Research Findings

Photo 1. Overview of soybean experiment site at Rio Verde Foundation, Brazil. Photo by the authors.

Evaluation of Potassium and Sulfur Fertilizers for Soybean in Brazil

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Abstract

Soybean production in several regions of Brazil is carried out on soils with medium to low sulfur (S) levels, which may be corrected using fertilizer. Several S fertilizers have been examined, some of which contain S in sulphate form and others in its elemental form. Polyhalite, a fertilizer comprised of sulphate, calcium (Ca), magnesium (Mg), and potassium (K), was shown to correct Ca, Mg, and S deficiencies, but could not always fully supply crops' K requirements. PotashpluS®, a new granular blend of polyhalite and potassium chloride (KCl), was evaluated as the sole K and S sources for soybean production and compared to alternative S fertilizers common in Brazil. The experiment took place at Rio Verde Foundation, Mato Grosso state, Brazil. The experiment included six fertilizer treatments in a completely randomized block design with four replications. Two treatments: Mono-ammonium phosphate (MAP)+PotashpluS®, and MAP+single superphosphate (SSP)+KCl, both comprising sulphate as their sole S source, showed greater response potential and gave rise to significantly higher yields (10%) compared with common fertilizers where the partial or total S supply was in the elemental

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form. PotashpluS® broadcast pre-planting was as efficient as the SSP applied in the planting furrow. Further research is needed to verify all potential benefits of PotashpluS® for soybean, as well as other crop species.

Keywords: Calcium; *Glycine max.* L.; magnesium; polyhalite; PotashpluS®.

Introduction

Brazil is one of the largest soybean (*Glycine max.* L.) producers in the world, with an annual production of about 120 million tonnes of grain. In the 2018/2019 season, the total harvested area reached 35.8 million ha with a mean grain yield of about 3,300 kg ha^{-1} (CONAB, 2019).

Soybean crops have a high potassium (K) requirement; the production of one tonne of grain requires 43 kg of K. Overall K uptake required for the production of 3,500 kg soybean grain and 9,500 kg total biomass ha^{-1} during a cropping season has been determined as 172 kg ha^{-1}, equivalent to 207 kg K_2O ha^{-1} (Bender *et al.*, 2015). The authors also estimated soybean's requirements for other essential macronutrients such as calcium (Ca), magnesium (Mg), and sulfur (S). To produce similar soybean grain yields and biomass, a crop required 113, 50, and 19 kg ha^{-1} of Ca, Mg, and S, respectively.

Management of K fertilization in Brazil must consider several serious edaphic challenges. In many regions, soils are acidic; K^+ ions fail to compete with H^+ ions and adsorb to the surface of the soil particles. Consequently, these K^+ ions are rapidly leached away from the rhizosphere, necessitating additional K application doses in order to meet crop requirements. Under such circumstances, K fertilizers with a lower risk of salinization are desirable. Furthermore, fertilizers with slower solubility rates are particularly advantageous in order to reduce K leaching.

Insufficient Ca and Mg levels in the relevant soil profile were detected in several regions in Brazil (Caires *et al.*, 2000; Vale, 2016). This phenomenon has been associated with the use of limestone broadcast aimed at alleviating soil acidity. Instead of penetrating into subsurface soil layers in forms available to plant roots (soluble ions), Ca and Mg remain associated with carbonate anions, concentrated on the soil surface as an insoluble limestone layer. Subsequently, root distribution is restricted to the upper soil layer. The inadequate root system fails to support plant water requirements during drought periods, often occurring within the rainy season. This scenario was suggested as a possible reason for the drastic reduction in soybean production (Roldão, 2015).

Soybean production in several regions of Brazil often takes place in areas with medium to low soil S status. In such cases, there is a considerable potential to improve soybean crop performance through S application. Several sources were utilized to enrich the soil with S, some were in the form of sulphate, and others in the elemental form.

In recent years, a new supplementary fertilizer, polyhalite, was introduced to Brazil. Polyhalite is comprised of K_2O (14%), Ca (12%), Mg (3.6%), and S (19%). Due to reduced levels of sodium and chloride, this fertilizer has a lower salinity rate compared to KCl (Fried *et al.*, 2019), in addition to gradual nutrient solubility (Yermiyahu *et al.*, 2017; Yermiyahu *et al.*, 2019). Studies have demonstrated the effect of applying polyhalite to crops, including soybean (Vale and Serio, 2017; Bernardi *et al.*, 2018; Pittelkow *et al.*, 2018).

