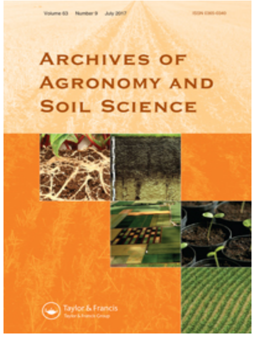

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Differential response of soybean genotypes to two lime rates

Adônis Moreira[a], Larissa Alexandra Cardoso Moraes[a], Isabelle Cristina Vilarino Lara[a] and Thiago Assis Rodrigues Nogueira[b]

[a]Department of Soil Science and Mineral Plant Nutrition, National Soybean Research Center of EMBRAPA, Londrina, Brazil; [b]Department of Soils and Environmental Resources, São Paulo State University, Botucatu, Brazil

ABSTRACT

Soybean [*Glycine max* (L.) Merril] is the leading food crop worldwide, and selection of soybean genotypes for different levels of soil acidity may raise crop yield without the need to increase in planted area. An experiment in greenhouse conditions was conducted to determine the effects of two lime rates on soil chemical properties, grain yield (GY), yield components, nutritional status and physiological components of 15 soybean genotypes adapted to tropical and subtropical conditions. Genotypes BMX Apolo RR, BMX Potência RR, BRS 295RR, BRS 359RR, FPS Solar IPRO and TMG 716 IRR were the least responsive to soil acidity reduction, and BMX Turbo RR and BRS 360RR were the most responsive. Number of pods per pot, shoot dry weight yield, GY, photosynthesis, stomatal conductance, transpiration and chlorophyll increased significantly with increase in lime rate. Cultivar FPS Solar IPRO showed the highest foliar P, K, Ca and Mg concentrations in soybean, which was not observed in the grain, indicating the presence of genetic factors and the dilution effect on nutrient uptake.

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KEYWORDS
Glycine max; soil acidity; grain yield; physiological components; yield components

Introduction

Soybean is Brazil's most important agricultural export product, with production of 95.6 million tons in the 2015/2016 season (CONAB 2016). This increase is mostly due to the high prices of the product in the international market, which resulted in expansion of cultivated areas, including sandy soils with lower fertility and degraded pastures, where soil acidity is a limiting factor in plant development because it restricts root growth and inhibits water and nutrient uptake (Fageria & Baligar 2008; Moreira & Fageria 2010).

Soil acidity is one major factor limiting nutrient availability and uptake (Fageria & Baligar 2001). In Brazil, especially in the center region where agricultural expansion was more pronounced, soils are mostly of low fertility, with pH values lower than 4.5, high aluminum (Al^{3+}) concentrations, high phosphorus (P) fixation capacity and potential acidity (H^{+} + Al^{3+}) predominant in the cation exchange capacity (CEC) in soil solution (Fageria & Baligar 2008; Moreira et al. 2015a).

Liming is the most widely used practice to neutralize acidity, increase nutrient availability, supply calcium (Ca^{2+}) and/or magnesium (Mg^{2+}), neutralize toxic Al^{3+}, manganese (Mn^{2+}) and hydrogen (H^{+}), improve root environment and restore soil productive capacity (Kamprath 1984; Soratto & Crusciol 2008). The amount of lime to be used depends on the soil type (clay content), quality, cost of material, species and/or genotype (Moreira & Fageria 2010). Concomitantly, exploration of genetic yield potential of plants can also be used in plant breeding programs in order to

CONTACT Adônis Moreira adonis.moreira@embrapa.br Department of Soil Science and Mineral Plant Nutrition, National Soybean Research Center of EMBRAPA, Londrina, Brazil

Table 1. Description of fifteen genotype used in the experiment.

Genotype	Characteristic	Growing habit	Maturation group	Cycle
BMX Apolo RR	Transgenic	Indeterminate	5.5	Super early
BMX Força RR	Transgenic	Indeterminate	6.2	Early
BMX Potência RR	Transgenic	Indeterminate	6.7	Semi-early
BMX Turbo RR	Transgenic	Indeterminate	5.8	Super early
BRS 294RR	Transgenic	Determinate	6.3	Early
BRS 295RR	Transgenic	Indeterminate	6.5	Early
BRS 359RR	Transgenic	Indeterminate	6.5	Early
BRS 360RR	Transgenic	Indeterminate	6.5	Early
NA 5909RR	Transgenic	Indeterminate	6.7	Semi-early
NA 6262RR	Transgenic	Indeterminate	6.4	Early
FTS Solar IPRO	Transgenic	Indeterminate	5.8	Super early
TMG 1066RR	Transgenic	Determinate	6.6	Semi-early
TMG 7161RR	Transgenic	Indeterminate	6.1	Early
TMG 7262RR	Transgenic	Indeterminate	6.2	Early
V_{max} RR	Transgenic	Indeterminate	6.4	Early

incorporate desirable traits in varieties susceptible to these limitations. In addition to ensure the appropriate management of chemical and biological soil properties, focus should be given to their recovery and conditioning of high-yielding cultivars under adverse conditions (Fageria & Morais 1987).

The hypothesis of the present study was that genotypes respond differently to the lime rates. Its purpose was to assess the behavior of different soybean genotypes, recommended for tropical and subtropical conditions, subjected to two lime rates on grain yield (GY), soil chemical properties, nutritional status, yield components and physiological components of the plant.

