such as insufficient N (Zheng *et al*., 2016) and/or

P, and drought or extreme weather events having some significant negative impact on the maize crop performance.

Soybean (Mercedes, Argentina)

On the same site, the soybean crop performed much better than the maize, and the yield achieved was closer to the expected potential of the area. Crop response to the different fertilizer treatments were observable on-field at the early reproductive stage, as well as at harvest (Figs. 5A, 5B). Soybean grain yield demonstrated a measurable increase, about 10% above the control, in response to additional S through SSP (Fig. 6). A similar S dose, combined with Ca through gypsum application, obtained a significant yield increase of about 0.5 Mg ha^{-1}, 26% above the control. Replacing the gypsum with polyhalite gave rise to a further significant yield increase, adding 303 kg grain ha^{-1}. This yield increase is attributed to the additional K_2O and MgO amounts - 14 and 6 kg ha^{-1}, respectively, supplied through the polyhalite, and under a similar S input of 19 kg ha^{-1}. Enriching the fertilizer blend with polyhalite at the partial expense of MAP (Table 2) brought about further yield increases of up to 3.089 Mg grains ha^{-1}. This is a 61% increase when compared to the control treatment, and 28% above the yield of the conservative treatment of MAP + gypsum (Fig. 6).

As a legume species, soybean plants can utilize atmospheric N and hence, their reliance on N fertilizer is significantly small, compared to cereal crops (Collino *et al.*, 2015; Ciampitti and Salvagiotti, 2018; Santachiara *et al.*, 2018; Tamagno *et al.*, 2018). Assuming that N limitation did not occur throughout the experiment, soybean crop requirements of other macronutrients could be met and studied. In the absence of Ca, a pivotal soil ameliorator in many regions of South America (Caires *et al.*, 2015; dos Santos *et al.*, 2018), crop response to S alone was very poor, though positive. The application of gypsum established a significantly higher yield level, demonstrating the importance of the two nutrients (Ca and S). However, polyhalite, providing both K_2O and MgO, in addition to Ca and S, supported higher yields still. Moreover, this study shows that soybean crops do require these nutrients, and maybe at even higher doses.

Paraguay

The experiments in Paraguay aimed to test the effects of the ratio between P and K in the fertilizer blend, applied at sowing, on the grain yields of two successive crops - soybean (I), and maize (II). Potassium was applied using KCl or through

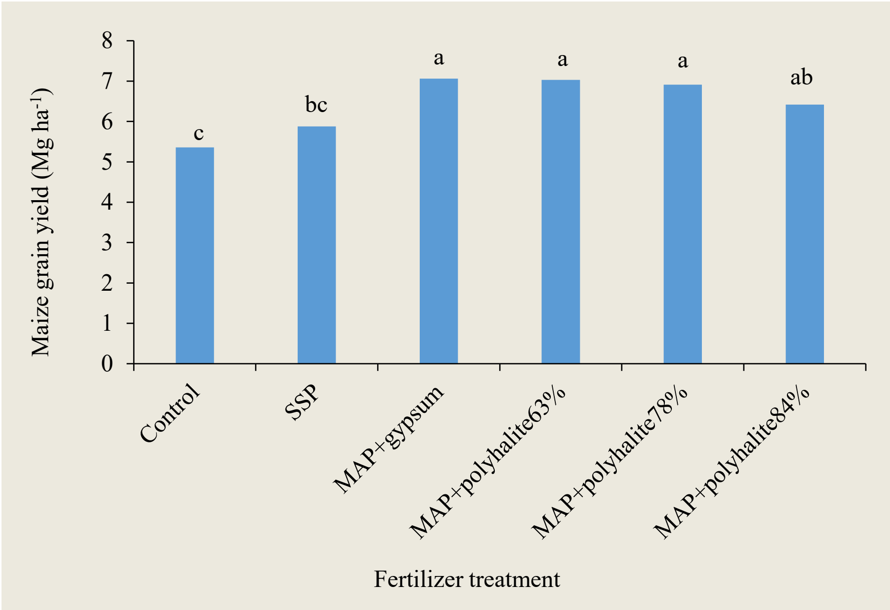

Fig. 4. Maize yield response to the fertilizer treatments at Mercedes, Argentina. For detailed treatment description, see Table 2. Similar letters indicate non-significant statistical differences between treatments at P=0.05.

Fig. 5A. Soybean plant samples from the Mercedes, Argentina study at an early reproductive stage. For detailed treatment description, see Table 2. Photo by R. Melgar.

Fig. 5B. Soybean plant samples from the Mercedes, Argentina study after harvest. For detailed treatment description, see Table 2. Photos by R. Melgar.

