Research Findings

Brazilian rainfed agriculture in the Cerrado, West Bahia State: No-Tillage production system. Photo by T. Wiendl.

Potassium Fertilizer Application Methods in a Medium Texture Soil in Western Bahia State, Brazil

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Abstract

In recent decades, the Brazilian field crops industry has been expanding into the Cerrado region, which has poor sandy oxisoils. In addition to heavy lime and phosphorus (P) applications, potassium (K) requirements are also difficult to meet. The objectives of this long-term (2005/06-2014/15) study were to assess application methods, timing, and doses of K applied to no-tillage soybean-maize rotation systems, and generate information supporting the establishment of new criteria for K fertilization on light soils in Western Bahia. The results shared here refer to the soybean crop cultivated during the 2014/15 harvest season. The experiment included eight treatments that were applied on plots throughout the nine years, as follows: non-fertilized control; P fertilized control; low, basal K dose; farmers' practice (N-P-K, 2-15-20); high, basal K; high, top-dressed K; high, split K dose;

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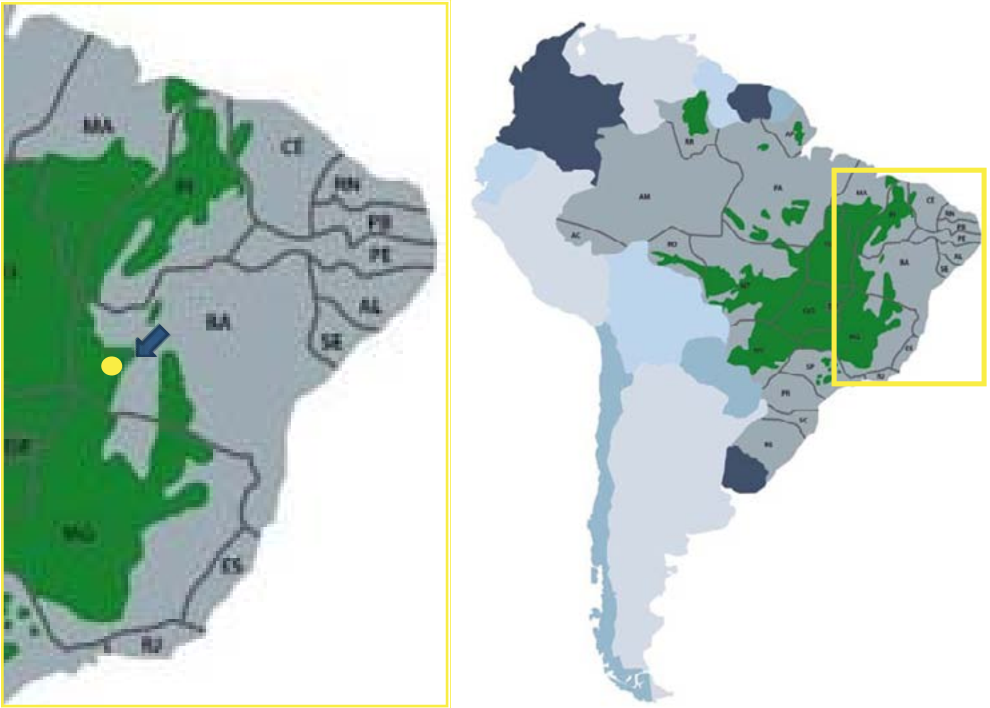
and farmers' practice and additional top-dressed K dose, with seasonal K doses of 0, 0, 60, 83, 120, 120, 120, and 203 kg K_2O ha^{-1}, respectively. All treatments, excluding the non-fertilized control, received a basal P dose of 62.3 (farmers' practices) or 96 kg P_2O_5 ha^{-1}. Soybean yields from the controls varied between 750-900 kg ha^{-1}, whereas K-applied treatments yielded 3,300-3,650 kg ha^{-1}, with no significant differences between application regimes or doses. It is concluded that K supply is essential for sustainable soybean production, as poor sandy oxisoils cannot meet soybean K demands. Degrading straw residues alone fails to support K crop requirements for high yields. When a high K dose was applied as basal, top-dress or split to two applications, K uptake remained constant at 60-70 kg K_2O ha^{-1}, K retrieval from the applied dose was less than 40-45 kg K_2O ha^{-1}, and the rest was wasted. One suggestion is to consider splitting K application when higher doses are used in order to benefit from higher pH, OM and K_2O soil content, and lower Al+H.

