Soil & Tillage Research 152 (2015) 29–38

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Soybean and wheat response to lime in no-till Argentinean mollisols

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ARTICLE INFO

Article history:
Received 23 May 2014
Received in revised form 25 March 2015
Accepted 27 March 2015

Keywords:
Argentina
Base saturation
Grain yield
Lime soil pH
Soil Ca^{+2} content
Soybean
Wheat

ABSTRACT

Crop production in Argentina has significantly increased over the past few years; this increase was consequence of better management practices which included P and N fertilization and, occasionally, S fertilization. Commonly used rates, however, are not sufficient to balance nutrients export in grain crops. This situation is particularly negative for meso-nutrients (Ca^{+2} and Mg^{+2}) because they are not normally applied by farmers. The objective of this study was to determine the effect of lime over four years period on soybean, one year period on wheat and on a one year double cropped wheat/soybean combination on no-till. The experimental design was a randomized complete blocks design with three replications and two combinations of lime (with and without). Results showed that lime application significantly increased soil pH, exchangeable Ca^{+2} content, and therefore, base saturation and Ca^{+2} saturation in cation exchangeable capacity (CEC). As average growing seasons, the relative increments due to lime application were 8, 22, 18, and 20% for pH, soil exchangeable Ca^{+2} content, base saturation and Ca^{+2} saturation in CEC, respectively. Results showed that soil bulk density and penetration resistance were not affected by lime application. Soil structure stability was significantly affected by lime application. Wheat grain yield was not affected by lime, but soybean grain yield was significantly increased by lime (7% average across year). Cumulative grain yield was significantly increased by lime application indicating that the benefits of liming were cumulative over time (27,556 vs 28,629 kg ha^{-1} for lime and no lime, respectively). Increments in relative grain yield were not associated with soil pH in both crops; however, significant relationships were determined between relative soybean grain yield and soil Ca^{+2} content, base saturation and Ca^{+2} content in CEC. A soil Ca^{+2} critical concentration of 12.4 meq 100 g^{-1} was determined to obtain 95% of relative soybean grain yield. The study concluded that soil Ca^{+2} content would limit soybean grain yield as a consequence of cation unbalance in intensive agriculture soil.

1. Introduction

The southeast of the humid Argentine Pampas is one of the regions in the world with superior conditions for grain crop production (Martínez et al., 2013), due to temperate climate, adequate rainfall and a large proportion of soils belonging to the great group Argiudolls, with high productivity. Because of this, the region has a high potential for winter and summer crop production. Most of the agricultural soils of this region belong to Typic Argiudoll and and Petrocalcic Paleudoll which present discontinuous layers of petrocalcic horizon below 0.8 m and greater clay contents at sub-surface layers than Typic Argiudolls (USDA Taxonomy). These soils have organic matter content ranging from 3 to 6%, low available P (6–10 ppm Bray-1-P) and pH values from moderately acidic (5.5–6.4) (Sainz Rozas et al., 2011, 2012).

Soil acidity can affect plant growth directly and indirectly by affecting availability of plant nutrients, levels of phytotoxic elements, microbial activity and other soil properties (Brady and Weill, 1999). Soils may become acidic in the long term as a result of several natural processes (leaching of basic cations). In the short term, however, soil acidity develops mainly due to removal of bases (e.g., Ca, Mg, K,) by harvested crops (Bouman et al., 1995), coupled with the residual acid that is left in the soil from N and P fertilization (Tarkalson et al., 2006). Soil acidity is a serious limitation for crop production in many regions of the world. Soil acidity problems are commonly corrected by application of limestone. However, the rate of lime to be applied is calculated

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http://dx.doi.org/10.1016/j.still.2015.03.013
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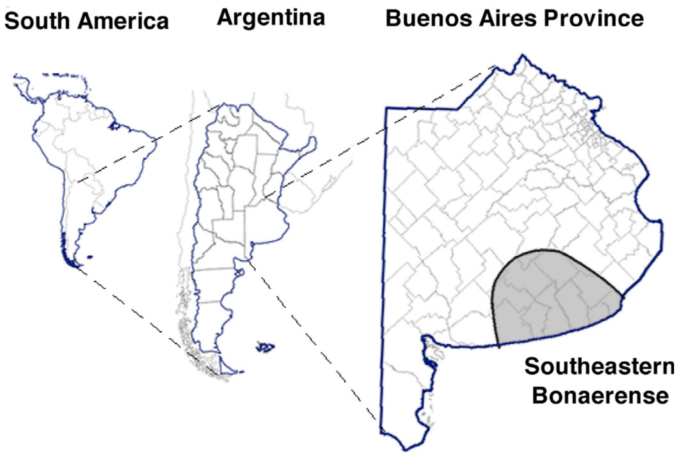

Fig. 1. Map of South America indicating Argentina, Buenos Aires province and the shadow area comprises South-Eastern Buenos Aires.

by different methods (Shoemaker–McLean–Pratt, Sikora, and Mehlich buffer pH, and titratable acidity). The common practice for liming no-tillage consists of applying lime to soil surface without incorporation into the soil. Surface applied lime is effective to improve soil pH and increased crop grain yields (Caires et al., 2005, 2010; Godsey et al., 2007; Joris et al., 2013; Fageria et al., 2013, 2014).