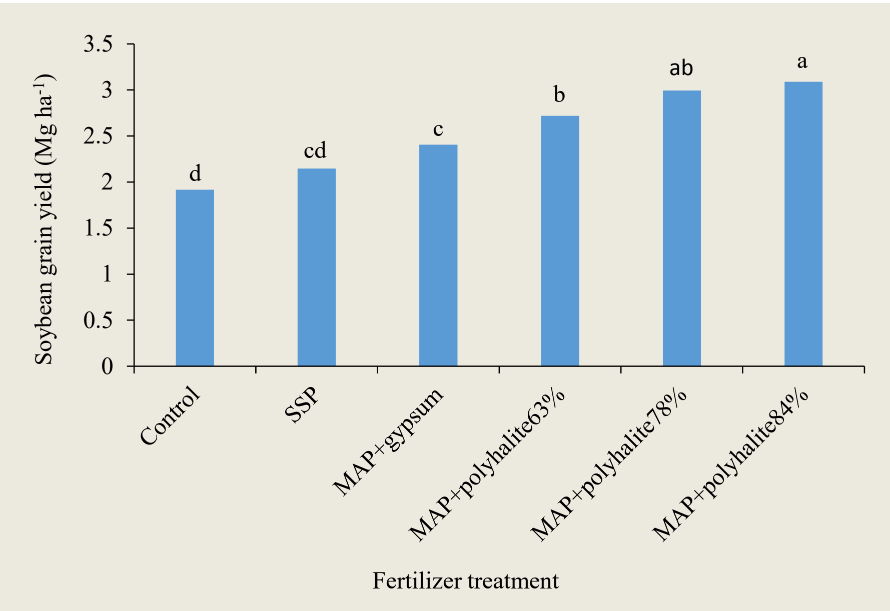

Fig. 6. Soybean yield response to the fertilizer treatments at Mercedes, Argentina. For detailed treatment description, see Table 2. Similar letters indicate non-significant statistical differences between treatments at P=0.05.

polyhalite, which also contributed Ca and MgO. Sulfur was applied through SSP or polyhalite. Generally, soybean and maize yields were within the range common for the region and in line with the weather conditions that prevailed during the cycle.

No significant yield increase was observed for the soybean crop following S and K application through SSP and KCl, respectively, at a P:K ratio of 3:1 (Table 4). However, similar doses of these two nutrients applied through polyhalite resulted in significant increases in grain size and yield. When the P:K ratio decreased to 2:1 by increasing the K_2O rate from 23 to 35 kg ha^{-1}, soybean grain size and yields increased further to about 166 g 1,000^{-1} seeds and 4.3 Mg ha^{-1}, which was roughly 11% more than the control treatment. At this paired treatments, there was no advantage to either KCl nor to polyhalite (Table 4).

Yields of the successive maize crop did not respond to the lower K rates of the initial fertilizer blends, compared to the control (Table 4). This may be due to the additional 14 kg K_2O ha^{-1} applied to all treatments at maize sowing. However, the fertilizer blend with the higher K rate did have a significant effect on the maize yield, with only a slight increase of about 300 kg grains ha^{-1} (Table 4). At the study in Paraguay, polyhalite did not have any significant effect on the maize yield. It is questionable whether the maize crop required the additional Ca and MgO provided through polyhalite. Alternatively, the postulated long-term impact of polyhalite might be over-estimated in the case of successive crops.

Conclusive remarks

Polyhalite can be very effective as part of fertilizer blends applied at the pre-plant stage. On S-deficient soils, polyhalite is a suitable source of this nutrient and has the same positive effect as other fertilizers currently used to support grain production in South America. In addition to S, polyhalite provides other essential nutrients - K, Ca, and MgO. Thus, polyhalite can successfully replace KCl fertilizers on K-deficient soils. Furthermore, the slower rate of K release from polyhalite expands the duration of K supply during the crop cycle, which is a considerable advantage over soluble-K fertilizers. However, the long-term impact of polyhalite in soils is quite limited and cannot be relied upon during successive cropping cycles. Moreover, the advantages of supplemented S, K, or MgO can be manifested only where the requirements of other essential macronutrients, such as N and P, are adequately met. Otherwise, polyhalite or other corresponding nutrient donors, are prone to fail in supporting grain production systems.

Table 4. Effects of pre-plant fertilizer treatments on the yield and seed weight of successive soybean and maize crops in Itapúa, Paraguay. For detailed description of treatments, see Table 2.

Treatment	P_2O_5:K_2O	Rate	K_2O	MgO	Yield (Mg ha^{-1})		Seed weight (g 1,000^{-1})	
					soybean	maize	soybean	maize
		---------------------*kg ha^{-1}*-------------------						
Control - MAP	-	135	0	0	3.898c	3.621b	159bc	269ab
MAP, SSP, KCl	3:1	233	23	0	3.952c	3.687b	159c	276a
MAP, SSP, polyhalite	3:1	233	23	2	4.163b	3.642b	164ab	263b
MAP, SSP, KCl	2:1	233	35	0	4.298a	3.945a	166a	276a
MAP, SSP, polyhalite	2:1	233	35	3	4.318a	3.953a	166a	278a
CV %					2.7	6.0	3.1	3.4
Pr > F					<0.001	0.007	0.005	0.02
LSD 5%					115	229	5	3.3

Note: Data followed by equal letters are not statistically different within a column.

The soybean experiment in Itapúa Dpt., Southern Paraguay, at vegetative stage and during harvest. Photos by R. Melgar.

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The paper "Polyhalite for Grain in Soybean-Based Production Systems in Argentina and Paraguay" also appears on the IPI website.

Dr. Ricardo Melgar

It is with deep sorrow we learned that Dr. Ricardo Melgar has left us. Dr. Melgar was a leading researcher at INTA (National Agricultural Research Institute) in Argentina. He dedicated his career to soils, crops fertilization and plant nutrition. We have lost a valued friend and an authority for soil science and agronomy. We will miss him greatly and will always cherish his great contribution to science and to our institute.