Introduction

Brazil's field crops industry is continuously expanding. Rotation of maize (*Zea mays*) and soybeans (*Glycine max* (L.) Merr.) is very common in Brazil, having significant economic importance. During recent decades, maize and soybean production in the Cerrado region has been challenged by poor sandy soils. Most soils of the Cerrado are highly weathered, presenting serious limitations for crop production in terms of low natural soil fertility. These soils are acidic and have low availability of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), molybdenum (Mo) and zinc (Zn). Such soils are also highly saturated in aluminum (Al^{3+}), which makes them toxic to most crop plants (Lopes *et al.*, 2012). Oxisoil (Latossolo Amarelo) and typical sandy soils (Neossolo Quartzarênico) that are predominant in the agricultural region of Western Bahia, in the Cerrado region, are characterized by low fertility and low organic matter (Silva *et al.*, 1994).

In Brazil, sandy and medium texture soils have been increasingly steered to intensive soybean, maize and cotton cropping systems. A major challenge of these production systems is the establishment of an efficient management of fertilizers. Due to its major role in maize and soybean production (Pettigrew, 2008), and its interactions and mobility in the soil profile, K in particular requires special focus. KCl, the most common K fertilizer in Brazilian agriculture, is highly soluble and mobile in Cerrado soils. Therefore, the risk of rapid K leaching and consequent loss of this nutrient below the crop rhizosphere is very high. A factor that is usually perceived to contribute to K loss in cultivated crops in these soils is that most K fertilization is made through basal application of NPK formulations, at sowing. The most common NPK fertilizers employed use the formulations 02-20-18 (50%), 08-20-18 (19%) and 02-23-10 (12%) (COMIGO, 2007). These composite fertilizers are usually applied directly to the furrow, creating a temporary but extremely ion-concentrated environment in the proximity of the germinating seed and young plant. This practice might lead to several undesirable processes and subsequently limit crop development and yield: 1) chloride (Cl^-) toxicity during crop establishment, endangering the initial vegetative stages of the plant (Moraes and Menezes, 2003); 2) inhibited root expansion and a consequent poor ability of the root system to explore the soil profile (Roder *et al.*, 1989); 3) imbalanced cationic ratios (K/Ca and K/Mg) in the soil sorption complex (Muñoz-Hernandez and Silveira, 1998).



Map 1. South America and distribution of the Cerrado region in Brazil (marked in green). Site of the experiment is located near Luis Eduardo Magalhães city, Western Bahia State (marked with yellow circle). *Source:* Adapted from Lopes and Guilherme, 1994. The Brazilian Cerrado is 2.04 million km^2, 23 percent of the total area of Brazil.

Another aspect of K nutrition is the underestimated K availability in soil sampled from no-tillage fields. The straw that remains in the soil after the preceding crop may hold large quantity of nutrients including K, which can be released rapidly into the soil during the first rains (Rosolem *et al.*, 2003; Benites *et al.*, 2010). Since straw K content is often ignored, the fertilizer recommendation may often be overestimated.

This long-term (2005/06-2014/15) study aimed to assess application methods, timing, and doses of K applied to no-tillage soybean maize rotation systems, and generate information supporting the establishment of new criteria for K fertilization on light soils in Western Bahia. The results shared here refer to the soybean crop cultivated during the 2014/15 harvest season.

Material and methods

The experiment was conducted in Alvorada Farm, located in the Luis Eduardo Magalhães city, Western Bahia State, Brazil (Map 1), in the period of 2005/06-2014/15. The climate is classified as Aw (Köppen classification), with a yearly average temperature and rainfall of 24°C and 1,200 mm, respectively. There are two well defined seasons: a rainy season between November and March with 94% of the yearly total rainfall, and a dry season between April and September.

The soil of the experimental area was characterized as Oxisoil (Latossolo Amarelo), with sandy-loam texture at the upper horizon of the soil profile (0-25 cm depth), shifting to sandy clay loam at the deeper horizons (Table 1a). Acidity, which is generally high, increases significantly below 25 cm from soil surface (Table 1b). Most soil fertility parameters, such as cation exchange rate (CEC) (Table 1b) as well as organic matter, N, and P contents (Table 1c) considerably decline below horizons Ap. In fact, the horizon B of the native soil seems too compact, poor, and acidic to support plant roots. The area was cropped in annual rotation with soybeans and maize.