In southeast of the humid Argentine Pampas region (Fig. 1), wheat and soybean are the most important winter and summer crops, respectively. However, over the last 30 years, the region has been intensively cultivated to soybean (*Glycine Max.* L. Merr.). This has led to serious deterioration of soil physical, biological and chemical properties. In this region, crop production has been significantly increased in the last years as consequence of better management practices which included P and N fertilization and, occasionally, S fertilization. On the other hand, a reduction in soil organic matter (Sainz Rozas et al., 2011) and the large area under no-tillage has increased markedly the N deficiencies and crop response to this nutrient (Sainz Rozas et al., 2008; Velasco et al., 2012; Barbieri et al., 2012). Therefore, applied N rate to crops has been increased contributing to progressive soils acidification (Sainz Rozas et al., 2011). However, until the moment, meso-nutrient fertilizers (Ca^{+2} and Mg^{+2}) were not used by farmers in field crops. The major effect of acidification is a depletion of exchangeable Ca^{+2} and Mg^{+2} (Bouman et al., 1995). Recently, a survey on pristine and agricultural soils (0–20 cm depth) in Pampas regions (Sainz Rozas et al., 2013) determined the reduction in exchangeable Ca^{+2} and Mg^{+2} content of 12% and 18%, respectively as consequence of agriculture. However, average soil Mg content was in the range of high and very high availability (254 ppm). Exchangeable Ca^{+2} in some of the areas surveyed was between 600 and 1200 mg kg^{-1} in which positive response to lime application were determined in soybean and alfalfa (Gambaudo and Fontanetto, 2011; Vázquez et al., 2010; Vázquez, 2011). This exchangeable Ca^{+2} could be limiting in soils with high cation exchangeable capacity (CEC) as those of southeast of Buenos Aires province because Ca^{+2} saturation would be lower than 50% (Havlin et al., 2005) in the most of situations. On the other hand, Ca^{+2} and Mg^{+2} together with organic matter are cementing agents involved in soil aggregate process (Brady and Weill, 1999). Therefore, liming

Table 1
Accumulated rainfall, temperature maximum ($T_{max.}$) and minimum ($T_{min.}$), relative humidity (R.H.) global radiation (G.R.) soil evapotranspiration (*E*), wind speed (WS), and heliophany for experimental site from 1984–2013.

Month	Rainfall (mm)	$T_{max.}$ (°C)	$T_{min.}$ (°C)	R.H. (%)	G.R. (Mj m^{-2})	*E* (mm)	WS (km h^{-1})	*H* (h)
Jan	109.3	27.8	14.2	70	22.6	141.0	6.9	8.77
Feb	83.5	26.5	13.8	74	19.9	108.5	7.0	8.17
March	92.1	24.3	12.4	77	15.2	82.1	6.5	6.77
April	75.6	20.5	9.0	78	11.0	46.0	6.1	5.77
May	56.9	16.3	6.2	81	7.3	23.1	6.1	4.44
June	49.6	13.2	3.9	83	5.9	15.3	6.6	3.96
July	48.8	12.3	3.1	83	6.4	17.2	7.1	3.96
Aug	54.6	14.4	4.1	80	8.8	31.7	7.1	4.71
Sept	62.6	16.2	5.1	78	12.4	49.7	7.7	5.54
Oct	88.2	19.4	7.8	77	16.3	77.3	7.5	6.43
Nov	98.7	22.8	10.1	73	20.4	106.7	7.3	7.81
Dec	92.2	25.9	12.3	69.0	23.1	137.4	7.49	8.87
Annual	912	19.9	8.5	76.9	14.1	835.8	6.9	6.3

Table 2
Some characteristics of the soil surface (0–20 cm depth) at the initial condition in 2006/07 and 2010/11 growing season.

2006/07									
p	MO	pH	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	CEC	BS	Ca sat in CEC
mg kg^{-1}	%	%	meq 100 g^{-1}	meq 100 g^{-1}	meq 100 g^{-1}	meq 100 g^{-1}	meq 100 g^{-1}	%	%
17.0	5.9	5.7	12.6	1.6	0.22	2.0	26.9	61.2	47.0
No lime 2013/14									
P	MO	pH	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	CEC	BS	Ca sat in CEC
mg kg^{-1}	%	%	meq 100 g^{-1}	meq 100 g^{-1}	meq 100 g^{-1}	meq 100 g^{-1}	meq 100 g^{-1}	%	%
44.2	5.6	5.8b	10.0b	1.5b[1]	0.21a	2.6a	26.1a	54.4b	38.2b
Lime 2013/14									
P	MO	pH	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	CEC	BS	Ca sat in CEC
mg kg^{-1}	%	%	meq 100 g^{-1}	meq 100 g^{-1}	meq 100 g^{-1}	meq 100 g^{-1}	meq 100 g^{-1}	%	%
45.0	5.6	6.5a	13.2a	2.4a	0.20a[1]	2.6a	25.8a	74.3a	51.2a

Ca, soil calcium content; CEC, cation exchangeable capacity; BS, base saturation; Ca sat in CEC, calcium saturation in cation exchangeable capacity.
[1] Means followed by the same letter are not significantly different from each other based on the LSD test.

would promote the formation of cementing process, exercising soil structuration (Vázquez et al., 2009). Therefore, it is necessary to evaluate if crops sensitive to soil acidity would response to Ca^{+2} fertilization. The objective of this study was to determine the effect of lime application in a long term field trial under no-till on grain yield and soil properties during six growing seasons (2006/07, 2007/08, 2008/09, 2009/10, 2010/11, and 2013/14) in a crop sequence that included five soybean crops and two wheat crops.

2. Materials and method

The study was performed in a long term field trial under no-till initiated in 2006 and crop sequence was: soybean (*Glycine max* L. Merr.) (2006/07, 2007/08), wheat (*Triticum aestivum* L.) (2008/09) - soybean (2010/11), wheat/soybean as double crop (2010/11) and - soybean (2013–11) and soybean (2013–/14). The experiment was located at the Instituto Nacional de Tecnología Agropecuaria (INTA)