Material and methods

Site and soil characteristics

The experiment was conducted in greenhouse conditions at the Embrapa Soja, Londrina County, Paraná State, Brazil (23°11′39″LS and 51°10′40″LW) to evaluate the development of tropical and subtropical soybean genotypes submitted to different soil acidity rates. The soil used was Typic Quartzipsamment, with sandy texture (142 g kg^{-1} clay and 841 g kg^{-1} sand), collected from 0 to 20 cm depth in the Luis Eduardo Magalhães County, Bahia State, Brazil (20°45′04″LS and 51°40′42″LW), with the following soil chemical properties (EMBRAPA 1997) before treatments application: pH (H_2O) = 3.9, organic matter (OM) = 9.3 g kg^{-1}, P (Mehlich 1 extractant) = 1.0 mg kg^{-1}, exchangeable potassium (K^+) = 0.02 cmol$_c$ kg^{-1}, exchangeable Ca^{2+} = 0.07 cmol$_c$ kg^{-1}, exchangeable Mg^{2+} = 0.05 cmol$_c$ kg^{-1}, exchangeable Al^{3+} (KCl 1.0 mol L^{-1} extractant) = 0.7 cmol$_c$ kg^{-1}, potential acidity (H^+ + Al^{3+}) = 3.4 cmol$_c$ kg^{-1}, sulfur (S–SO_4^{2-}) = 5.8 mg kg^{-1}, CEC (∑K^+, Ca^{2+}, Mg^{2+}, H^+ + Al^{3+}) = 3.5 cmol$_c$ kg^{-1}, effective CEC – CECE = (∑K^+, Ca^{2+}, Mg^{2+}, Al^{3+}) = 0.84 cmol$_c$ kg^{-1}, base saturation – V [(∑K^+, Ca^{2+}, Mg^{2+}/CEC) × 100] = 4.1%, available boron – B (hot water) = 0.13 mg kg^{-1}, available copper – Cu (Mehlich 1) = 0.1 mg kg^{-1}, available iron – Fe (Mehlich 1) = 59.0 mg kg^{-1}, available manganese – Mn (Mehlich 1) = 0.3 mg kg^{-1} and available zinc – Zn (Mehlich 1) = 0.2 mg kg^{-1}.

Experimental design, fertilization and planting

Completely randomized design in 15 × 2 factorial arrangement of treatments, with four replicates, was used. The treatments consisted of 15 genotypes (Table 1) and 2 liming rates with calcium oxide (CaO) 27.8%, magnesium oxide (MgO) 19.6% MgO and reactive power to completely neutralize (RPCN) 85.5%. The rates were calculated to raise soil base saturation to 40% and 70% – equivalent to 1.5 and 2.7 t ha^{-1}, and defined as low and high lime rates application, according to the following formula:

$$LQ\left(\text{kg ha}^{-1}\right) = \frac{(V_2 - V_1)}{\text{RPCN}} \times \text{CEC}$$

where LQ is amount of lime (kg ha^{-1}), V_2 (desired base saturation) is 40% (high acidity) or 70% (low acidity), V_1 (base saturation found in soil) is 4.1%, RPCN is 85.5% and CEC is 3.5 cmol$_c$ kg^{-1}.

The experiment clay pots with 3.0 dm^3 of soil passed through a 2.0-mm sieve were used. Except for N, which was supplied by inoculation of seeds with *Bradyrhizobium elkanii* + *Bradyrhizobium japonicum*, fertilizations with P, K, S, B, Co, Cu, Fe, Mn, molybdenum (Mo), nickel (Ni) and Zn were performed according to Moreira and Fageria (2010) adapted from Allen et al. (1976) for experiments conducted in greenhouse condition [150 mg kg^{-1} of P – monoammonium phosphate, 50 mg Ca kg^{-1} – calcium sulfate ($CaSO_4$), 0.5 mg B kg^{-1} boric acid (H_3BO_3), 1.5 mg Cu kg^{-1} – copper sulfate ($CuSO_4{\cdot}7H_2O$), 0.1 mg Mo kg^{-1} – sodium molybdate ($Na_2Mo_4{\cdot}2H_2O$), 2.5 mg Fe kg^{-1} – iron sulfate ($FeSO_4{\cdot}2H_2O$), 0.01 mg Co kg^{-1} – cobalt chloride ($CoCl_2$), 0.01 mg Ni kg^{-1} – nickel sulfate ($NiSO_4{\cdot}6H_2O$), 5.0 mg Mn kg^{-1} – manganese sulfate ($MnSO_4{\cdot}3H_2O$), and 5.0 mg Zn kg^{-1} – zinc sulfate ($ZnSO_4{\cdot}7H_2O$)]. In V2 and V4 growth stages, top-dressing fertilizations were made twice with 50 mg K kg^{-1} (K_2SO_4), totaling 100 mg K kg^{-1} in the cycle. The pots were daily irrigated with deionized water to compensate for losses by evapotranspiration and maintain moisture content around 70% of total pore volume, using the method described by Cassel and Nielsen (1986). Ten seeds were sown, and after trimming, there were two plants per pot.

Harvest and laboratory analysis

At R2 reproductive stage (Fehr et al. 1971), in the morning, the following measurements were made from the third–fourth leaf pair from the apex: photosynthetic rate, A (μmol CO_2 m^{-2} s^{-1}), stomatal conductance, g_s (mol H_2O m^{-2} s^{-1}), transpiration, Tr_{mmol} (mmol H_2O m^{-2} s^{-1}), internal carbon dioxide concentration, C_i (μmol CO_2 mol^{-1}) and intrinsic water use efficiency [IWUE] = A/Tr_{mmol} (μmol CO_2 m^{-2} s^{-1}) was determined with a portable photosynthesis analyzer (LI-6400XT; LICOR®, Lincoln, NE). At this stage, Konica Minolta SPAD-502 Plus was used for the measurement of the SPAD units of these leaves. The SPAD data were converted into chlorophyll content (mg cm^{-2}) using the equation $\hat{y} = 16.033 + (7.5774 \times \text{SPAD})$ (Fritschi & Ray 2007). After the measurements, the same trifoliates were collected from the apex (diagnostic leaf) of each treatment and dried in forced circulation at 65 ± 2°C for determination of total N, P, K, Ca, Mg and S concentrations (Malavolta et al. 1997).