One of a new generation of polyhalite fertilizers, PotashpluS®, has been introduced recently and is available to soybean farmers in Brazil and parts of the world. While primarily a potash and sulphate fertilizer, it 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. Encapsulated in the same granule, nutrient segregation is avoided, even when fertilizer is broadcast at pre-planting. Sulfur, Mg and Ca are all in sulphate (SO_4) form, ensuring high availability to plants.

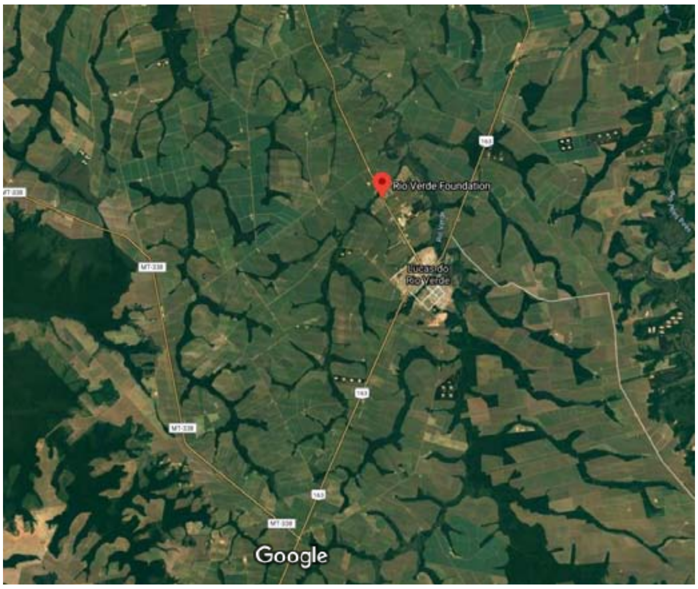
The objective of the present study was to evaluate the effect of applying the new compact fertilizer combination of KCl with polyhalite as a source of K and S, and to compare it with other S-donor fertilizers commonly used in soybean production in Brazil.

Materials and methods

The experiment was carried out at the Rio Verde Research and Technological Development Foundation, located between the geographic coordinates 13°00'27"S - 55°58'07"W and 12°59'34"S - 55°57'50"W, at an average altitude of 387 meters, in the city of Lucas do Rio Verde, Mato Grosso state, Brazil (Map 1). The region is comprised of the Cerrado biome and its predominant climate is Aw type (Tropical Savannah) according to the Köppen-Geiger classification (Peel *et al.*, 2007), presenting two well-defined seasons: rainy, from October to April; and drought, from May to September.

The soil of the experiment site was a Typic Hapludox, or a dystrophic Red-Yellow Latosol, as defined in the Brazilian system of soil classification (Embrapa, 2013). The pre-experiment physical and chemical soil properties are shown in Table 1.

The interpretation of soil fertility as it relates to soybean production, characterized according to critical levels defined by Embrapa (2014), indicated that phosphorus (P), copper (Cu), iron (Fe) and zinc (Zn) contents were high, while S, Ca and manganese



Map. 1. Location of the trials, Rio Verde Foundation, Brazil. *Source:* Google maps.

Table 1. Texture and chemical properties of the local topsoil (depth of 0-20 cm) used in the soybean experiment.

Soil property	Quantity	Units
Sand	465	g kg^{-1}
Silt	75	g kg^{-1}
Clay	460	g kg^{-1}
pH ($CaCl_2$)	4.6	
Organic matter	21	g dm^{-3}
Cation exchange capacity (CEC)	6.9	cmol$_c$ dm^{-3}
Basic saturation (V%)	32	
Phosphorus, as $P_{Mehlich}$	13.5	mg dm^{-3}
K	0.1	cmol$_c$ dm^{-3}
Ca	1.8	cmol$_c$ dm^{-3}
Mg	0.3	cmol$_c$ dm^{-3}
S, as SO_4	11	mg dm^{-3}
B	0.2	mg dm^{-3}
Cu	1.0	mg dm^{-3}
Fe	52	mg dm^{-3}
Mn	4	mg dm^{-3}
Zn	1.8	mg dm^{-3}

(Mn) contents were medium. Potassium, Mg, boron (B) and organic matter contents were classified as low, showing the potential for fertilization.