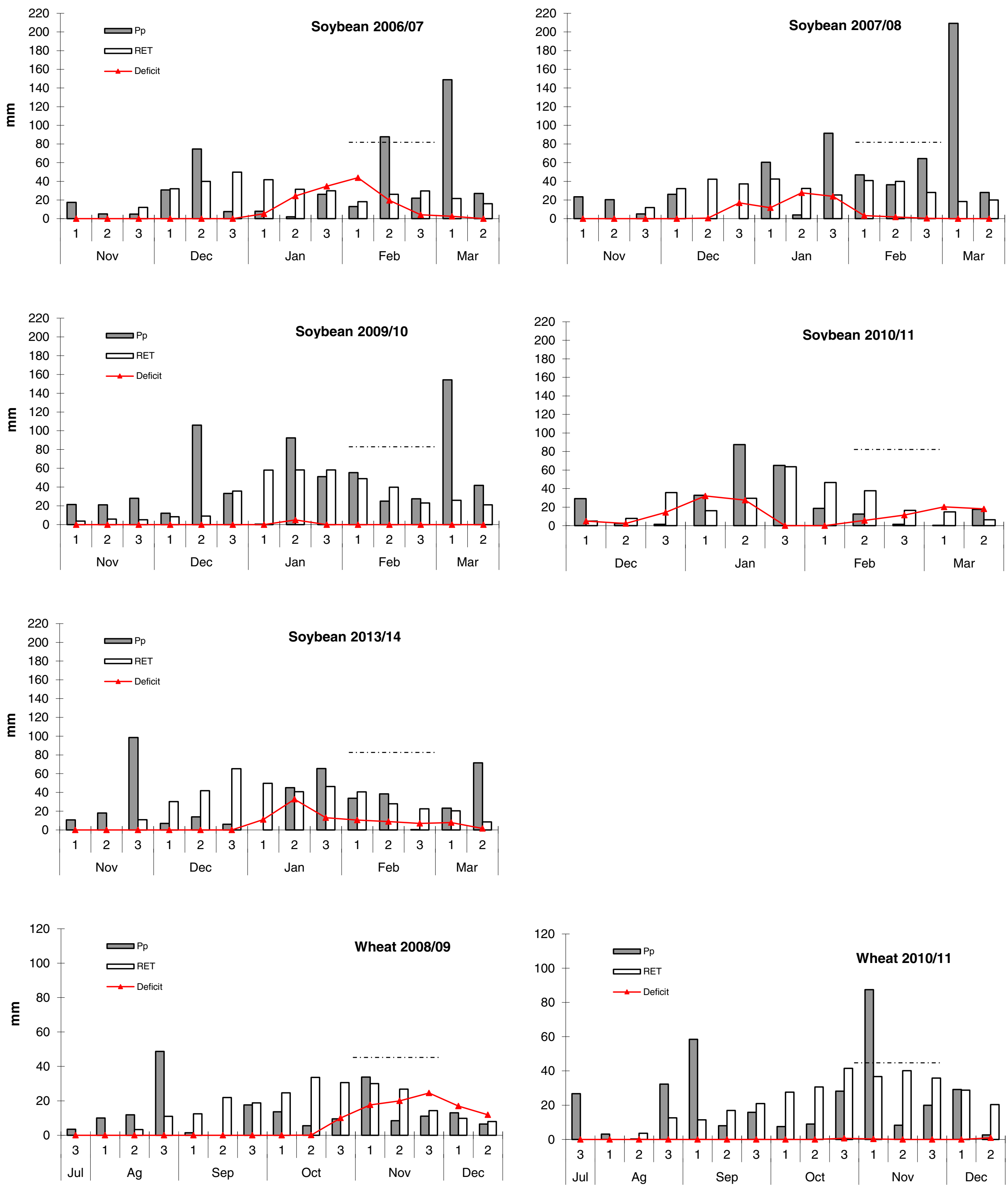

Fig. 2. Precipitation (Pp), real evapotranspiration (RET) and water deficit during 2006/07, 2007/08, 2009/10 and 2010/11 soybean growing season and 2008/09 and 2010/11 wheat growing season. Dotted line indicates critical period to kernel set.

Table 3
Soil pH, soil calcium content, base saturation and calcium saturation in cation exchangeable capacity affected by lime application.

	pH	Ca^{+2}	BS	Ca sat in CEC
Treatment (*T*)	0.0001	0.0001	0.0001	0.0001
Year (*Y*)	0.0001	0.0001	0.8007	0.0930
$T \times Y$	0.0001	0.0003	0.0003	0.0005

Ca, soil calcium content; BS, base saturation; Ca sat in CEC, calcium saturation in cation exchangeable capacity.

Research Station, Balcarce (37°45′S; 58°18′W; 130 m above sea level) Buenos Aires, Argentina. Average climate data for experimental sites from 1984 to 2013 are shown in the Table 1. The soil was a fine mixed Typic Argiudoll (USDA Taxonomy), with a loam texture at the surface layer (0–25-cm depth), loam to clay-loam at sub-surface layers (25–110-cm depth) and sandy-loam below 110-cm depth (C-horizon). The soil where the experiment was conducted is representative of an area about 2.2 million ha (Fig. 1). Some soil characteristics determined at the beginning of experiment in 2006/07 growing season and the last growing season 2013/14 growing season are presented in Table 2.

The experimental design was a randomized complete blocks design (RCBD) with three replications and two combinations of lime (with and without). Lime requirements were calculated as 80% of base saturation in CEC. Lime was applied broadcast on the soil surface by hand only on soybean crops. The rate of lime (dolomite) applied (Ca^{+2} 24%, Mg^{+2} 9.2%) was 6.2, 5.3, 4.6 Mg ha^{-1}, and 3.1 Mg ha^{-1} in 2006–07, 2007–08, 2009–10, and 2013–14 growing seasons, respectively. Plot size was 75 m^2 in size (5 m wide by 15 m long). At all growing seasons, soil organic matter (Walkley and Black, 1934), P Bray content (Bray and Kurtz, 1945), pH (water 1:2.5), soil Ca concentration and cation exchange capacity (CEC) were measured at 0–20 cm depth (Chapman, 1965; Schollenberger and Simon, 1945). At the beginning of experiment in 2006/07 growing season, before soybean sowing, exchangeable acidity (Thomas, 1982) and titratable acidity (Peech, 1965) were measured at 0–20 cm depth.