Throughout the vegetative cycle, foliar senescent for the shoot dry weight yield (SDWY) was collected. After the physiological maturity stage (R8), GY, number of pods per pot (NPP), number of grain per pot (NGP) and number of pods were quantified. Again, the total N, P, K, Ca, Mg and S concentrations in grain were determined. After collection, soil sample of each pot was removed for determination of soil chemical properties (pH, OM, P, K^+, Ca^{2+}, Mg^{2+}, H^+ + Al^{3+}, Al^{3+} and CEC), according to the methodologies described by EMBRAPA (1997). Relative yield (RY) of the genotypes was determined with the following equation:

$$\text{RY}\,(\%) = \frac{W}{W_1} \times 100$$

where W is GY in treatment V = 40% (high acidity) for each variety and W_1 is GY in treatment V = 70% (low acidity) for each variety.

Statistical analyses

The results for soil chemical properties, yield and physiological components and nutritional status were subjected to normality tests (Hicks 1973), and subsequently to analysis of variance, F test and Scott–Knott test for multiple comparison of means (Scott & Knott 1974), at 5% of probability.

Result and discussion

Soil chemical properties

Significant effect was reported for rates and genotypes and lack of interaction of these two factors on soil chemical properties after soybean harvest (Table 2). Regardless of the genotypes, increased lime rate provided a significant increase (23.2%) in pH values, while regarding the genotypes, BMX Apolo RR, NA 6262RR and TMG 7262RR caused the least statistically significant soil acidity (Table 2). Such results corroborate other studies (Castro & Crusciol 2013; Fageria et al. 2012; Moreira et al. 2014, 2015b), by demonstrating that lime in contact with soil moisture produces the following consequences: increased Ca^{2+} and Mg^{2+} levels, dissociation of (OH^-) hydroxyl groups and reduction of H^+ ions in soil solution and consequent rise in pH value.

Similarly to what was observed by Moreira et al. (2014) in soybean growing, increased lime rates generated a significant increase in exchangeable Ca^{2+} and Mg^{2+} and in CEC, as well as decrease in exchangeable Al^{3+}, K^+ and $H^+ + Al^{3+}$ of soil (Table 2). Regarding the genotypes, only the exchangeable Ca^{2+} and Mg^{2+} levels were significant, and Mg^{2+} showed genotype × lime rates interaction, indicating that the genotypes responded differently to the two lime rates (Table 2). The lowest nutrient concentrations in the soil were reported in genotypes BMX Potência RR (0.2 $cmol_c\ kg^{-1}$) in V = 40% and in genotype V_{max} RR (0.4 $cmol_c\ kg^{-1}$) in V% = 70, while the highest rate was NA 6262RR (0.3 $cmol_c\ kg^{-1}$) and TMG 7161RR (0.7 $cmol_c\ kg^{-1}$). The referred increase in Ca^{2+} and Mg^{2+} soil concentrations was expected because the dolomite lime used has 27.8% of CaO and 19.6% of Mg in its composition. Moreira and Fageria (2010) and Castro and Crusciol (2013) reported a significant increase in the levels of these nutrients after lime application.

Among the genotypes, Ca^{2+}/K^+ and Mg^{2+}/K^+ ratios increased from 1.4 to 3.2, and from 0.6 to 1.6, and Ca^{2+} and Mg^{2+} saturations in CEC from 14.9% to 25.3% and 6.8% to 8.0% with increased concentration of Ca^{2+} and Mg^{2+} in the soil, as a result of the higher lime rate used to raise base saturation from 40% to 70%. Fageria et al. (2013, 2014) and Moreira et al. (2015a) reported similar results regarding the increase of these variables after application of larger lime rates. Regardless of the rates and genotypes, Ca^{2+} and Mg^{2+} base saturations in the CEC were below 65–85% and 10–20%, while K^+ saturation in CEC was above 2–5% reported by Eckert (1987) as an adequate balance of these ions in soil CEC allowing the plants to express their potential yield.

GY and yield components

Genotypes and lime rates showed significant interaction for GY, NPP and SDWY, indicating that the genotypes responded differently to each lime rate used (Table 3). GY ranged from 10.9 g pot^{-1} (BRS 360RR) to 19.1 g pot^{-1} (BMX Potência RR), at lowest rate (V = 40%), with a mean value of 15.5 g pot^{-1}. At higher lime rate (V = 70%), SY varied from 16.1 g pot^{-1} (BMX Força RR) to 22.9 g pot^{-1} (BMX Turbo RR), with a mean value of 20.3 g pot^{-1}. In the mean of genotypes, increase in the lime rate applied resulted in an increase of 31.1% in GY. This was also observed for SDWY, which had a positive significant correlation with GY ($\hat{y} = 10.482 + 0.171x$, $r = 0.51$, $p \leq 0.05$), and ranged from 23.2 g pot^{-1} (TMG 7161RR) to 48.4 g pot^{-1} (BRS 294RR) and 37.5 g pot^{-1} (NA 6262RR) to 62.1 g pot^{-1} (BMX Força RR) at low (V = 40%) and high (V = 70%) lime rates (Table 3). Moreira et al. (2015b) reported that soybean genotypes adapted to tropical and subtropical conditions showed different responses of growth for SDWY and GY, which has been stressed by RY, since genotype BRS 360RR was the most sensitive (58.7%) and NA 5909RR the least sensitive (88.8%) to soil acidity. Among the genotypes, the average RY value was 74.6% (Table 3).

