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Modern High-Yielding Maize, Wheat and Soybean Cultivars in Response to Gypsum and Lime Application on No-Till Oxisol

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ABSTRACT: Modern maize, wheat, and soybean cultivars are usually characterized by a short cycle, high shoot-root ratio, and high responsiveness to nutrient input. Continuous no-tillage management (NTS) frequently leads to a steep gradient in soil chemical quality with depth, thus decreasing yield under conditions of acid subsoil and water stress. This study aimed to evaluate the effect of gypsum, applied separately or in combination with lime, on the yield of cultivars used in the state of Rio Grande do Sul, Brazil. The study consisted of four experiments conducted on a typic Hapludox under NTS. The experiment was arranged in a randomized block design with three replications. Experiments I and II were carried out on soils with a satisfactory chemical soil quality and tested treatments of gypsum applications ranging from 0.0 to 6.5 Mg ha^{-1}. The other experiments were carried out on acid soil (experiment III) and a soil with an abrupt drop in chemical quality (experiment IV). Experiment III was arranged in a split plot design, where plots corresponded to gypsum rates between 0.0 and 5.0 Mg ha^{-1}, and subplots to two lime rates (0.0 and 2.0 Mg ha^{-1}). Experiment IV was conducted in a split plot design, with plots consisting of gypsum rates from 0.0 to 6.0 Mg ha^{-1} and subplots of lime rates from 0.0 to 4.8 Mg ha^{-1}. Of a set of 17 harvests investigated during the experimental period, 82 % responded with yield increases to gypsum and lime inputs. The gypsum rate that induced the highest grain yield was high (4.7 Mg ha^{-1}) and similarly, the maximum technical efficiency of lime was higher than the currently recommended. Furthermore, the combined application of lime and gypsum increased yield. There was a correlation between grain yield with the chemical quality of the soil layer 0.25-0.40 m in experiment I, 0.00-0.40 m in experiment II, and the 0.00-0.25 m in experiment IV. Only in experiment III, where the surface layer was acidic, the diagnostic layer usually sampled (0.00-0.10 m) was correlated with grain yield. Therefore, the use of the 0.00-0.25 m soil layer with critical base saturation values of 65 % and maximum Al saturation of 5 % could improve the current recommendations for soil correction. To exploit the yield potential of modern grain cultivars on dystrophic Oxisol, the formation of a thicker layer with high chemical quality is an efficient strategy.

Keywords: base saturation, Al saturation, root zone, grain yield.

INTRODUCTION

To achieve food security in the 21st century by increasing the agricultural production is a worldwide challenge, in view of a scenario of population increase and greater purchasing power (Amundson et al., 2015). The no-tillage system (NTS) has been consolidated as an efficient alternative to control erosion (Derpsch and Friedrich, 2009), increase water infiltration (Machado and Brum, 1978), and restore soil organic matter (SOM) (Amado et al., 2009), while reducing the cost, labor, and fuel demand for grain yield in tropical environments.

The feasibility of maintaining high grain yields under continuous NTS, however, has recently been questioned due to diverse reasons related to plant growth-limiting factors (Ogle et al., 2012). This suggests a need for adaptation/modifications in NTS to optimize crop performance to achieve food production goals. Generally, the improvement of soil chemical properties under continuous NTS is restricted to a thin top layer, and in acid subsoils of Oxisols, this may compromise water use efficiency and grain yield (Dalla Nora and Amado, 2013; Bortoluzzi et al., 2014; Caires et al., 2015; Zandoná et al., 2015). The surface or low-depth application of fertilizers and amendments (Bortoluzzi et al., 2014), associated with the occurrence of soil compaction and low biological activity, have been identified as main causes for an abrupt chemical quality decline from the surface to subsurface layers of Oxisols under NTS. The low chemical quality of subsoil restricts the plant root system to a surface layer and causes yield losses in modern cultivars under water stress (Blanco-Canqui and Lal, 2008; Caires et al., 2011a,b; Dalla Nora and Amado, 2013; Bortoluzzi et al., 2014; Powlson et al., 2014).

Gypsum ($CaSO_4.2H_2O$) has been recognized as an alternative for improving the chemical quality properties of the root layer under NTS, especially when combined with lime input (Rampim et al., 2011; Watts and Dick, 2014; Caires et al., 2015).