Table 1a. Pre-experiment soil texture and structure at horizons Ap1 to Bw3 of the soil profile.

Horizon	Depth	Soil textural composition (particle size, mm)					Clay dispersed in water	Flocculation	Silt/clay
		Gravel 20-2	Coarse sand 2-0.2	Fine sand 0.2-0.05	Silt 0.05-0.002	Clay <0.002			
	-----*cm*-----	---------*g kg*$^{-1}$---------						---------%---------	
Ap1	0-5	0	422	398	60	120	80	33	0.5
Ap2	6-12	0	432	392	35	141	60	57	0.25
AB	12-25	0	422	382	35	161	120	25	0.22
Bw1	25-50	0	426	341	32	201	60	70	0.16
Bw2	50-65	0	386	322	51	241	0	100	0.21
Bw3	>65	0	372	318	69	241	0	100	0.29

Table 1b. Pre-experiment soil acidity and adsorptive complex characteristics at horizons Ap1 to Bw3 of the soil profile.

Horiz.	pH (1:2.5)		Adsorptive complex							
	Water	KCl 1N	Ca^{2+}	Mg^{2+}	K^+	Na^+	Base satur. (sum)	Al^{3+}	H^+	CEC
			---------*cmol*$_c$ *kg*$^{-1}$---------							
Ap1	6.3	5.3	1.7	1.0	0.13	0.01	2.8	0.1	2.2	5.1
Ap2	6.1	4.9	0.9	0.5	0.17	0.01	1.6	0.1	1.7	3.4
AB	6.1	4.8	0.6	0.5	0.05	0.01	1.2	0	1.8	3.0
Bw1	5.2	4.3	0.6		0.05	0.01	0.7	0.2	1.9	2.8
Bw2	4.7	4.3	0.4		0.02	0.01	0.4	0.3	2.0	2.7
Bw3	5.1	4.6	0.5		0.01	0.01	0.5	0.1	1.7	2.3

Table 1c. Organic carbon, N, and P contents in the pre-experiment soil profile.

Horiz.	Organic carbon	N	C/N	Available P
	---------*g kg*$^{-1}$---------			*mg kg*$^{-1}$
Ap1	9.2	1.0	9	24
Ap2	4.9	0.5	10	9
AB	3.7	0.4	9	1
Bw1	3.3	0.4	8	1
Bw2	3.1	0.3	10	1
Bw3	3.2	0.3	11	1

The experiment was established in the 2005/06 season with soybeans as the first crop of a yearly seasonal rotation with maize. The experiment comprised of eight treatments - fertilization practices - that were consistently preserved in fixed plots throughout the nine years of the trial. These included two controls, a farmers' practice, four practices with differing K dose or application time, and another farmers' practice fortified with an additional late K application. A detailed description of the treatments is given in Table 2.

The experimental design consisted of two blocks, each comprising eight 250 x 18 m plots, with one plot per treatment. Soil sampling was carried out in 2014, right

Table 2. A detailed description of eight fertilization practices (treatments) carried out during the long-term experiment from 2005/6-2014/15. The order of treatments follows an ascending K dose and timing of application.

Treatment	N	P_2O_5	K_2O	Commercial fertilizer	Time of application	Notes
	----------------	*kg ha^{-1}*	----------------			
Pr1	0	0	0			Non-fertilized control
Pr2	0	96	0	SSP 300 STP 100	P - basal	P fertilized control
Pr3	0	96	60	SSP 300 STP 100 KCl 100	P - basal K - top dressing	Low K dose
Pr4	8.3	62.3	83	2-15-20, 415	Basal	Farmers' practice
Pr5	0	96	120	SSP 300 STP 100 KCl 200	P - basal K - basal	High, basal K dose
Pr6	0	96	120	SSP 300 STP 100 KCl 200	P - basal K - top dressing	High, late K dose
Pr7	0	96	120	SSP 300 STP 100 KCl 200	P - basal K - 50% basal, and 50% top dressing	Split K dose
Pr8	8.3	62.3	203	2-15-20, 415 KCl 100	Basal K - top dressing	Farmers' practice and additional K

Note: SSP: single super phosphate; STP: super triple phosphate; 2-15-20: a composite fertilizer comprising of N-P-K (%).

after the last maize harvest. Soil was collected in the internal part of each plot to avoid border effects. Soil samples were from 2.75 m deep trenches dug perpendicularly to the planting lines (Photo 1). The samples were sieved in a 2 mm sieve after being dried in the air. Chemical characteristics were assessed according to Embrapa methodologies (1997).