Corroborating Fageria et al. (2014), NPP showed a significant correlation with GY ($\hat{y} = 5.163 + 2.610x$, $r = 0.52$, $p \leq 0.05$) and was also significantly increased with lime rate, which has not been reported for the mean NGP, regardless of the genotype and lime rate used (Table 3). Fageria et al. (2014) reported that decrease in soil acidity significantly increased NPP (Table 2),

Table 2. Soil chemical properties after soybean harvest cultivated with two lime rates [low-base saturation of 40% (1.49 t ha^{-1} of lime) and high of 70% (2.73 t ha^{-1} of lime)] application.[a]

	pH		P		K		Ca		Mg		Al		H^+ + Al		CEC	
	($CaCl_2$)		(mg kg^{-1})		($cmol_c$ kg^{-1})		($cmol_c$ kg^{-1})		($cmol_c$ kg^{-1})		($cmol_c$ kg^{-1})		($cmol_c$ kg^{-1})		($cmol_c$ kg^{-1})	
Genotype	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
BMX Apolo RR	4.3a	5.5a	40.1a	43.7a	0.33a	0.33a	0.6a	0.9a	0.3a	0.5a	0.22a	0.00a	2.7a	2.0a	3.94a	3.92a
BMX Força RR	4.3a	5.3b	38.1a	32.8a	0.47a	0.37a	0.6a	0.9a	0.3a	0.4b	0.18a	0.02a	2.5a	2.1a	3.83a	3.86a
BMX Potência RR	4.2a	5.3b	40.6a	41.6a	0.47a	0.30a	0.5b	1.0a	0.2b	0.5b	0.29a	0.01a	2.7a	1.9a	3.79a	3.69a
BMX Turbo RR	4.3a	5.5b	44.4a	36.9a	0.47a	0.30a	0.6a	1.0a	0.3a	0.6a	0.22a	0.00a	2.5a	1.9a	3.86a	3.79a
BRS 294RR	4.2a	5.3b	39.6a	33.0a	0.43a	0.37a	0.5b	1.0a	0.2b	0.5b	0.27a	0.03a	2.5a	2.0a	3.68a	3.88a
BRS 295RR	4.4a	5.1b	36.6a	33.4a	0.33a	0.37a	0.6a	0.8b	0.3a	0.4b	0.17a	0.04a	2.5a	2.4a	3.65a	3.99a
BRS 359RR	4.2a	5.2b	46.6a	35.6a	0.40a	0.40a	0.6a	1.0a	0.3a	0.4b	0.25a	0.03a	2.4a	2.3a	3.81a	3.93a
BRS 360RR	4.3a	5.3b	36.7a	43.3a	0.37a	0.27a	0.6a	1.1a	0.2a	0.4b	0.21a	0.03a	2.5a	2.2a	3.70a	3.98a
NA 5909RR	4.3a	5.3b	43.1a	38.4a	0.33a	0.23a	0.6a	1.1a	0.3a	0.5b	0.21a	0.03a	2.6a	2.2a	3.75a	3.98a
NA 6262RR	4.4a	5.6a	47.0a	44.2a	0.40a	0.30a	0.6a	1.1a	0.3a	0.7a	0.15a	0.00a	2.3a	1.8a	3.68a	3.85a
FTS Solar IPRO	4.2a	5.3b	41.0a	36.1a	0.37a	0.23a	0.5a	0.9a	0.3a	0.5b	0.24a	0.05a	2.7a	2.2a	3.88a	3.84a
TMG 1066RR	4.2a	5.3b	43.4a	36.6a	0.53a	0.33a	0.5a	1.0a	0.2b	0.5a	0.29a	0.02a	2.7a	2.1a	4.03a	4.04a
TMG 7161RR	4.4a	5.4b	47.3a	49.7a	0.52a	0.30a	0.6a	1.1a	0.3a	0.7a	0.17a	0.00a	2.5a	2.1a	3.97a	4.10a
TMG 7262RR	4.4a	5.5a	51.5a	41.5a	0.48a	0.27a	0.6a	1.1a	0.3a	0.6a	0.17a	0.00a	2.5a	1.9a	3.94a	3.91a
V_{max} RR	4.2a	5.1b	48.8a	41.6a	0.43a	0.30a	0.5a	0.9	0.3a	0.4b	0.26a	0.05a	2.7a	2.3a	3.88a	3.92a
Mean	4.3B	5.3A	43.0A	39.2A	0.42A	0.31B	0.6B	1.0A	0.3B	0.5A	0.22A	0.02B	2.6A	2.1B	3.83B	3.91A
F test																
Genotype	2.501*		0.995^{NS}		0.699^{NS}		2.388*		5.305*		1.408^{NS}		1.702^{NS}		1.238^{NS}	
Rates	223.194*		0.905^{NS}		16.722*		601.501*		354.01*		231.125*		124.541*		4.610*	
Genotype × rates	1.351^{NS}		0.954^{NS}		0.552^{NS}		1.823^{NS}		2.771*		1.376^{NS}		1.187^{NS}		0.752^{NS}	
CV (%)	3.01		27.98		28.15		10.33		16.25		38.26		8.54		4.91	

*,[NS]Significant at the 5% probability level and not significant, respectively.