The experiment took place in the 2018/2019 season. Soybean crop (cultivar M 8372 IPRO) was sown on 19 October 2018, under no-tillage on residual straw from a second corn crop. Seeds were treated with Standak Top insecticide at a dose of 2.0 ml kg^{-1} of seeds.

The experiment design was completely randomized blocks with six treatments distributed in four repetitions. Each plot consisted of 10 seeding lines at a spacing of 0.45 x 13.0 meters, in a total area of 58.5 m^2 per plot and 234 m^2 per treatment. Detailed description of the treatments employed is given in Table 2.

The rates of N, P_2O_5 and K_2O applied in all treatments were 17, 80 and 80 kg ha^{-1}, respectively, while the rate of S was 20 kg ha^{-1}, adjusted according to the blends of the fertilizers used in the experiment.

Two K sources were tested: KCl (60% K_2O), and PotashpluS® (37% K_2O; 5.7% Ca; 1.8% Mg and 9.2% S). Four S sources were examined: single superphosphate (SSP) (18% P_2O_5, 16% Ca, 8% S); pastille elemental S (90% S); PotashpluS®; and a composite granulated NPK fertilizer (8% N, 40% P_2O_5, and no K) that also contained 3.2% Ca and 9.3% S (3.5% S-SO_4 and 5.8% elemental S). The fertilizer MAP (11% N and 52% P_2O_5) was the standard source of P in all treatments, excluding treatment three (MAP+SSP+KCl), where the P_2O_5 rate was adjusted with a blend of MAP and SSP, and in treatment six (NPK+KCl), which received all P from the composite fertilizer. In treatment three, the adjustment of N rate was made using urea fertilizer (45% N).

All phosphate sources (MAP, SSP, and NPK 8-40-0), as well as the pastille elemental S were applied in the planting furrow. KCl and PotashpluS® were broadcast pre-planting, one day before sowing.

Climate data, starting 10 days before sowing until harvest, are presented in Fig. 1. A 13-day period of restricted soybean development occurred during mid-December, characterized by very low precipitation, and coincided with

Table 2. Description of treatments tested in the soybean experiment in Lucas do Rio Verde, Mato Grosso state, Brazil. Rio Verde Foundation, 2018-2019.

Treatment	Pre-planting broadcast		Applied at sowing				
	KCl (MOP)	PotashpluS®	MAP	Urea	NPK 8-40-0	SSP	PES
	--------------------------------------*kg ha^{-1}*--------------------------------------						
MAP	-	-	154	-	-	-	-
MAP+KCl	134	-	154	-	-	-	-
MAP+SSP+KCl	134	-	69	20	-	245	-
MAP+PES+KCl	134	-	154	-	-	-	22
MAP+PotashpluS®	-	217	154	-	-	-	-
NPK 8-40-0+KCl	134	-	-	-	200	-	-

Abbreviations: MAP: mono-ammonium phosphate; KCl: potassium chloride; MOP: muriate of potash; SSP: single superphosphate; PES: pastille elemental sulfur; NPK: composite N-P-K fertilizer with determined N-P_2O_5-K_2O.