According the crop rotation, soybean was grown on 2014/15, the last season of the experiment. Plant density was 320,000 per ha^{-1}, with 0.50 m space between rows. Seeds were sown on a no-till system with 'boot opener' at depth of 3-4 cm at the furrow bottom. At harvest, yield was sampled from each experimental plot, harvested from 3 x 5 m random patches (Photo 2), avoiding border effects, at three replications. Grain yield was calibrated to 14% humidity.

Potassium Use Efficiency (KUE) is defined as "the amount of increase in grain yield per unit of fertilizer nutrient applied" (Barber, 1976; Fageria and Baligar, 2001; Fageria and Baligar, 2005). The following formula was employed to calculate KUE:

$$KUE = (GY_F - GY_{NF})/K_{DOSE}$$

Where:
KUE = Potassium use efficiency (kg kg^{-1});
GY_F = treatment grain yield (kg ha^{-1});
GY_{NF} = grain yield of non-fertilized control (kg ha^{-1});
K_{DOSE} = applied K quantity (kg K_2O ha^{-1}).

This calculation is valid for treatments Pr3-Pr8 that were fertilized with K. Pr1 served as the relevant non-fertilized control.

Statistical analyses included the ANOVA F-test (5%) for soybeans grain yield, and T test ($p < 0.05$) to compare the means between treatments. All statistical analyses were performed using the 'Assistat' version 7.7 beta.

Photo 1. Trench opened for soil sampling. Photo by authors.

Photo 2. Overview of harvested soybean from treatment Pr1. Photo by authors.

Results and discussion

Genetic and physiological improvements as well as amended irrigation practices brought about a steady increase in soybeans yields, from less than 500 kg ha^{-1} in 1924 to 8,000 kg ha^{-1} towards the end of the 20th century (Specht *et al.*, 1999; Grassini *et al.*, 2014; Koester *et al.*, 2014). Recent estimations of soybean's potential yield range from 7,000 to 11,000 kg ha^{-1} (van Roekel *et al.*, 2015). This potential is characterized by physiological traits and environmental factors impacting seed number and average mass per seed. However, the realization of soybean's yield potential largely depends on local, often transient conditions, and on agronomic practices. Thus, the USA average soybean yield in 2015 was much smaller than the estimated potential, at about 3,200 kg ha^{-1} (Indexmundi, 2015). In Brazil, the second largest world soybean producer, with a mean yield of 3,000 kg ha^{-1}, soil fertility appears to be the major factor limiting further yield increases.

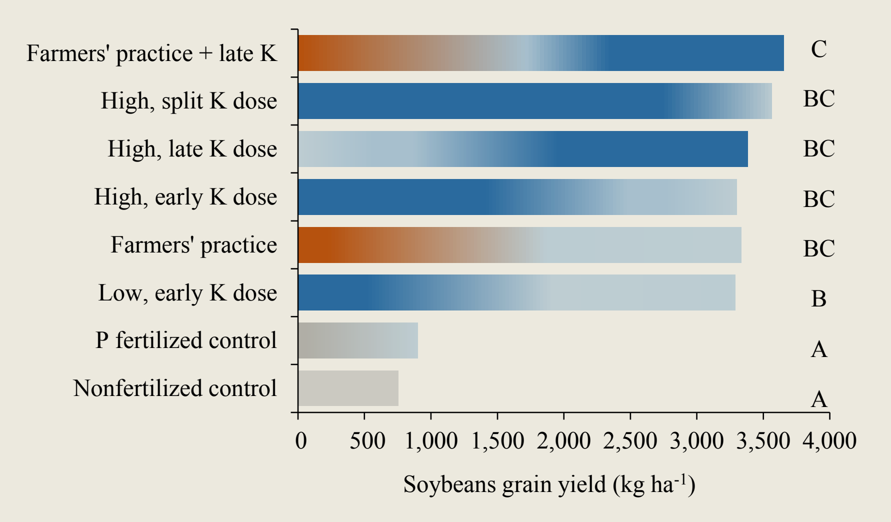


Fig. 1. Soybean grain yield from the 2014/15 harvest season, as affected by the different fertilization regimes. Different letters indicate the statistical difference at p <1% according to the T-test.