[a]Values followed by similar lowercase letters in the same column and uppercase letter in the same line within the same variables are not significantly different at $p \leq 0.05$ by Scott–Knott test. Low-base saturation (V) = 40%. High-base saturation (V) = 70%. CV: Coefficient of variation.

Table 3. Grain yield (GY), number grain per pod (NGP), number of pods per pot (NPP), shoot dry weight yield (SDWY) and relative yield (RY) of 15 cultivars at 2 lime rates [low-base saturation of 40% (1.49 t ha^{-1} of lime) and high of 70% (2.73 t ha^{-1} of lime)] application.[a]

	Grain yield (g pot^{-1})		Grain per pod (*n*)		Number of pods (*n*)		SDWY (g)		
Genotype	Low	High	Low	High	Low	High	Low	High	RY (%)
BMX Apolo RR	17.3a	20.2a	2a	2a	41b	43c	30.2c	40.2b	85.7
BMX Força RR	12.2b	16.1b	2a	2a	27c	53b	34.9b	62.1a	75.6
BMX Potência RR	19.1a	22.6a	2a	2a	51a	52b	42.8a	54.6b	84.8
BMX Turbo RR	13.4b	22.9a	2a	2a	30c	61b	28.7c	43.4c	58.8
BRS 294RR	14.7b	17.5b	2a	2a	61a	80a	48.4a	59.6a	84.0
BRS 295RR	13.3b	20.6a	2a	2a	59a	81a	36.7a	59.3a	64.5
BRS 359RR	17.1a	21.1a	2a	2a	49a	71a	41.1a	52.4b	81.1
BRS 360RR	10.9b	18.5b	2a	2a	36b	44c	38.5a	47.9b	58.7
NA 5909RR	18.2a	20.5a	2a	2a	50a	51b	38.8a	50.8b	88.8
NA 6262RR	14.5b	20.1a	2a	2a	39b	47c	30.2c	37.5c	72.1
FTS Solar IPRO	17.1a	19.8a	2a	2a	41b	72a	35.7b	48.4b	86.4
TMG 1066RR	18.0a	21.2a	2a	2a	44b	78a	45.1a	52.7b	85.1
TMG 7161RR	14.6b	21.2a	2a	2a	24c	55b	23.2c	38.4c	68.9
TMG 7262RR	15.7a	20.4a	2a	2a	35b	42c	34.8b	39.8c	76.8
V_{max} RR	15.6a	21.0a	2a	2a	39b	78a	41.2a	55.8a	74.0
Mean	15.5B	20.3A	2A	2A	42B	52A	36.7B	49.5A	74.6
F test									
Genotype	4.799*		1.438^{NS}		17.404*		14.279*		
Rates	127.646*		1.721^{NS}		167.627*		185.125*		
Genotype × rates	2.696*		0.923^{NS}		6.017*		2.456*		
CV (%)	11.29		9.49		14.11		10.39		

*,[NS]Significant at the 5% probability level and not significant, respectively.

[a]Values followed by similar lowercase letters in the same column and uppercase letter in the same line within the same variables are not significantly different at $p \leq 0.05$ by Scott–Knott test. Low-base saturation (V) = 40%. High-base saturation (V) = 70%. CV: Coefficient of variation.

while NGP is more related to genetic characteristics of each genotype. Among the genotypes, the highest NPP level in the two lime rates (V = 40% and 70%) was observed in genotype BRS 295RR, and in the mean of genotypes, it was 47.6% higher for the higher lime applied (Table 3). Lime is an important source of Ca and Mg, improves root environment and biological N fixation (Moreira & Fageria 2010), which are directly related to GY.

Leaf and grain nutrient concentration

Leaf N, K, Ca, Mg and S concentrations were significantly influenced by increase in lime rates and genotype variety, with genotype × rates interaction observed for N and S concentrations and different responses only regarding P concentration (Table 4). Regardless of the treatments, leaf N, K and S concentrations were below 45.0–55.0 g N kg^{-1}, 17.0–25.0 g K kg^{-1} and 2.0–2.5 g S kg^{-1}, while leaf P, Ca and Mg concentrations were within the ranges of 2.6–5.0 g P kg^{-1}, 4.0–20.0 g Ca kg^{-1} and 3.0–10.0 g Mg kg^{-1} recommended as suitable for soybean crop (Malavolta et al. 1997; TPS 2013). Increase in lime rate increased leaf N, K, Mg, S, Mg and S concentrations by 39.2%, 10.2%, 35.5%, 27.2% and 19.7%, respectively, compared to the lower lime application. Fageria (2008) reported that in soils with higher acidity, the plants have visual symptoms of N deficiency, which was not observed in the present study. Among the genotypes, except for N and S, Intact RR2 technology (FPS Solar IPRO) soybean showed the highest leaf P, K, Ca and Mg concentrations compared to the genotypes with gene RR1 (Table 4). Regarding P, the lack of lime effect, this nutrient concentration on the leaves and increase in the soil exchangeable Ca^{2+} concentration was also reported by Key et al. (1962) and Moreira et al. (2015a). Increase in pH value from 3.9 to 4.3 and 3.9 to 5.3, respectively, with the low and high lime application (Table 2), was possibly not sufficient to change P

Table 4. Macronutrients (N, P, K, Ca, Mg and S) concentration in leaves (3rd and 4th) of soybeans at R2 growth stage, depending on the two lime rates [low-base saturation of 40% (1.49 t ha^{-1} of lime) and high of 70% (2.73 t ha^{-1} of lime)] application.[a]