In 2010/11 growing season, soil bulk density (BD) 0–5 and 5–10 cm depth was determined by the core method (Blake and Hartge, 1986) using a core sampler of 50.0 mm diameter and 50.0 mm height. Undisturbed soil cores (2 sub-samples per plot) were taken randomly from each treatment at 0–5 and 5–10 cm depths using a core sampler. Cores were oven dried at 105 °C and weighed; BD was calculated as the quotient between the weight of each core and its volume. Penetration resistance (PR) was measured at 0–5 and 5–10 cm depths when soil water content was close to field capacity, with an Eijkelkamp penetrologger M1.06.15.E (P.O. Box 4, 6987 ZG Giesbeek, The Netherlands) with a cone basal area of 1 cm^2 and a cone angle of 60°. Nine sub-samples per plot were recorded and the results were averaged at the selected depths to get one measurement per plot per depth considered. Soil structural stability was assessed by a dry–wet sieving method (De Boodt et al., 1961). Samples were delicately taken using a shovel from the whole layer (0–10 cm), when soil water content was close to field capacity. Aggregates in the sample were manually fragmented along their planes of weakness to pass an 8 mm sieve, exerting the least possible force, and then dried at 30 °C. Dried samples were sieved through a nest of sieves (4.80, 3.36, and 2.00 mm opening sieves), and a proportion of each dry fraction obtained was wetted with deionized water and incubated for 24 h to 35 °C. After that samples were sieved under water through a set of six stacking sieves (4.80, 3.36, 2.00, 0.84, 0.50, and 0.30 mm opening sieves) for 30 min. Change in mean weight diameter (CMWD) was calculated as change in diameter of aggregates after being sieved dry and then wet. As CMWD increased soil aggregates were less resistant to water effect.

Management practices such as varieties, plant population, row spacing weeds and insects were chemically controlled with

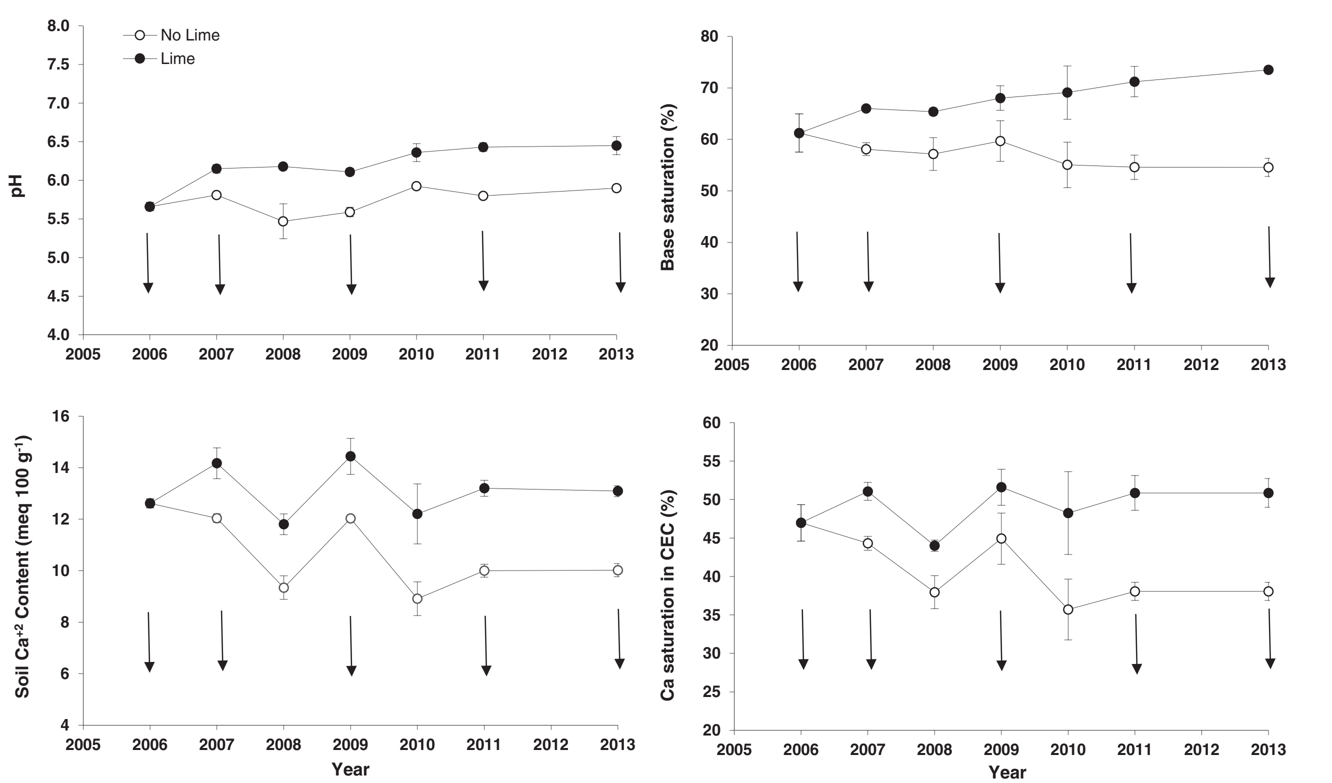

Fig. 3. Evolution of soil pH, soil Ca^{+2} content, base saturation and Ca saturation in CEC affected by lime application and growing seasons. Lines represent standard errors. Arrows indicate lime application time.

recommended products and rates utilized were the same one that those utilized by the farmer. At planting time, experiments were fertilized with 20 kg P ha^{-1} as triple superphosphate (0–46–0), and 15 kg S ha^{-1} as calcium sulfate (18.6% of S). Crop evapotranspiration (CET) was determined as the product between potential evapotranspiration (ET_0) and crop coefficient (K_c). The ET_0 was estimates using the Penman–Monteith equation (Allen et al., 1998). The ET_0 is defined as the ET rate from a hypothetical grass reference crop with specific characteristics and not short of water (Allen et al., 1998). The K_c values (CET/ET_0) are those reported for the area by Della Maggiora et al. (2000).