In the present study, soil analyses executed after nine years of experiment indicated that the non-fertilized control treatment (Pr1), did not differ significantly from most other treatments, in regard to mineral contents and other assessed characteristics (Table 3). This finding may suggest that this soil can provide very poor nutritional support to crop plants, as the yields obtained by the non-fertilized controls were much lower than those of the fertilized treatments (Fig. 1). Under no fertilization, the poor cropping systems maintain a certain minimum balance with the soil weathering rate, so over-exploiting symptoms do not occur even after nine years. In counterpart, treatments with high fertilizer dose produced significantly higher grain yields (Fig. 1; Photo 3), suggesting complete crop dependence on fertilizer supplies. The effects of the different fertilization regimes on soil fertility parameters are unequivocal (Table 3). However, several

Photo 3. General overview of treatment Pr5 (96 kg P_2O_5 and basal 120 kg K_2O) (left), and treatment Pr2 (96 kg P_2O_5) (right). Photo by authors.

Table 3a. Soil analyses at 0-20 cm depth, following eight years of fixed fertilization regimes: pH, OM, macronutrients, CEC, and base saturation.

Treatment		pH	OM	P	K	Ca	Mg	CEC	S	Base Satur.
			%	------------------$g\ m^{-3}$------------------			--------$cmol_c\ L^{-1}$--------		$g\ m^{-3}$	%
Pr1	Nonfertilized control	4.97	1.72	26.82	22.05	1.65	0.57	4.36	5.07	52.06
Pr2	P fertilized control	5.08	2.03	29.93	21.00	1.47	0.52	3.95	5.55	51.13
Pr3	Low, early K dose	5.27	1.98	30.22	48.23	1.93	0.60	4.47	5.38	59.18
Pr4	Farmers' practice	5.31	1.87	22.22	33.23	2.05	0.73	4.70	6.28	60.47
Pr5	High, early K dose	4.71	1.70	40.47	63.83	1.18	0.48	4.25	4.33	42.68
Pr6	High, late K dose	5.03	1.83	31.03	29.07	1.75	0.58	4.42	5.68	54.19
Pr7	High, split K dose	5.28	2.07	31.70	66.60	1.93	0.63	4.49	5.65	60.45
Pr8	Farmers' practice and late K	4.83	1.60	20.77	23.53	1.50	0.53	4.34	4.92	47.94

Table 3b. Soil micronutrients content at 0-20 cm depth, following eight years of fixed fertilization regimes.

Treatment		Al	H+Al	Zn	B	Cu ³	Fe	Mn
		cmol$_c$ L^{-1}		*g m^{-3}*				
Pr1	Nonfertilized control	0	2.08	1.65	0.24	0.91	61.32	1.35
Pr2	P fertilized control	0	1.92	1.70	0.18	0.89	60.62	1.48
Pr3	Low, early K dose	0	1.82	1.92	0.23	0.92	58.08	1.85
Pr4	Farmers' practice	0	1.83	1.82	0.22	0.90	57.87	1.67
Pr5	High, early K dose	0.12	2.42	1.48	0.12	0.83	62.25	1.25
Pr6	High, late K dose	0	2.02	1.80	0.23	0.94	60.87	1.48
Pr7	High, split K dose	0	1.75	1.87	0.18	0.86	57.15	1.65
Pr8	Farmers' practice and late K	0	2.25	1.40	0.16	0.77	62.02	1.15

trends could be observed. Among the treatments with a high K dose (Pr5-Pr8), the practice of split K application (Pr7) seemed to better preserve soil fertility; values of pH, and organic matter (OM), K, and Ca contents were the highest (Table 3a). Also, the risk of Al toxicity, as indicated by the H+Al value (Table 3b), was the lowest. On the contrary, a single application of a high K dose increased soil acidity, reduced the contents of OM and Ca, reduced base saturation values, and increased the risk of Al toxicity. These phenomenon were not observed with the low K dose treatment (Pr3).

Interestingly, P application did not have any significant influence on soybean grain yield, when applied alone (Fig. 1). On the contrary, substantial yield increases were obtained in response to any K application, compared to the controls (Pr1 and Pr2). Furthermore, while the yield response to the lower K dose (60 kg K_2O ha^{-1}) was dramatic, 337% more than the control, a double dose gave rise to a much smaller further impact.