	N (g kg^{-1})		P (g kg^{-1})		K (g kg^{-1})		Ca (g kg^{-1})		Mg (g kg^{-1})		S (g kg^{-1})	
Genotype	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
BMX Apolo RR	18.9b	26.7a	4.8b	4.5b	13.3a	14.7a	6.4b	8.9b	3.5a	4.0b	1.3b	1.8a
BMX Força RR	15.5b	22.8a	4.4b	5.7b	10.7b	11.8a	5.8b	8.2b	3.2a	3.8b	1.1b	1.2b
BMX Potência RR	18.1b	29.2a	5.1a	4.6b	11.3b	15.0a	6.8a	5.6b	3.3a	4.3a	1.2b	1.3b
BMX Turbo RR	24.2a	24.2a	5.8a	5.4a	13.9a	12.0a	6.9a	9.1b	3.4a	4.4a	2.3a	1.4b
BRS 294RR	17.8b	21.6b	5.6a	4.8b	12.0b	14.2a	7.8a	8.9b	3.6a	4.3a	1.4b	1.4b
BRS 295RR	15.5b	16.1b	5.8a	6.0a	14.9a	13.2a	5.4b	8.4b	3.2a	4.2a	1.2b	1.2b
BRS 359RR	14.5b	24.2a	5.7a	4.9b	13.5a	12.9a	5.5b	7.5b	2.7a	3.7b	1.2b	1.3b
BRS 360RR	15.0b	20.8b	4.1b	3.7b	12.3b	13.7a	5.8b	7.9b	2.3b	3.1c	1.1b	1.2b
NA 5909RR	14.2b	23.7a	3.9b	4.1b	12.2b	12.4a	6.2b	7.5b	3.0b	3.7b	0.9b	1.3b
NA 6262RR	14.6b	22.6a	5.3a	4.7b	12.2b	14.0a	5.8b	7.3b	2.9b	3.4c	1.2b	1.3b
FTS Solar IPRO	17.2b	23.4a	5.9a	6.7a	14.7a	16.9a	8.0a	13.1a	3.8a	4.8a	1.2b	1.5a
TMG 1066RR	18.2b	21.9b	4.3b	4.8b	11.5b	14.6a	5.5b	7.4b	2.8b	3.3c	1.1b	1.1b
TMG 7161RR	14.3b	23.5a	4.8b	4.1b	13.9a	14.5a	4.6b	7.7b	2.8b	3.7b	1.2b	1.3b
TMG 7262RR	21.6a	28.7a	4.6b	4.7b	10.7b	13.7a	5.4b	8.6b	3.1b	4.6a	1.1b	1.9a
V_{max} RR	15.5b	25.6a	4.4b	4.2b	12.3b	15.4a	5.8b	8.3b	2.9b	3.7b	1.2b	1.6a
Mean	17.0B	23.7A	5.0A	4.9A	12.6B	13.9A	6.1B	8.3A	3.1B	3.9A	1.2B	1.4A
F Test												
Genotype	2.296*		4.934*		3.768*		9.779*		11.263*		5.401*	
Rates	66.812*		1.382^{NS}		11.347*		173.284*		169.537*		21.012*	
Genotype × rates	2.933*		0.625^{NS}		1.646^{NS}		1.923^{NS}		1.271^{NS}		5.284*	
CV (%)	17.58		16.89		13.45		11.71		8.63		15.34	

*,^{NS}Significant at the 5% probability level and not significant, respectively.

[a]Values followed by similar lowercase letters in the same column and uppercase letter in the same line within the same variables are not significantly different at $p \leq 0.05$ by Scott–Knott test. Low-base saturation (V) = 40%. High-base saturation (V) = 70%. CV: Coefficient of variation.

uptake by the plants, and consequently, the leaf P concentration was not affected regardless of the genotypes.

Potassium, Ca, Mg and S concentrations in soybean grain (SG) were significantly influenced by the genotypes, and K, Ca and S concentrations were influenced by lime rates, with genotypes × rates interaction reported only for Ca concentration (Table 5). Ca concentration in SG increased with the higher lime rate application (V = 70%) compared to the lower rate (V = 40%), and the opposite was observed for K and S. In turn, N, P and Mg concentrations in the grain were not affected by the treatments. This result can be associated to nutrient mobility (Marschner 1995; Malavolta 2006) and to higher GY in response to increase in the lime rate applied (Table 5). Unlike the findings for leaf nutrients concentration, genotype variability was observed for each macronutrient concentration in soybean grain (Table 4).

Regardless of the lime rate applied, macronutrient concentrations in soybean leaves across the genotypes were as follows N > K > P > Ca > Mg > S (Table 4), and in grain: N > K > P > Ca > S > Mg (Table 5). Higher N, P and K concentrations in soybean were also reported by Moreira et al. (2015b) in an experiment with the same type of soil and by Fageria et al. (2012) with common bean (*Phaseolus vulgaris*).

Physiological components (A, g_s, C_i, Tr_{mmol} and IWUE)

Interaction genotypes × lime rates for photosynthesis rate (A), stomatal conductance (g_s), respiratory rate (Tr_{mmol}), IWUE, internal CO_2 concentration (C_i) and chlorophyll content were not significant (Table 6) indicating that there was no differential response of genotypes to the different lime rates used. An independent significant response of genotypes and lime rate was observed for A, g_s, Tr_{mmol} and chlorophyll content, while IWUE only differed among the genotypes and C_i did not respond significantly to the treatments (Table 6).