Grain yield was measured by experimental combine harvesting an area of 12 m^2 (10 m long by 1.2 m wide), and corrected to 13.5 and 14.0% grain moisture content for soybean and wheat crops, respectively. Relative grain yield (RY) was calculated as the ratio between average grain yield of non-lime (NL) application treatment divided by average grain yield of lime (L) application treatment multiplied by 100. Crop relative yield response to lime (relative increase over the control) was calculated as difference between grain yield of lime (L) application and control (NL) divided by the yield of the control (NL) multiplied by 100.

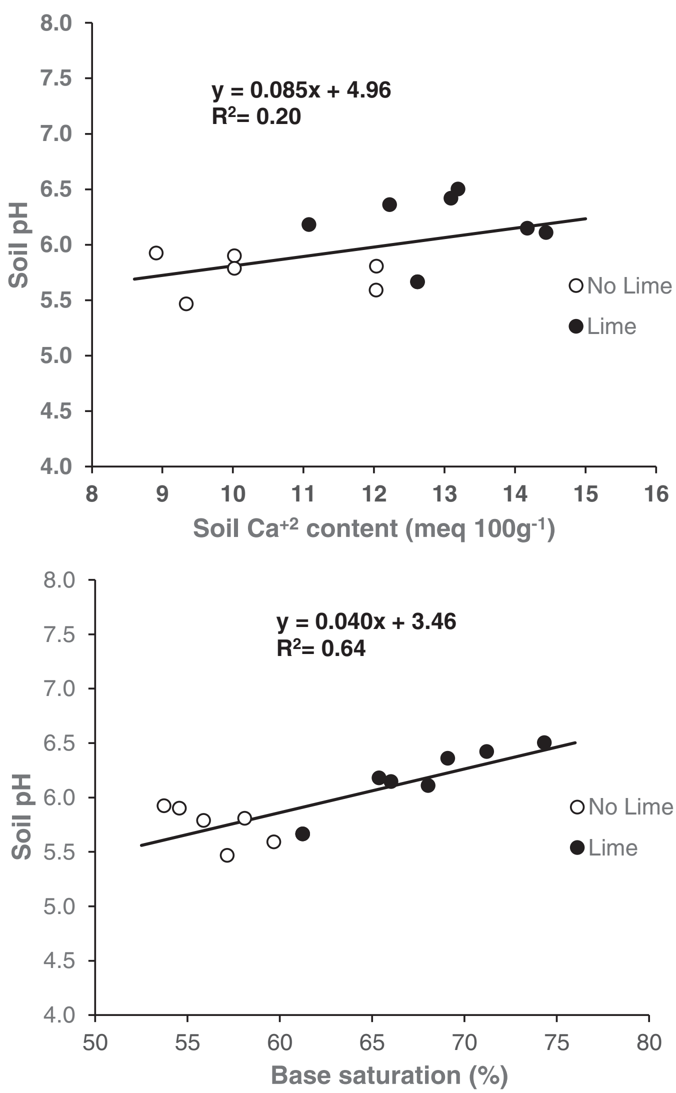

Fig. 4. Relationships between soil pH, soil calcium content, and base saturation.

$$\text{Relative yield} = \left(\frac{\text{no lime}}{\text{lime}}\right) \times 100$$

$$\text{Crop relative yield} = \left(\frac{\text{lime} - \text{no lime}}{\text{lime}}\right) \times 100$$

Analysis of variance (ANOVA) was accomplished using the PROC GLM procedure of SAS 9.2 (SAS Institute, 2008). Data were analyzed using a split-plot design. The main plot was the year and the subplot was lime treatments. The means were separated using least significant difference (LSD) at the 0.05 level of significance. Regression and stepway multiple regression analyses were performed using (NLIN) procedure of SAS 9.2 software (SAS Institute, 2008). Soil Ca^{+2} critical concentrations were calculated with the statistical Cate–Nelson method (Cate and Nelson, 1971) for the soybean grain yield and soil Ca^{+2} content relationship. The critical concentration for the Cate–Nelson model is the concentration that splits the data into two groups, and the critical concentration for either segmented model is the concentration at which the two portions of the model join.

3. Results and discussion

3.1. Climatic condition

The water balances for the soybean and wheat crops during the growing seasons are presented in Fig. 2. In general water availability did not limit soybean growth at any growing seasons. Only light water stress events were registered at the beginning of critical kernel set period (Egli et al., 1985; Vega et al., 2001) at 2006/07 and 2007/08 growing season, respectively (Fig. 2). At 2010/11 soybean growing season light water stress events were registered during later December to January and early March. However, these water stresses would lightly affect soybean grain yield.

In the wheat crop at 2008/09 growing season, where the rainfall registered from July to December was only 62% (278 mm) of period 1983–2013 (Table 1), a pronounced stress took place during November and December (Fig. 2), a period in which water availability is crucial for obtaining high wheat yields (Calviño and Sadras, 2002). Thus, wheat grain yield was affected by water availability, mainly as consequence of lower kernel number. On the other hand, in the 2010/11, growing season had favorable hydric conditions because rainfall was higher than crop evapotranspiration and therefore no stress was determined (Fig. 2). Multiple analysis regression of grain yield (using as variables rainfall, temperature, crop evapotranspiration and water deficit), determines that water deficit ($p < 0.01$) in the period during 30 days before and 10 days after flowering was the variable that explained variation in yield. These results were agreement with the findings by Calviño and Sadras (2002).

Table 4
Change in mean weight diameter, soil bulk density and penetration resistance in 2010/11 growing season.

Treatments depth (cm)	CMWD (mm)	BD ($Mg\,m^{-3}$)		PR (M Pa)	
	0–10	0–5	5–10	0–5	5–10
No lime	0.31a	1.19 a[1]	1.29a	0.98a	1.66a
Lime	0.22b	1.21a	1.28a	1.01a	1.43a
p	0.023	0.509	0.651	0.860	0.189

MWD, change in mean weight diameter; BD, bulk density; PR, penetration resistance.