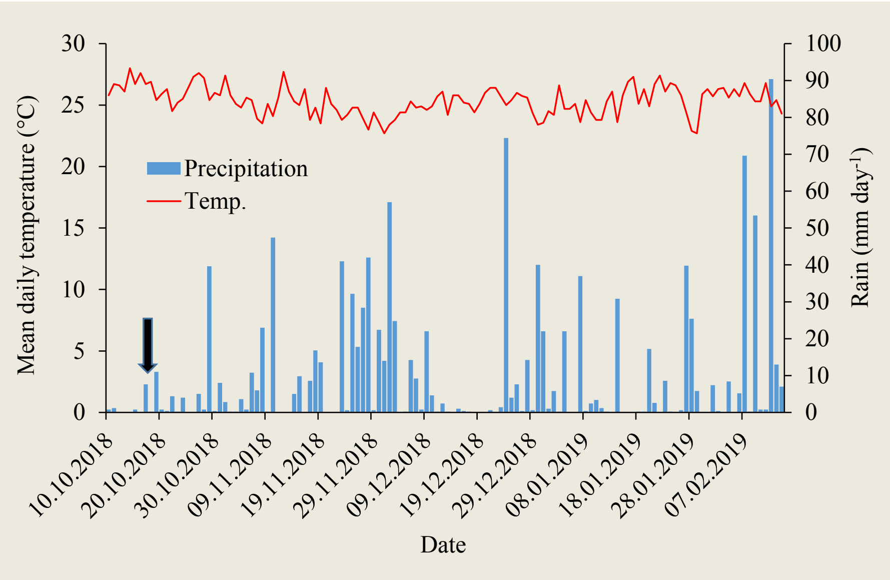


Fig. 1. Mean daily temperature and rainfall occurred from 10 days before sowing (black arrow) until harvest during the soybean experiment at Rio Verde Foundation, 2018-2019. Accumulated rainfall during the period was 1.197 mm.

final vegetative and early reproductive crop phases.

Harvest took place on 14 February 2019, and the crop duration was 118 days. Disease, pest, and weed controls were performed according to the technical recommendations for the crop. Crop performance was evaluated throughout the season, including phenological follow-up and sampling, as described below.
Initial and final plant population (IPP and FPP, respectively; plants ha^{-1}) were determined at crop phenological stages V3 and R9 (8 November 2018 and 8 February 2019, respectively) by counting two linear meters of two rows twice per experimental plot in order to estimate plant emergence and establishment rates. Foliar nutrient status was recorded at crop phenological stage R1 (bloom initiation). Twenty trifoliate leaves per experiment plot were randomly sampled, including petioles. Samples were put in tagged paper bags and delivered to the laboratory for macro and micronutrient analyses that were carried out according to Embrapa (2014). Plant height (PH) and first pod insertion height (FPIH), and the distances from soil surface to plant apex and to the first pod peduncle, were determined using two random plants per plot at phenological stage R9 (8 February 2019).

At harvest, grain yield (kg ha^{-1}) was determined for each treatment by manual sampling of all plants within a 4 m length from two central lines, twice in each experiment plot. Grain moisture content was determined and yield was adjusted according to the standard commercial moisture content of 13%. Additionally, weight of 1,000 grains was determined as a commercial quality parameter.

Data of each evaluated attribute were subjected to analysis of variance by applying the F test ($P < 0.05$); means were then compared by the Scott-Knott test ($P < 0.05$) using the statistical analysis program Sisvar 5.6 (Ferreira, 2008).

Results and discussion

Fertilization treatments did not affect the phenological course of the soybean crop. At bloom initiation, N and S concentrations in indicative trifoliate leaves were slightly below the Embrapa standard range for soybean (Embrapa, 2014); P and Ca levels were at the lower edge of this range, Mg at its middle, while K concentrations were

Table 3. Macro- and micronutrient concentrations in soybean indicative leaves at bloom initiation as a function of the evaluated fertilization treatments at Rio Verde Foundation, 2019.

Treatment	Macronutrients						Micronutrients				
	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	---------g kg^{-1} DM---------						---------mg kg^{-1} DM---------				
MAP	39.7	3.2	24.2b	6.9	5.3	1.9	29.0	5.1	149.5	27.0	25.6
MAP+KCl	39.2	3.2	26.4a	6.7	5.1	1.8	31.4	5.1	151.9	29.4	25.6
MAP+SSP+KCl	38.5	3.1	25.4a	6.6	5.0	1.8	30.9	6.2	144.6	27.0	25.9
MAP+PES+KCl	39.2	3.1	25.7a	6.4	5.2	1.9	29.3	5.8	149.5	31.9	26.5
MAP+PotashpluS®	39.3	3.0	25.8a	6.6	5.0	2.0	29.7	5.9	144.6	39.2	28.7
NPK 8-40-0+KCl	40.0	3.0	22.5b	6.5	5.1	1.9	28.4	5.5	147.0	29.4	27.2
Mean	39.3	3.1	25.0	6.6	5.1	1.9	29.8	5.6	147.9	30.7	26.6
Covariance	2.82	6.1	6.13	5.2	5.5	5.2	11.2	27.4	9.24	25.4	10.7
Significance	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS
Embrapa std. range	45-55	2.5-5.0	17-25	3.5-20	2.5-10	2-4	20-55	6-14	50-350	20-100	20-50