Table 5. Macronutrients (N, P, K, Ca, Mg and S) concentration in grain of soybeans, depending on the two lime rates [low-base saturation of 40% (1.49 t ha^{-1} of lime) and high of 70% (2.73 t ha^{-1} of lime)] application.[a]

	N ($g\ kg^{-1}$)		P ($g\ kg^{-1}$)		K ($g\ kg^{-1}$)		Ca ($g\ kg^{-1}$)		Mg ($g\ kg^{-1}$)		S ($g\ kg^{-1}$)	
Genotype	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
BMX Apolo RR	56.2a	55.1a	5.6a	5.7a	19.4a	18.5a	3.3a	4.5a	2.7a	2.9a	3.4a	3.3a
BMX Força RR	54.1a	55.7a	6.2a	5.9a	19.9a	16.4b	3.3	3.0b	2.3b	2.3b	3.2a	2.4b
BMX Potência RR	52.5a	53.9a	4.8a	5.5a	17.0b	17.2a	2.9b	3.1b	2.4b	2.4b	3.1a	2.3b
BMX Turbo RR	53.0a	52.7a	5.9a	5.7a	19.2a	18.2a	2.6b	2.8b	2.3b	2.3b	3.3a	3.0a
BRS 294RR	52.0a	55.8a	6.1a	5.5a	17.9b	16.6b	2.7b	3.4b	2.3b	2.2b	3.2a	2.2b
BRS 295RR	52.5a	54.4a	6.6a	5.8a	18.8b	16.3b	3.7a	3.9a	2.3a	2.4b	2.8b	2.6b
BRS 359RR	53.7a	56.9a	6.3a	6.4a	17.8b	17.7a	3.2a	2.7b	2.7a	2.6a	3.4a	2.8b
BRS 360RR	51.1a	54.1a	6.4a	5.8a	18.3b	17.7a	3.7a	3.1b	2.7a	2.4b	3.2a	2.6b
NA 5909RR	53.2a	53.0a	5.9a	5.8a	17.0b	15.7b	3.8a	4.1a	2.7a	2.7a	3.1a	2.8b
NA 6262RR	51.8a	53.4a	5.9a	6.1a	19.0a	18.0a	3.5a	3.5a	2.6a	2.5b	2.9b	3.2a
FTS Solar IPRO	49.9a	50.9a	6.5a	5.8a	19.4a	17.3a	3.3a	4.1a	2.6a	2.6a	3.3a	2.5b
TMG 1066RR	48.5a	52.7a	5.3a	5.7a	18.0b	17.1a	2.7b	2.9b	2.4b	2.3b	3.0a	2.5b
TMG 7161RR	48.8a	49.5a	6.9a	5.8a	20.5a	17.8a	3.4a	3.0b	2.8a	2.3b	3.4a	3.4a
TMG 7262RR	51.1a	49.7a	5.4a	5.7a	18.6b	17.5a	2.8b	3.0b	2.5a	2.4b	3.4a	3.2a
V_{max} RR	54.6a	55.5a	5.8a	5.7a	17.8b	15.4b	3.5a	3.7a	2.7a	2.6a	3.1a	2.9b
Mean	52.2A	53.6A	6.0A	5.8A	18.5A	17.2B	3.2B	3.4A	2.6A	2.5A	3.2A	2.8B
F test												
Genotype	2.037^{NS}		2.355^{NS}		3.429*		5.805*		4.357*		2.154*	
Rates	3.518^{NS}		2.536^{NS}		35.140*		3.288*		2.263^{NS}		20.229*	
Genotype × rates	0.371^{NS}		1.244^{NS}		1.342^{NS}		1.871*		0.792^{NS}		1.063^{NS}	
CV (%)	6.46		9.15		6.06		12.55		7.46		1.361	

*,[NS]Significant at the 5% probability level and not significant, respectively.

[a]Values followed by similar lowercase letters in the same column and uppercase letter in the same line within the same variables are not significantly different at $p \leq 0.05$ by Scott Knott test. Low-base saturation (V) = 40%. High-base saturation (V) = 70%. CV: Coefficient of variation.

Photosynthesis rate varied from 6.93 µmol CO_2 m^{-2} (TMG 7161RR) to 15.62 µmol CO_2 m^{-2} (TMG 1066RR) at a lower lime rate (V = 40%) and 11.57 (BRS 295RR) to 21.15 µmol CO_2 m^{-2} (TMG 7262RR) at a higher lime rate (V = 70%), with an average value of 12.92 µmol CO_2 m^{-2} and general average increase of 35.5% of *A* when lime rate was increased. Regarding g_s, C_i, Tr_{mmol}, IWUE and chlorophyll content, this range was 41.4, 1.3, 29.1, 4.9 and 17.3%, respectively (Table 6). For plants, the photosynthetic activity of leaves had increased significantly ($\hat{y}$ = 11.366 + 0.502x, r = 0.51, $p \leq 0.05$) with increase of lime application. According to Marschner (1995), Malavolta et al. (1997) and White and Broadley (2003), the use of a greater dolomite lime rate significantly increases the Ca and Mg concentration, nutrients that participate directly or indirectly on photosynthetic activities, either in cell division and/or as enzyme activator via calmodulin protein, in the case of Ca, or as a constituent of chlorophyll molecule and ion uptake, in the case of Mg (Table 6). Roots functions can be altered by rhizosphere acidity. Production and translocation of such growth hormones as cytokinins possibly are affected by acidity (Tolley-Henry & Raper Junior 1986).