[1] Means followed by the same letter are not significantly different from each other based on the LSD test.

Table 5
Soybean and wheat grain yield as affected by lime application and growing seasons, and cumulative grain yield as affected by lime application.

Treatment	Soybean grain yield (kg ha^{-1})						Wheat grain yield (kg ha^{-1})			Cumulative grain yield (kg ha^{-1})
	2006/07	2007/08	2009/10	2010/11	2013/14	Average	2008/09	2010/11	Average	
Lime	4226	3377	4607	1057	3355	3225a	4483	7523	6003a[1]	28629a[1]
No lime	4176	3060	4234	997	3103	3114b	4585	7401	5993a	27556b
Average	4201a	3218b	4420a	1027c	3229b	–	4534b	7462a	–	0.0455
Treatment (*T*)	0.0356						0.9678			
Year (*Y*)	0.0001						0.0018			
$T \times Y$	0.6810						0.6450			

[1] Means followed by the same letter are not significantly different from each other based on the LSD test.

3.2. Soil determination

In 2006 growing season, tritatable acidity was 11.2 meq 100 g soil^{-1}, exchangeable acidity was 0.12 meq 100 g soil^{-1} and, Al^{+3} was not detected, and therefore crop yield may not be decreased by Al toxicity. Similar values of tritatable and exchangeable acidity were reported by Fabrizzi (1998) in the same region for agricultural soils.

After seven years of experiment, significant changes were determined on soil pH, soil Ca^{+2} content, base saturation, and Ca^{+2} saturation in CEC by lime application (Table 2). In the lime pots increase of 14, 5, 21 and 9% were determined for soil pH, soil Ca^{+2} content, base saturation, and Ca^{+2} saturation in CEC, respectively (Table 2). In the no lime plots small changes in soil pH was determined; however, reduction of 21, 11, and 19% were determined in soil Ca^{+2} content, base saturation, and Ca^{+2} saturation in CEC, respectively (Table 2). Caires et al. (2011a,b); Caires et al. (2011a,b) determined significantly changes in soil properties in a long term experiment (7–8 years) by lime or gypsum application.

Significant interaction (year × lime) was observed on soil pH, soil Ca^{+2} content, base saturation and % Ca^{+2} saturation in CEC (Table 3). Soil pH was significantly affected by years and lime application (Table 3). Average soil pH by years ranged from 5.7 to 6.2, and was high in 2011, 2010 and 2013 (i.e., 6.14, 6.12 and 6.18, respectively), medium 2007 (5.98) and low 2008 and 2009 (i.e., 5.83 and 5.85, respectively). Higher soil pH values (2010, 2011 and 2013) were consequence of accumulative effects of previous lime application. Medium or lower soil pH were determined at the beginning of experiment or year without lime application (2007–2009). Lime application increased significantly soil pH from 5.7 at the beginning in 2006 to 6.5 in 2013/14 growing season, whereas no lime treatment showed pH values ranging from 5.7 to 5.9 across years (Fig. 3). The average increment in soil pH across year in response to lime application was 6%. Soil Ca^{+2} content was significantly affected by year and lime application (Table 3). Average soil Ca^{+2} content by years ranged from 10.6 to 13.2 meq 100 g^{-1}, and it was high in 2007 and 2009 (13.1 and 13.2 meq 100 g^{-1}, respectively), medium in 2011 and 2013 (11.6 meq 100 g^{-1}, and 11.5 meq 100 g^{-1}, respectively) and low in 2008 and 2010 (10.8 and 10.8 meq 100 g^{-1}, respectively). Soil Ca^{+2} content ranged from 12.6 to 13.9 in lime treatment and 12.6 to 10.0 in no lime treatment from 2006 to 2014 growing seasons, respectively (Fig. 3). The average increment in soil Ca^{+2} content across years in response to lime application was 11.8% (Fig. 3). Base saturation only was increased significantly by lime application (Table 3). Base saturation at 2006 was 61%, and at 2014 growing season were 74 and 55% to lime and no lime treatments, respectively (Fig. 3). The increment in base saturation in response to lime application was by 20.1%. Calcium saturation in CEC was significantly affected only by lime application (Table 3). Calcium saturation in CEC at 2006 was 47.0% and at 2014 growing season were 38.1 and 50.9% to lime and no lime treatments, respectively (Fig. 3). The increment in Ca^{+2} saturation in response to lime application was by 8.3%. A positive and significant ($p < 0.05$) association was determined between soil pH and soil Ca^{+2} content, and soil pH and base saturation (Fig. 4). The greater R^2 determined by soil pH and base saturation than soil pH and soil Ca^{+2} content relationships ($R^2 = 0.64$ vs 0.20) indicates that other ions affected soil pH variation. Similar relationships between soil pH and base saturation were informed by Caires et al. (2000, 2006a),) and Alleoni et al. (2010) from Brazilian soils. These authors reported that soil pH increased by lime applications was accompanied by increase on base saturation. Several experiments reported increments in soil pH, soil Ca^{+2} content, base saturation and % Ca^{+2} saturation in CEC by lime application (Caires et al., 2006a, 2010; Moreira and Fagaria, 2010; Pagani and Mallarino, 2012; Gómez-Paccard et al., 2013; Fagaria et al., 2014)

Soil bulk density and penetration resistance (PR) were not affected by lime application (Table 4). The results our experiment do not agree with informed by Chan et al. (2007) and Scott et al. (2003) who determined significantly reduction in BD and PR for lime application, respectively. In spite of this, BD or PR data were lower in lime than in no lime treatments (Table 4). However, significant change in CMWD was determined by lime application (Table 4). Liming affected the aggregate binding agents, in soils