Means followed by the same letters do not differ from each other. *Significant by the Scott-Knott test ($P < 0.05$).

at the upper edge or above this standard range (Table 3). Although beyond any risk of deficiency, K concentration was significantly lower with the MAP and the NPK+KCl treatments, compared to the other four treatments. While these results could be easily justified for the MAP treatment, which did not included any external K source, the case of the sixth treatment (NPK 8-40-0+KCl) was less clear. The low N concentration in the leaves throughout this experiment may indicate a serious N deficiency that, in consequence, might have restricted the uptake of other nutrients. Closure of this gap may lead to overall improvement of the nutrient status in soybean crops. Under these circumstances, the performance of PotashpluS® as a K-donor to soybean plants was comparable to that of KCl (Table 3).

Among micronutrients examined, Cu concentrations were below the Embrapa standard range, indicating deficiency levels. With the exception of Fe, the remaining micronutrients tended to be at the lower edge of the Embrapa (Table 3), supporting the assumption that crop development may be restricted to some extent if the supply of N is too low.

Plant emergence, as indicated by IPP evaluated at phenological stage V3 (Photo 2) was very slightly affected by the fertilization treatments, showing a tendency to increase in response to improved S and K supply (Table 4). This tendency became significant towards the end of the cropping season, with greater numbers of persisting plants under MAP+SSP+KCl and MAP+PotashpluS® fertilizers (Table 4), suggesting an advantage for SSP and PotashpluS® as sulphate sources. An addition indication of better crop performance was provided by the slight, though insignificant tendency of PH to increase under these two treatments. FPIH varied between treatments, expressing no clear influence by the different fertilizer treatments; however, as all measurements were above 10 cm, the parameter did not affect mechanical harvesting (Table 4).

The small, not always significant, advantages observed in crop development parameters for treatments MAP+SSP+KCl and MAP+PotashpluS® were augmented to establish a significant effect on soybean grain yield (Fig. 2). Although all other treatments supported yields that met the

Photos 2 A-B. Visual appearance of the soybean experiment at phenological stages V3 (A) and R9 (B). While no differences between treatments occurred at V3 stage, slight but significant differences in FPP were recorded at R9 stage (Table 4). Photos by the authors.

Table 4. PH, FPIH, IPP, FPP and grain weight of soybean as a function of the evaluated fertilization treatments at Rio Verde Foundation, 2019.

Treatment	PH	FPIH	IPP	FPP	Grain weight
	-------------cm-------------		-----*1,000 plants ha^{-1}*-----		*g 1,000^{-1} grains*
MAP	68.0	19.6	202.8	188.8b	178.3
MAP+KCl	69.8	16.1	200.7	181.9b	182.6
MAP+SSP+KCl	71.6	18.5	208.3	193.8a	182.7
MAP+PES+KCl	72.6	15.6	209.7	188.0b	185.6
MAP+PotashpluS®	72.0	18.2	204.9	194.8a	185.0
NPK 8-40-0+KCl	74.5	20.9	203.4	190.4b	183.9
Mean	71.4	18.2	205.0	189.6	183.0
COV	5.92	17.5	7.4	3.64	2.22
Significance	NS	NS	NS	*	NS

Means followed by the same letters do not differ from each other. *Significant by the Scott-Knott test ($P < 0.05$).

local common average of 3,500 kg ha^{-1} (Bender *et al.*, 2015), these two treatments obtained a significant yield increase of about 10%. Sulfur supply through fertilizers harboring all nutrients in the form of sulphate, such as SSP and PotashpluS®, demonstrated significantly higher productivity over those comprising a blend of sulphate and mineral S (NPK 8-40-0+S). Moreover, the lowest yields were obtained when S was applied in an elemental form (MAP+PES+KCl) or was not applied at all (Fig. 2). These results confirm that S is essential to obtain reasonable soybean yields, and that the delivery of this nutrient in the elemental form is less effective (Pittelkow *et al.*, 2018).