Conclusion

In Brazil, soybean culture is expanding in degraded pasture areas where soils have low clay content and high acidity. The selection of acid tolerant soybean genotypes is an effective strategy to yield costs reduce and yield increase. BMX Potencia RR had the greatest GY in soil with higher acidity. In this study, the genotypes showed different responses to the two lime rates. Increase in base saturation from 40 to 70% increased GY by 31.1%, raised pH, Ca^{2+}, Mg^{2+} and soil CEC values and reduced K^+, Al^{3+} and H^+ + Al^{3+}. In turn, yield and physiological components, NPP, shoot dry weight (SDW), photosynthesis (*A*), stomatal conductance (C_i), transpiration (Tr_{mmol}) and chlorophyll, increased significantly with the application of higher lime doses. Leaf macronutrient uptake was

Table 6. Physiological components in soybean with two lime rates [low-base saturation of 40% (1.49 t ha^{-1} of lime) and high of 70% (2.73 t ha^{-1} of lime)] application.[a]

Lime (mg kg^{-1})	Genotype	A µmol CO_2 m^{-2} m^{-1}	g_s (mol H_2O m^{-2} s^{-1})	C_i (µmol CO_2 mol^{-1})	Tr_{mmol} (mmol H_2O m^{-2} s^{-1})	IWUE (mmol H_2O m^{-2} s^{-1})	Chlorophyll (mg m^{-2})
Low	BMX Apolo RR	10.81b	0.25b	284.45a	5.72b	2.04a	240.13a
	BMX Força RR	10.49b	0.27b	291.97a	7.14b	1.47a	212.76b
	BMX Potência RR	13.45a	0.29b	278.94a	7.25b	1.88a	219.93b
	BMX Turbo RR	8.47b	0.17a	273.02a	5.26b	1.62a	201.55b
	BRS 294RR	12.48a	0.45a	306.57a	9.15a	1.38a	206.48b
	BRS 295RR	11.08b	0.41b	308.47a	8.89a	1.37a	206.73b
	BRS 359RR	9.70b	0.22a	287.54a	5.79b	1.68a	180.08b
	BRS 360RR	9.93b	0.28b	283.76a	7.31b	1.46a	195.43b
	NA 5909RR	8.57b	0.23a	299.85a	6.19b	1.38a	198.46b
	NA 6262RR	10.00b	0.23a	262.35a	5.50b	2.24a	221.13b
	FTS Solar IPRO	10.98b	0.28b	276.53a	6.53b	1.71a	213.68b
	TMG 1066RR	15.62a	0.34b	272.45a	8.55a	1.83a	220.62b
	TMG 7161RR	6.93b	0.26b	269.57a	4.78b	1.51a	202.18b
	TMG 7262RR	14.95a	0.43a	283.30a	9.48a	1.58a	248.22a
	V_{max} RR	11.16a	0.32b	296.57a	8.84a	1.27a	190.50b
High	BMX Apolo RR	18.35a	0.77a	292.39a	8.09b	2.27a	300.88a
	BMX Força RR	15.58b	0.58b	297.36a	12.04a	1.29a	243.73b
	BMX Potência RR	16.19b	0.37a	261.95a	7.29b	2.41a	287.49a
	BMX Turbo RR	13.22b	0.38a	283.01a	7.57b	1.74a	237.61b
	BRS 294RR	12.71b	0.50a	303.77a	11.36a	1.12a	247.96b
	BRS 295RR	11.57b	0.34a	297.31a	8.77b	1.34a	210.84b
	BRS 359RR	14.26b	0.39a	283.33a	9.89b	1.44a	233.13b
	BRS 360RR	16.01b	0.38a	273.80a	7.40b	2.27a	262.87a
	NA 5909RR	12.92b	0.42a	297.39a	9.89b	1.36a	233.82b
	NA 6262RR	14.15b	0.38a	286.86a	7.89b	1.81a	259.71a
	FTS Solar IPRO	12.29b	0.55b	309.47a	11.81a	1.05a	219.93b
	TMG 1066RR	15.77b	0.47b	287.66a	8.64b	1.83a	223.84b
	TMG 7161RR	15.19b	0.40a	287.57a	7.89b	1.94a	251.18b
	TMG 7262RR	21.15a	0.67a	287.57a	9.75b	2.18a	273.22a
	V_{max} RR	13.66b	0.41b	280.77a	9.14b	1.58a	216.58b
	Low (V% = 40)	10.97B	0.29B	285.02A	7.09B	1.63A	210.52B
	High (V% = 70)	14.87A	0.41A	288.68A	9.16A	1.71A	246.85A
	Mean	12.92	0.35	286.85	8.13	1.67	228.69
F test							
Genotype		4.435*	4.283*	1.585^{NS}	2.589*	3.899*	4.439*
Rates		59.877*	21.754*	0.735^{NS}	25.804*	1.047^{NS}	56.078*
Genotype × rates		1.774^{NS}	0.866^{NS}	0.798^{NS}	1.424^{NS}	1.749^{NS}	1.278^{NS}
CV (%)		18.47	26.66	7.06	23.79	22.66	10.06

*Significant at 5% probability. [NS]Not significant.

[a]Values followed by similar lowercase letters in the same column and uppercase letter in the same line within the same variables are not significantly different at $p \leq 0.05$ by Scott–Knott test. Low-base saturation (V) = 40%. High-base saturation (V) = 70%.

CV: Coefficient of variation; A: photosynthesis rate; g_s: stomatal conductance; C_i: intercellular CO_2 concentration; Tr_{mmol}: respiratory rate; IWUE: relative water use efficiency; CV: coefficient of variation.

as follows: N > K > P > Ca > Mg > S, and in grain, it was N > K > P > Ca > S > Mg, with the highest levels of N, P, K and S reported in grain.

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