Illustrating soybean yield response to K application dose (Fig. 2A) shows that between K doses of 60 to 213 kg K_2O ha^{-1}, the marginal grain production of K is extremely poor, 2.56 kg kg^{-1}. This contribution, whether significant, does not justify any K input within this dose range. Moreover, when inputs exceeded 60 kg K_2O ha^{-1}, KUE declined according to a power function (Fig. 2B), also indicating the ineptness of K application at a higher dose under the terms of the present study. However, in spite of the remarkable surge in soybean grain yield in response to 60 kg K_2O ha^{-1}, the yield response function to K dose below that level is obscure. The significant discrepancy between the yield responses to the lower and higher K dose ranges raise possible hypotheses for further research.

According to Liebig's law, plant growth and development would be limited by the least available nutrient. Somewhere below the dose of 60 kg K_2O ha^{-1}, K is obviously the limiting nutrient. Is there another nutrient that might have become restrictive above that K dose? Nitrogen can be excluded from the list of candidates as when supplied as part of the farmers' practice (Pr4 and Pr8) it did not yield any exceptional results. In addition it is widely reported that *Bradyrhizobium spp*, which is associated with the crop roots, is able to provide the necessary N for the crop (Mendes *et al*., 2008; Aratani *et al*., 2008; Embrapa Soja, 2011). Also assuming that the high supplemental P doses applied to treatments Pr2-Pr8 were available and effective, this nutrient does not appear to be a limiting factor. There is no other evidence in the data provided here that could support a hypothesis regarding any macro- or micronutrient other than K, which might limit soybean yield.

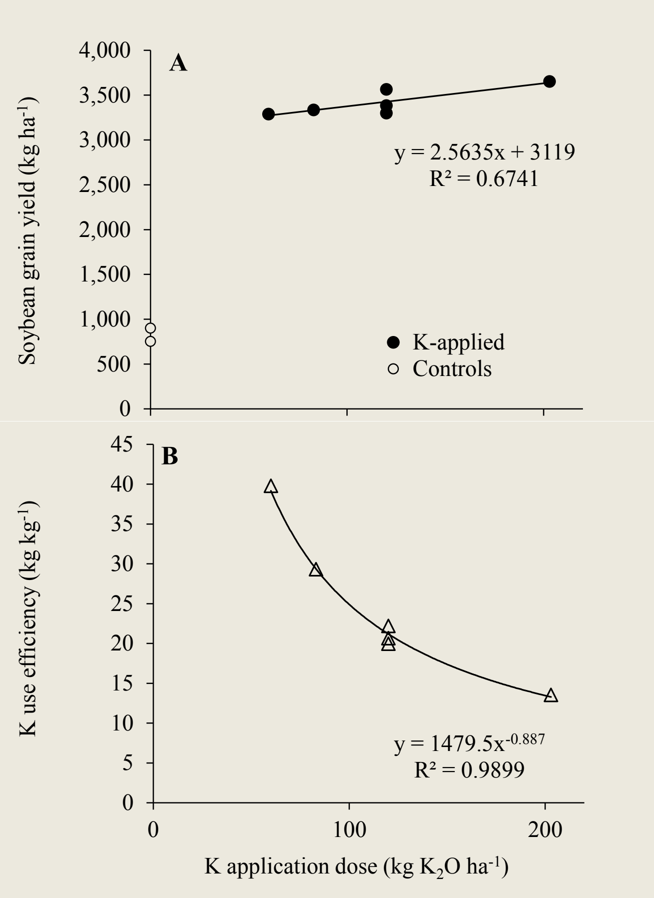


Fig. 2. Soybean yield (A) and KUE (B) as functions of K application dose.

Table 4. Potassium supply vs. uptake by soybean grain yield.