In the United States, the benefits of gypsum as nutrient source for plants and as soil conditioner are recognized since colonial times, dating back to the late 18th century (Crocker, 1922). Sulfur ($S\text{-}SO_4^{2-}$), a secondary macronutrient, plays a key role in biological nitrogen fixation in soybean for being a driver of nitrogenase enzyme functions (Nunes et al., 2003). Recent studies have indicated that modern cultivars with high yield potential demand more $S\text{-}SO_4^{2-}$ than traditional plants (Broch et al., 2011; Bender et al., 2015). Calcium (Ca^{2+}), another nutrient supplied by gypsum, is required at the root tips (Taiz and Zeiger, 2009) at high amounts by modern cultivars (Bender et al., 2015). As a consequence, the supply of this nutrient is critical for high grain yields, especially at low pH levels, as generally found in Oxisol subsoil (Toma et al., 1999).

In tropical acid soils, Ca^{2+} is usually supplied by lime, but the vertical movement of this nutrient in the soil profile is limited. Gypsum is about 200 times more soluble in water than lime (Cabrera, 2009), and its higher solubility favors the Ca^{2+} movement as well as $S\text{-}SO_4^{2-}$ displacement along the soil profile (Chen and Dick, 2011). Therefore, the use of gypsum favors the formation of a thicker layer with high chemical quality increasing the depth of the root system and of water uptake (Dalla Nora et al., 2014a) and the N use efficiency (Caires et al., 2015).

Aside from supplying Ca^{2+} and $S\text{-}SO_4^{2-}$, gypsum acts as a soil conditioner, with positive impacts on chemical and physical properties, especially on aggregation, soil compaction alleviation, water infiltration, erosion control, and mitigation of Al^{3+} toxicity (Shainberg et al., 1989; Rampim and Lana, 2015). Gypsum has been increasingly used in the United States, for different soil types and crops, due to its multiple benefits (Buckley and Wolkowski, 2014).

Recent studies on tropical and subtropical soils in Brazil have generally reported increases in grain yields in response to gypsum input (Alleoni et al., 2005; Raij, 2008;

Caires et al., 2011a,b; Dalla Nora and Amado, 2013; Blum et al., 2014; Dalla Nora et al., 2014b; Pauletti et al., 2014; Zandoná et al., 2015). Assessing the long-term effects of gypsum in 11 maize crops, Farina et al. (2000) reported an average yield increase of 135 kg ha^{-1} yr^{-1}. Linear increases ($p<0.05$) in wheat yield in response to increasing gypsum rates up to 5.0 Mg ha^{-1} were reported by Rampim et al. (2011). In a study of Raij (2008), a gypsum rate of 6.0 Mg ha^{-1} increased soybean yield by 184 kg ha^{-1}. Results obtained by Zandoná et al. (2015) indicated increases of 9.3 % in maize yield and 11.4 % in soybean yield after gypsum application to an Oxisol under NTS in Rio Grande do Sul (RS). In addition, the yield increase with gypsum combined with lime was higher than the increase in response to the separately applied inputs. This was confirmed even in soils with initial conditions that would not require liming according to the current criteria of CQFS-RS/SC (2004), based on the acidity properties of the surface soil layer (0.00-0.10 m): pH(H_2O) <5.5; base saturation (BS) <65 %, and Al^{3+} saturation >10 %. However, to date the findings with regard to combined gypsum-lime applications in NTS in RS are inconclusive.

In the last decade, modern high-performance cultivars of soybean and maize were widely adopted, featuring a short cycle, low height, reduced root system, and high input demands. In general, these cultivars are more sensitive to the soil chemical quality, aluminum content, compaction, and to water stress. Therefore, updated recommendations for liming may be required to explore the yield potential of the new cultivars efficiently. The objective of this study was to evaluate the effect of gypsum, applied separately or in combination with lime, on the yield of modern cultivars currently used in the state of RS under NTS.