This is due to the rapid solubility and, hence, availability of the nutrient in the sulphate form, while the elemental form requires a long time to become available to plants (Horowitz and Meurer, 2006). Thus, S application in the mineral form is impractical in most cases, where immediate effects are desired for a current crop.

Partial replacement of KCl by polyhalite, as performed through PotashpluS®, was expected to reduce salinity problems that emerge from high KCl application doses (Bernardi *et al.*, 2018). Nevertheless, no evidence could be observed in the present study regarding such effects. This might have been due to some changes made during the experiment in KCl application practices, such as spreading it over the whole area rather than directly to the sowing line. The anticipation that uptake of Ca and Mg would be enhanced through PotashpluS® application was not fulfilled (Table 3). Whether the yield increase recorded under the PotashpluS® treatment was due to better distribution of the root system in the soil profile requires further research.

Practically, the use of PotashpluS® holds some benefits to large-scale soybean farmers when compared to SSP, even in cases of comparable yields. The soybean-sowing window in the Brazilian Cerrado is quite short, and the farmer's challenge is to make it between mid-October and mid-November. The use of low-concentration P fertilizers requires more frequent refill of the spreading machines, and reduces the planting capacity, thus delaying the operation. Therefore, farmers often sow a considerable proportion of their fields out of the optimum window. Soybean, as a C3 plant species, is sensitive to photoperiod, thus synchronization between day-length and phenological events is crucial for obtaining an acceptable yield (Meotti *et al.*, 2012; Sentelhas *et al.*, 2015). PotashpluS® application is significantly faster than SSP and, therefore, increases the proportion of areas sown on time, leading to a higher yield potential.

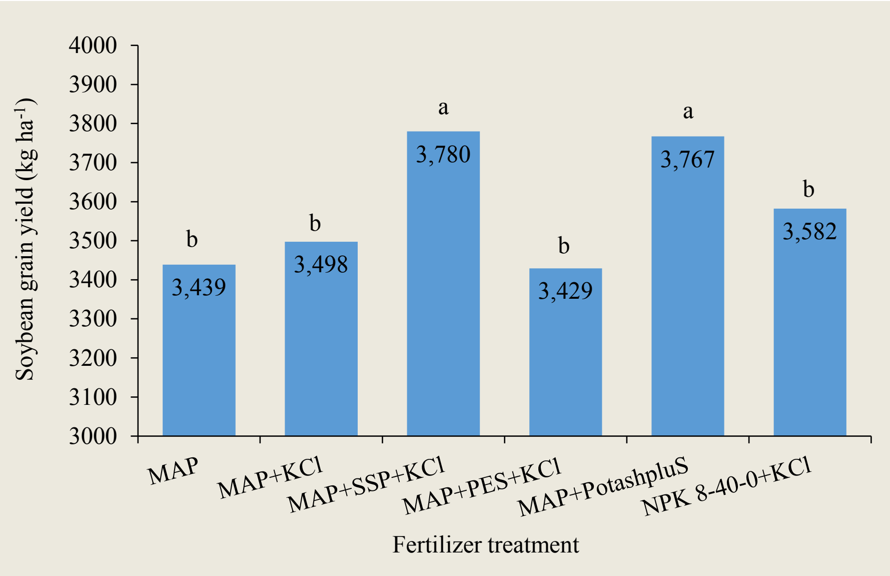


Fig. 2. Effects of fertilizer treatments on soybean grain yield at Rio Verde Foundation, 2019. Means followed by the same letters do not differ from each other.

Conclusions

The competence of PotashpluS®, a granular blend of polyhalite and KCl, to supply all K and S requirements of soybean crop in a single application was examined in Brazil. PotashpluS®, and MAP+SSP+KCl, both comprising sulphate as their sole S source, showed greater response potential and gave rise to significantly higher yields compared with fertilizers, where the partial or total S supply is in the elemental form. PotashpluS®, broadcast pre-planting, was as efficient as SSP applied in the planting furrow. However, the full promise of PotashpluS®, which also contains considerable amounts of the essential nutrients Ca and Mg, remains unclear in the present study, probably due to serious N deficiency. Further research is needed to verify the potential benefits of PotashpluS® for soybean as well as other crop species.

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The paper "Evaluation of Potassium and Sulfur Fertilizers for Soybean in Brazil" also appears on the IPI website.