Treatment	K application regime	K application dose	K uptake by soybean grain yield
		---------------------*kg K_2O ha^{-1}*	---------------------
Pr1	Non-fertilized control	0	15.1
Pr2	P fertilized control	0	18.0
Pr3	Low, early K dose	60	65.8
Pr4	Farmers' practice	83	66.7
Pr5	High, early K dose	120	66.0
Pr6	High, late K dose	120	67.7
Pr7	High, split K dose	120	71.3
Pr8	Farmers' practice and late K	203	73.0

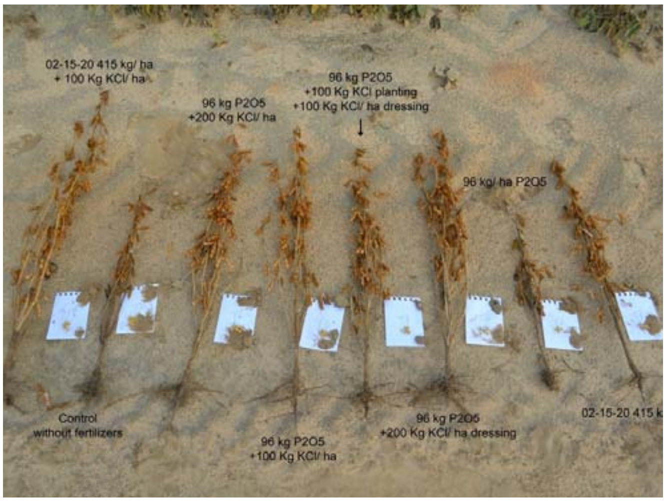


Photo 4. Effects of fertilization practice on plant size and reproductive status, demonstrated by representative plant samples at harvest. Photo by authors.

The idea that K availability might limit soybeans growth, development, and yield, despite the high doses applied, requires further thought. Soybean K demands are functions of plant growth and biomass, but they increase significantly during pod set and grain filling (Pettigrew, 2008). Considering removal of 20 kg K_2O ha^{-1} as verified by Oliveira Jr. *et al.* (2013), while checking K balance in soybean crop, the Cerrado soil was not able to supply more than 15-18 kg K_2O ha^{-1} (Table 4). Indeed, severe K deficiency symptoms were observed in plants of Pr1 and Pr2, such as empty pods, malformed seeds, and green leaves at harvest (Photo 4). As already shown for maize production (Wander *et al.*, 2015), the extremely poor yields obtained under practices lacking K application do not allow for any sustainable long-term production system. Nevertheless, the significant yield increase obtained in response to K application, is unsatisfactory due to the substantial gap from an achievable yield potential, and moreover, the clear inefficiency of K doses above the 60 kg K_2O ha^{-1} threshold to produce further yield increase.

In more fertile soils, with a higher CEC range, a single basal application of the seasonal K dose should establish an adequate K reserve available throughout the season (Clover and Mallarino, 2013; IPI, 2014). Here, when a high K dose was applied as basal, top-dress or split to two applications, K uptake remained constant at 60-70 kg K_2O ha^{-1} (Table 4), some of which may be attributed to nutrients released from straw (Wilhelm *et al.*, 1986; Silva *et al.*, 1994). Thus, K retrieval from the applied dose was less than 40-45 kg K_2O ha^{-1}, and the rest vanished below the rhizosphere. This interpretation suggests that soybean plants grown on sandy acidic soils have a short opportunity to exploit K fertilizer whenever applied, before the latter is leached away by rainfall. Splitting the annual K dose into several applications may provide the crop with more opportunities to utilize the nutrient. This way, root expansion might improve and K retrieval may increase. Additionally, precise nutrient delivery, at the right time and quantity, is more likely to be attained. Thus, it becomes more likely that soybean yield will be significantly more responsive to further K doses. Alternatively, foliar K applications may be considered. This approach was tested experimentally and seemed promising (Garcia and Hanway, 1976) but provided ambiguous results when tested on fertile soils (Poole *et al.*, 1983; Haq and Mallarino, 1998). Yet, foliar nutrient application can be beneficial and deserves careful consideration in soybean grown on poor sandy oxisoils.

Conclusions

Spreading in recent decades from the South States to Southwest Bahia, the successful maize-soybean industry also brought the paradigm that 'fertilization works for any situation'. It has been postulated that a generous application of lime and P is key for success in the region as this worked elsewhere. However, K supply is essential for sustainable soybean production, as the poor sandy oxisoils cannot meet soybean K demands. Degrading straw residues alone fail to support K crop requirements for high yields. When a high K dose was applied as basal, top-dress or split to two applications, K uptake remained constant at 60-70 kg K_2O ha^{-1}, K retrieval from the applied dose was less than 40-45 kg K_2O ha^{-1}, and the rest was wasted. One suggestion is to consider splitting the K application when higher doses are used in order to benefit from higher pH, OM and K_2O soil content, and lower Al+H.

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