MATERIALS AND METHODS

Description of the experimental areas

Four fields with similar soil type under long-term NTS were selected in Rio Grande do Sul, Brazil. Two experiments were implemented in 2009 in Carazinho (experiment I and II). In the area of experiment I (28° 19' S, 52° 55' W; 595 m a.s.l.) and experiment II (28° 17' S, 52° 47' W; 617 m a.s.l.), the annual rainfall is 1,821 mm and average annual temperature 16.0 °C. In 2011, experiment III was installed in São Miguel das Missões (28° 40' S, 54° 23' W; 265 m a.s.l.), with an annual rainfall of 1,651 mm and average annual temperature of 15.0 °C and experiment IV in Tupanciretã (29° 00' S, 53° 94' W; 507 m a.s.l.), with an annual rainfall of 1,766 mm and average annual temperature of 17.0 °C. In all experiments, the soil was classified as Typic Hapludox (Soil Survey Staff, 2014) [*Latossolo Vermelho distrófico* (Santos et al., 2013)]. According to Köppen system (1931), the climate is classified as humid subtropical (Cfa). The rainfall during the experimental period is shown in figure 1.

Prior to the experiments, the fields were cultivated under continuous NTS for more than 15 years, they were limed in intervals of 4 to 5 years with around 2.0 Mg ha^{-1} of lime with an effective $CaCO_3$ equivalent value of 80 %. Immediately before the experiments, the fields were cultivated with black oats (*Avena strigosa* Schreb), which was chemically managed with glyphosate [N- (phosphonomethyl) glycine] and then gypsum rates were applied manually on the soil surface in August 2009, for experiments I and II. For experiments III and IV, the inputs were applied according to the treatments in 2011. In experiment III, gypsum was applied in August 2011 and lime in August 2013. In experiment IV, the combined gypsum and lime rates were applied simultaneously in August 2011. The crop cycle, fertilizer applications, and evaluations carried out in the four experimental areas are shown in table 1.

Before initiating the experiment, a first chemical analysis was carried out, based on five soil cores sampled randomly in each experimental area in the layers: 0.00-0.05; 0.05-0.10;