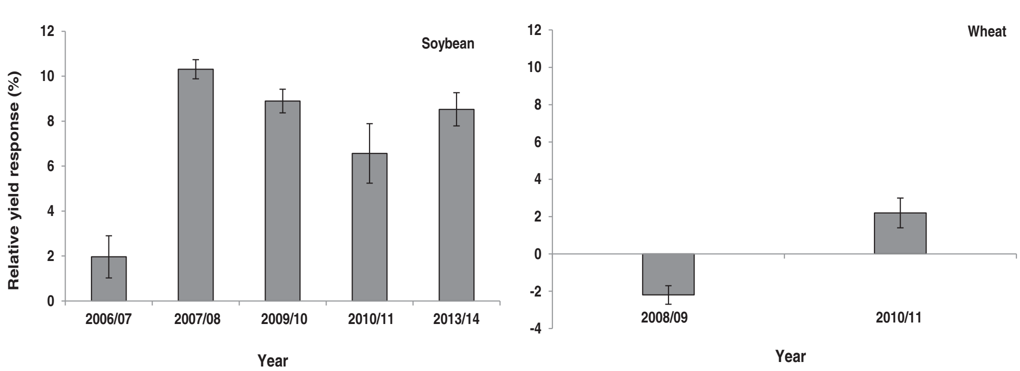

Fig. 5. Relative grain yield response to lime application by soybean and wheat crop. Lines represent standard errors.

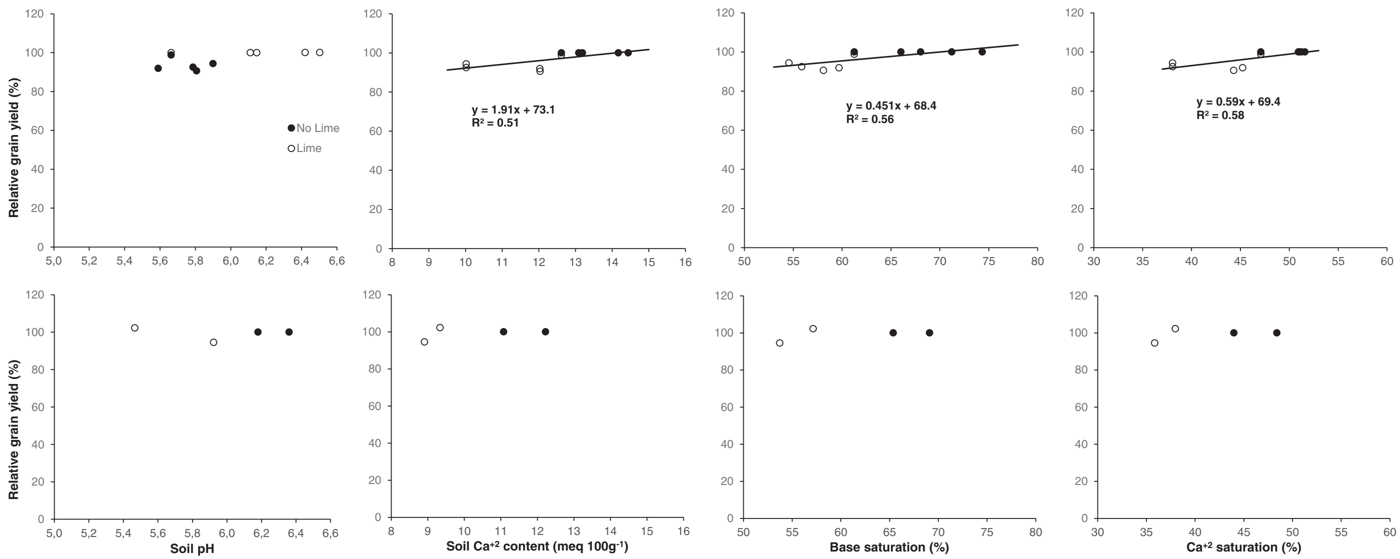

Fig. 6. Relationships between relative grain yield and soil pH, soil Ca^{+2} content, base saturation (BS) and calcium saturation in cation exchangeable capacity for soybean and wheat crops.

Table 6
Regression models for relationships between relative grain yield (RY) and soil pH, soil calcium content, base saturation and calcium saturation in cation exchangeable capacity for soybean and wheat crops.

	Soybean		
	Equation	R^2	p
pH	RY = 49.3 + 7.99x	0.30	0.09
Soil Ca^{+2} content	RY = 71.9 + 1.98x	0.56	0.01
Base saturation	RY = 61.9 + 0.54x	0.49	0.02
Ca^{+2} saturation	y = 58.0 + 0.80x	0.64	0.01
	Wheat		
	Equation	R^2	p
pH	RY = 110.4 – 1.88*x*	0.05	0.84
Soil Ca^{+2} content	RY = 91.6 + 0.72*x*	0.14	0.63
Base saturation	RY = 87.0 + 0.19*x*	0.15	0.60
Ca^{+2} saturation	RY = 89.4 + 0.24*x*	0.17	0.60

with illite dominance, and secondarily, montmorillonite in the clay fraction would promote the formation of cementing process of Ca^{+2} between mineral and organic fractions, exercising soil structuration (Vázquez et al., 2009; Clever et al., 2012). Positive effect on aggregate stability and soil aggregation by lime application were informed by Chan et al. (2007), Hati et al. (2008), Chaplain et al. (2011), Arshad et al. (2012) and Bennett et al. (2014).

3.3. Grain yield

No significant interaction (year × lime) was observed on soybean and wheat crops grain yield. Soybean grain yield was affected by year ($p < 0.01$) and lime application ($p < 0.05$), grain yield ranged from 1000 to 4500 kg ha^{-1} depending on growing season, the lower value corresponding to double crop wheat/soybean (Table 5). Lime application increased average soybean grain yield 7%, which coincides with the findings by others authors (Caires et al., 2005; Costa and Rosolem, 2007; Vázquez et al., 2010; Pagani and Mallarino, 2012; Castro and Crusciol, 2013). The grain yield increments in response to lime application varied from 2 to 10% depending to growing season (Fig. 5).