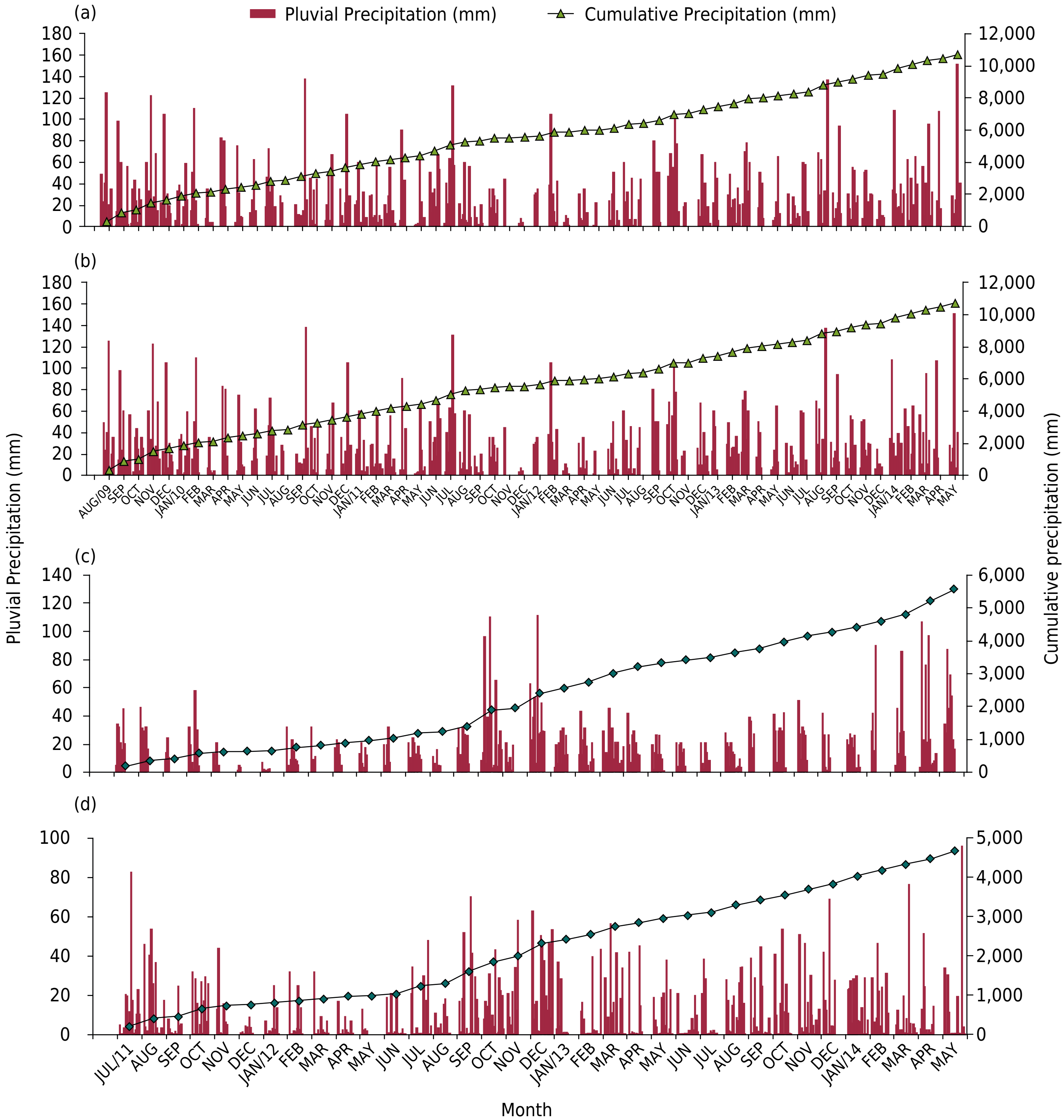

Figure 1. Daily and cumulative precipitation during the experimental period for experiments I (a), II (b), III(c), and IV (d). Source: Instituto Nacional de Meteorologia.

0.10-0.15; 0.15-0.25; 0.25-0.40; and 0.40-0.60 m. The table 2 shows the results of this initial assessment, according to the methods described by Tedesco et al. (1995).

Experimental Design

A randomized block design with three replications was used in all experiments, in 8.0 × 8.0 m plots, covering an area of 64.0 m^2. In experiments I and II, in which the acidity of the surface layer was already corrected, the treatments consisted of the following gypsum rates: 0.0; 1.0; 2.0; 3.0; 4.0; 5.0; and 6.5 Mg ha^{-1}, applied on the soil surface. Experiments I and II were selected to test whether modern cultivars respond to inputs

Table 1. Sequence of crops cultivated in experiments I, II, III, and IV; crop cycle, fertilizer application, and time of yield evaluation

Crops	Cycle	Fertilization	Yield Evaluation
		Experiment I	
Black oats	May to Sep. 2009	Without fertilization	Experimental implementation
Maize	Sep. 2009/Feb. 2010	85.5 kg of N ha^{-1} (9 kg ha^{-1} at seeding and 76.5 kg ha^{-1} topdressed), 120 kg ha^{-1} of P_2O_5, and 120 kg ha^{-1} of K_2O; urea as N source	Feb. 2010
Wheat	July to Nov. 2010	11.5 kg of N, 57.5 kg of P_2O_5, and 57.5 kg of K_2O; 20.25 kg ha^{-1} of N topdressed	Not harvested due to frost at flowering
Soybean	Nov. 2010/Apr. 2011	4.8 kg of N, 48 of P_2O_5, and 48 kg of K_2O	Apr. 2011
Black oats	May to Oct. 2011	Without fertilization	Cover crop
Soybean	Nov. 2011/Apr. 2012	4.8 kg of N, 48 kg of P_2O_5, and 48 kg of K_2O	Feb. 2012
Black oats	May to Aug. 2012	Without fertilization	Cover crop
Maize	Sep. 2012/Feb. 2013	85.5 kg ha^{-1} of N (9 kg ha^{-1} at seeding and 76.5 kg ha^{-1} topdressed), 120 kg ha^{-1} of P_2O_5, and 120 kg ha^{-1} of K_2O	Feb. 2012
Wheat	Jul. to Nov. 2013	11 kg of N, 55 of P_2O_5, 55 kg of K_2O, and 18 kg ha^{-1} of N	Nov. 2013
Soybean	Nov. 2013/Mar. 2014	4.4 kg of N, 44 kg of P_2O_5, and 44 kg of K_2O	Mar. 2014
		Experiment II	
Black oats	May to Sep. 2009	Without fertilization	Experimental implementation
Soybean	Nov. 2009/Apr. 2010	4.8 kg of N, 48 kg of P_2O_5, and 48 kg of K_2O	Apr. 2010
Oats/Radish	May to Aug. 2010	Without fertilization	Cover crop
Maize	Out. 2010/Feb. 2011	85.5 kg ha^{-1} of N (9 kg ha^{-1} at seeding and 76.5 kg ha^{-1} topdressed), 120 kg ha^{-1} of P_2O_5, and 120 kg ha^{-1} of K_2O	Feb. 2011
Black oats	May to Sep. 2011	Without fertilization	Cover crop
Soybean	Nov. 2011/Mar. 2012	4.8 kg of N, 48 kg of P_2O_5, and 48 kg of K_2O	Mar. 2012
Black oats	May to Sep. 2012	Without fertilization	Cover crop
Soybean	Nov. 2012/Mar. 2013	4.8 kg of N, 48 kg of P_2O_5, and 48 kg of K_2O	Mar. 2013
Wheat	Jul. to Nov. 2010	11 kg of N, 55 kg of P_2O_5, 55 kg of K_2O, and 18 kg ha^{-1} of N	Nov. 2013
Soybean	Nov. 2013/Mar. 2014	4.4 kg of N, 44 kg of P_2O_5 and 44 kg of K_2O	Not evaluated due to harvest problems
		Experiment III	
Black oats	May to Sep. 2011	Without fertilization	Experimental implementation
Soybean	Nov. 2011/Mar. 2012	4.2 kg of N, 42 kg of P_2O_5, and 42 kg of K_2O	Prior to evaluations.
Wheat	Jul. to Nov. 2012	10.5 kg of N, 52.5 kg of P_2O_5, 52.5 kg of K_2O, and 18 kg ha^{-1} of N	Nov. 2012
Soybean	Nov. 2012/Mar. 2013	4.2 kg of N, 42 kg of P_2O_5, and 42 kg of K_2O	Mar. 2013
Wheat	Jul. to Nov. 2013	10.5 kg of N, 52.5 kg of P_2O_5, and 52.5 kg of K_2O, and 18 kg ha^{-1} of N	Nov. 2013
Soybean	Nov. 2013/Mar. 2014	4.2 kg of N, 42 kg of P_2O_5, and 42 kg of K_2O	Mar. 2014
		Experiment IV	
Black oats	May to Sep. 2011	Without fertilization	Experimental implementation
Soybean	Nov. 2011/Mar. 2012	4.6 kg of N, 46 kg of P_2O_5, and 46 kg of K_2O	Prior to evaluations
Wheat	Jul. to Nov. 2012	11 kg of N, 55 kg of P_2O_5, and 55 kg of K_2O, and 22.25 kg N ha^{-1}	Nov. 2012
Soybean	Nov. 2012/Mar. 2013	4.4 kg of N, 44 kg of P_2O_5, and 44 kg of K_2O	Mar. 2013
Black oats	May to Sep. 2013	Without fertilization	Cover crop
Soybean	Nov. 2013/Mar. 2014	4.6 kg of N, 46 kg of P_2O_5, and 46 kg of K_2O	Not evaluated due to harvest problems

Urea as N source $[CO(NH_2)_2]$ (45 % N), P was supplied as triple superphosphate $Ca(H_2PO_4)_2.H_2O$ (45 % P_2O_5), and K in potassium chloride (60 % K_2O).

Table 2. Soil chemical properties before treatment application to a dystrophic Oxisol in four experimental areas under no-tillage management in Rio Grande do Sul