Wheat grain yield was affected only by year ($p < 0.01$). In the 2008 growing season, a pronounced stress took place during November (Fig. 2), which was reflected in crop yields (4500 kg ha^{-1}) while in 2011 growing season higher grain yield (7500 kg ha^{-1}) was obtained as consequence of favorable hydric conditions. No significant differences were determined for lime application on wheat grain yield (Table 5). These results are in agreement with those obtained in other reports (Caires et al., 1999, 2002; Liu et al., 2004; Brown et al., 2008; Pisa Lollato et al., 2013). The grain yield increments in response to lime application were −2.2 to 2.2% in 2008 and 2011 growing season, respectively (Table 5). The negative grain yield response determined in the lime treatment in 2008 growing season, would be consequence to greater dry matter accumulated during vegetative stages (17%) compared to no lime application treatments. This situation would lead to more crop water consumption and, therefore, water stress was more pronounced during critical period to kernel set (data not sown). Cumulative grain yield was significantly effected ($p < 0.05$) by lime application (Table 5) indicating that the benefits of liming were cumulative over time, in spite of wheat grain yield variability. Similar results were reported by others (Caires et al., 2000, 2006b; Arshad et al., 2012; Fageria et al., 2013, 2014).

The major grain yield response to lime application, determined in soybean than wheat crop, would be consequence to growth responses in leguminous attributed to favorable soil pH for rhizobium activity (Mengel and Kamprat, 1978; Brauer et al., 2002; Ouertatania et al., 2011). Optimum soil range pH for soybean and wheat is around 5.5–7.5 for both crops (Fageria and Zimmermann, 1998; Bongiovanni and Lowenberg-DeBoer, 2000; Sawyer et al., 2002; Pagani, 2011). However, no significant relationship was determined between RY and soil pH in both crops, in spite of pH values in no lime treatment was from 5.5 to 5.9 (Fig. 6, Table 6). Only in soybean crop, a significant relationship was determined between RY and soil Ca^{+2} content ($R^2 = 0.51$), base saturation ($R^2 = 0.56$) and, Ca^{+2} saturation in CEC ($R^2 = 0.58$) (Fig. 6, Table 6). Significant and positive correlation between soybean grain yield and soil Ca and base saturation were informed by others (Costa and Rosolem, 2007; Fageria, 2008; Dalla Nora and Amado, 2013; Fageria et al., 2014). A significant ($p < 0.01$; $R^2 = 0.26$) soil critical Ca^{+2} content was determined to obtain 95% of relative grain yield only for responsive soybean crop (Fig. 7). The critical value of 12.4 meq 100 g^{-1} was greater than 3.8 meq 100 g^{-1} (Fageria et al., 2010) for common beans, and 4 meq 100 g^{-1} (Fageria, 2001), 1.8 meq 100 g^{-1} (Fageria et al., 2013) and 1.6 meq 100 g^{-1} (Fageria et al., 2014) for soybean.

The response to lime application on soybean would be consequence of Ca^{+2} saturation content in CEC, which for no lime treatment ranged from 47% (2006) at the beginning of experiment and 37% in 2013–14 growing season. These values were below 67% reported by Fageria (2008) for no-till bean; Eckert (1987) reviewed work of many studies and reported that ideal Ca saturation should be around 65%. High Ca saturation indicates a favorable pH for plant growth and microbial activity and will usually reflect low exchangeable Al^{+3} in acid soils and Na^{+} in in sodic soils (Havlin et al., 2005). Lime application would produce a several chemical and biological changes in the soil, which are beneficial or helpful in improving crop yield (Bennett et al., 2014). On the other hand, soybean in particular, is a highly demanding crop in Ca; this requirement are about 16 kg Tn^{-1}, while in wheat are about 4 kg Tn^{-1} (Ciampitti and García, 2007). Regarding the influence of Ca^{+2} on the production of soybean, it would be desirable to increase soil Ca available levels rather than increasing pH, as consequence of decreased levels of Ca^{+2} in CEC. Therefore, lime rates would be lower applied on those required to increase the soil pH (Fontanetto et al., 2009). Alternative application strategies such as placement of lime in a band beneath the row at seeding could be used to Ca fertilization.

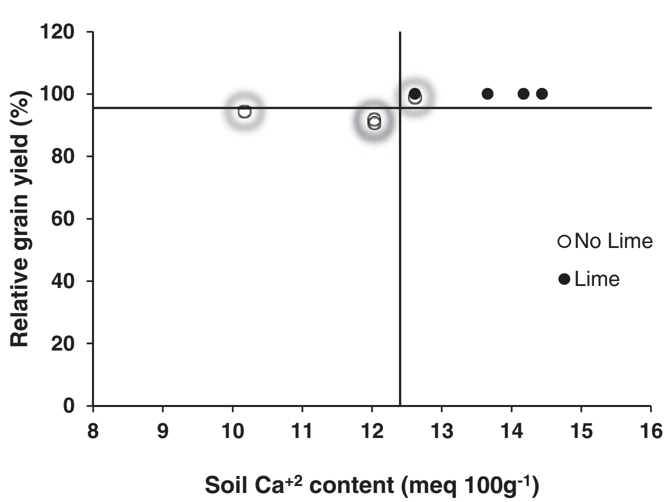

Fig. 7. Relationship between relative grain yield and soil Ca^{+2} content.

4. Conclusion

Lime application increased soil pH, soil Ca^{+2} content, base saturation and Ca^{+2} content in CEC. Wheat grain yield was not affected by lime, but soybean grain yield was significantly increased by lime. Increments in relative grain yield were not associated with soil pH in both crops; however, significant relationships were determined between relative soybean grain yield and soil Ca^{+2} content, base saturation and Ca^{+2} content in CEC. A soil Ca^{+2} critical concentration of 12.4 meq 100 g^{-1} was determined to obtain 95% of relative soybean grain yield. These results would indicate that soil Ca^{+2} content would limit soybean grain yield as a consequence of cation unbalance in intensive agriculture soil.

Acknowledgments

This study was supported by the INTA Project PNSUELO 1134024, and FONCyT-PICT 2011-796.

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