Depth	pH(H_2O)	Al^{3+}	Ca^{2+}	Mg^{2+}	K^{+}	Ca/Mg	CEC	P	S	BS	Al saturation	Clay	SOM
m		—— $cmol_c\ dm^{-3}$ ——					$cmol_c\ dm^{-3}$	— $mg\ dm^{-3}$ —		—— % ——		— $g\ kg^{-1}$ —	
Experiment I (August 2009)													
0.00-0.05	5.6	0.0	6.7	3.5	0.18	1.9	15.6	28.3	8.6	68.2	0.0	530.0	3.9
0.05-0.10	5.6	0.0	6.1	3.5	0.13	1.7	14.9	10.1	17.3	67.6	0.0	600.0	3.4
0.10-0.15	5.4	0.2	5.4	3.2	0.07	1.7	14.8	5.0	12.9	59.9	1.8	670.0	2.8
0.15-0.25	5.2	0.4	4.3	3.0	0.05	1.4	15.2	2.6	10.8	49.5	4.6	680.0	2.0
0.25-0.40	4.9	0.8	2.5	2.6	0.04	1.0	15.6	1.1	14.0	34.8	16.1	700.0	1.6
0.40-0.60	4.5	0.9	2.1	2.3	0.03	0.9	15.3	0.8	15.1	30.9	23.9	740.0	1.1
Experiment II (August 2009)													
0.00-0.05	5.9	0.0	4.9	2.2	0.40	2.2	11.6	62.8	16.9	65.6	0.0	240.0	3.6
0.05-0.10	5.7	0.0	4.2	2.0	0.36	2.1	10.3	27.0	14.5	64.9	0.0	320.0	2.3
0.10-0.15	5.7	0.0	3.3	2.0	0.35	1.6	9.7	16.6	10.4	59.1	0.0	370.0	1.7
0.15-0.25	5.4	0.1	2.6	1.8	0.33	1.4	9.4	4.07	8.05	51.4	1.3	460.0	1.3
0.25-0.40	5.1	0.4	2.5	1.3	0.25	1.9	11.4	2.40	9.6	37.8	8.1	500.0	1.3
0.40-0.60	4.8	1.2	1.8	0.7	0.17	2.5	12.2	0.97	7.2	22.3	30.9	520.0	0.7
Experiment III (August 2011)													
0.00-0.05	5.0	0.5	4.5	2.8	0.46	2.0	16.2	29.2	4.9	54.4	5.6	420.0	3.9
0.05-0.10	4.6	1.2	3.1	3.1	0.23	1.0	13.4	6.8	2.3	43.1	15.3	600.0	1.5
0.10-0.15	4.3	1.8	1.9	1.2	0.15	0.9	14.8	3.6	1.1	27.7	29.9	650.0	0.9
0.15-0.25	4.2	2.5	1.5	1.7	0.09	0.9	13.2	2.4	6.2	21.0	42.3	770.0	0.9
0.25-0.40	4.2	2.4	1.4	1.6	0.06	0.9	11.6	1.6	4.7	23.3	43.2	750.0	0.6
0.40-0.60	4.2	2.1	1.2	1.4	0.06	0.8	11.5	1.8	1.6	23.8	43.3	650.0	0.7
Experiment IV (August 2011)													
0.00-0.05	6.2	0.0	6.5	3.5	0.37	1.9	12.5	14.7	5.2	82.2	0.0	295.0	3.3
0.05-0.10	6.1	0.0	4.7	2.3	0.23	2.0	10.5	2.7	5.2	68.4	0.0	335.0	2.6
0.10-0.15	5.0	0.5	2.3	2.2	0.15	1.1	12.5	10.7	4.2	37.0	9.9	400.0	2.5
0.15-0.25	4.7	1.3	1.7	1.8	0.11	0.9	13.0	4.0	2.4	28.0	25.7	440.0	2.3
0.25-0.40	4.4	2.9	1.4	1.1	0.10	1.2	20.0	2.3	5.7	13.4	52.6	500.0	1.9
0.40-0.60	4.2	4.3	1.1	0.5	0.08	1.1	22.3	0.9	12.1	9.6	66.9	610.0	1.2

Al^{3+} saturation: extracted with 1 KCl mol L^{-1} and titrated with NaOH 0.0125 mol L^{-1}; Ca^{2+} and Mg^{2+}: extracted with KCl 1 mol L^{-1} and determined by atomic absorption spectrophotometry; K^{1+}: extracted with Mehlich-I solution; CEC: cation exchange capacity at pH 7.0; P: extracted with Mehlich-I; S: extraction with $Ca(H_2PO_4)_2$ (500 mg L^{-1} of P) and determined by turbidimetry; BS: base saturation; and SOM: soil organic matter extracted by wet combustion.

even under satisfactory soil conditions. The treatments of experiment III consisted of 0.0; 1.0; 2.0; 3.0; 4.0; and 5.0 Mg ha^{-1} of gypsum applied on the soil surface. In April 2013, 22 months after gypsum input, the main treatments were divided and the subplots corresponded to dolomitic lime rates of 0.0 and 2.0 Mg ha^{-1}. In experiment IV, arranged in a 4 × 4 factorial design, the treatments consisted of four gypsum rates: 0.0; 2.0; 4.0; and 6.0 Mg ha^{-1} and four lime rates: 0.0; 2.4; 3.6; and 4.8 Mg ha^{-1}. The gypsum and lime inputs were applied simultaneously on the soil surface. The intermediate lime rate (3.6 Mg ha^{-1}) was determined to achieve 70 % BS in the 0.00-0.20 m layer. The intermediate gypsum rate was determined according to equation 1, proposed by Quaggio and Raij (1996), recommended for gypsum application on soils of the Cerrado region and in Central Brazil.

$$Gypsum\ rate = clay\ content \times 60 \qquad \text{Eq. 1}$$

The composition of the agricultural gypsum ($CaSO_4.2H_2O$) used in the experiments was as follows: 210 g kg^{-1} of Ca^{+2}, 155 g kg^{-1} of S-SO_4^{2-}, 0.024 g kg^{-1} of F^-, and 9.0 g kg^{-1} of P_2O_5. The dolomitic lime contained 30 % CaO and 20 % MgO, with an effective $CaCO_3$ equivalent value of 80 %.

Soybean, wheat, and maize cultivars

The cultivars and hybrids selected for this study were the currently most commonly planted in Rio Grande do Sul: *Pioneer* 3069 in experiments I and II and *Dekalb* 240 in the others for maize (*Zea mays* L.); *Nidera* 5909 in experiments I and II and *Coodetec* 235RR in the others for soybean; *Quartzo* in experiments I and II and BRS *Tarumã* in the others for wheat (*Triticum aestivum* L.). The soybean [*Glycine max* (L.) Merr.] cultivars and maize hybrids used in the experiments were transgenic, featuring a short cycle, short height and high yield potential. Maize was sown at a density of 4 seeds per meter in rows spaced 0.50 m apart; soybean at 12 seeds per meter (inoculated with *Bradyrhizobium japonicum*) in rows spaced 0.50 m apart; and wheat at 60 seeds per meter, in rows spaced 0.20 m apart.

Description of the main evaluations

In experiment I, the soil was sampled 6, 14, 22, 32, 44, and 56 months after treatment application and 6, 22, 32, 44, and 56 months after treatments in experiment II. In experiments III and IV, the samples were taken 15 and 30 months after treatment application. In experiment III, the soil sampling after 30 months occurred eight months after lime application in subplots. Three subsamples were blended to form a composite sample of the layers 0.00-0.05; 0.05-0.10; 0.10-0.15; 0.15-0.25; 0.25-0.40; and 0.40-0.60 m, taken from hand-dug trenches (0.3 × 0.3 × 0.6 m). The soil samples were collected with a spatula from the front wall of the trench, dried, and the roots and plant residues removed.

The following soil chemical properties were determined: Al^{+3} content extracted with KCl 1 mol L^{-1} and titrated with NaOH 0.0125 mol L^{-1}; Ca^{+2} and Mg^{+2} extracted with KCl 1.0 mol L^{-1} and determined by atomic absorption spectrophotometry. The K^+ ions were extracted with Mehlich-I solution and determined by flame photometry. From these properties, the values of base saturation (BS) and Al saturation were calculated.

Samples of maize, soybean, and wheat were collected by hand near the soil sampling points to evaluate their yield at physiological maturity. Were collected 4 m of the crops and the grain weight was corrected to a moisture content of 13 %.

The relative grain yield (RY) of the crops were determined for each experimental unit by equation 2:

$$RY\ (\%) = \frac{\textit{Crop yield}\text{ in }\textit{the plot}}{\textit{Maximum crop yield}\text{ in }\textit{the experiment}} \times 100 \qquad \text{Eq. 2}$$

The maximum crop yield was determined by fitting the equation to the yield and rates used in the treatments.

Statistical analysis

The effect of the gypsum rates on grain yields was assessed by regression analysis using the PROC REG procedure in SAS (Statistical Analysis Systems Institute Inc., 2009). In experiment IV, where an interaction between gypsum and lime rates was observed, the yield results were assessed using response surface methodology and a binomial function between the wheat and soybean yields and gypsum and lime rates. In case of significant effects of gypsum rates on yield and between the relative yield and BS and Al^{3+} saturation in the different soil layers, regression analysis as used.

RESULTS AND DISCUSSION

Soybean, maize, and wheat yield in the control treatment

As the experimental areas had different levels of chemical soil quality at the beginning of the experiment, the yields in the control treatments varied according to the soil quality. The highest maize yield among the control treatments (Figure 2a) was found in experiment II, in which the chemical quality in the root zone (RZ) was the best (BS >65 % and Al^{3+} saturation close to 0.0 %) (Table 2). Thus, the average maize yield in experiment II was 5.9 % higher than in experiment I.

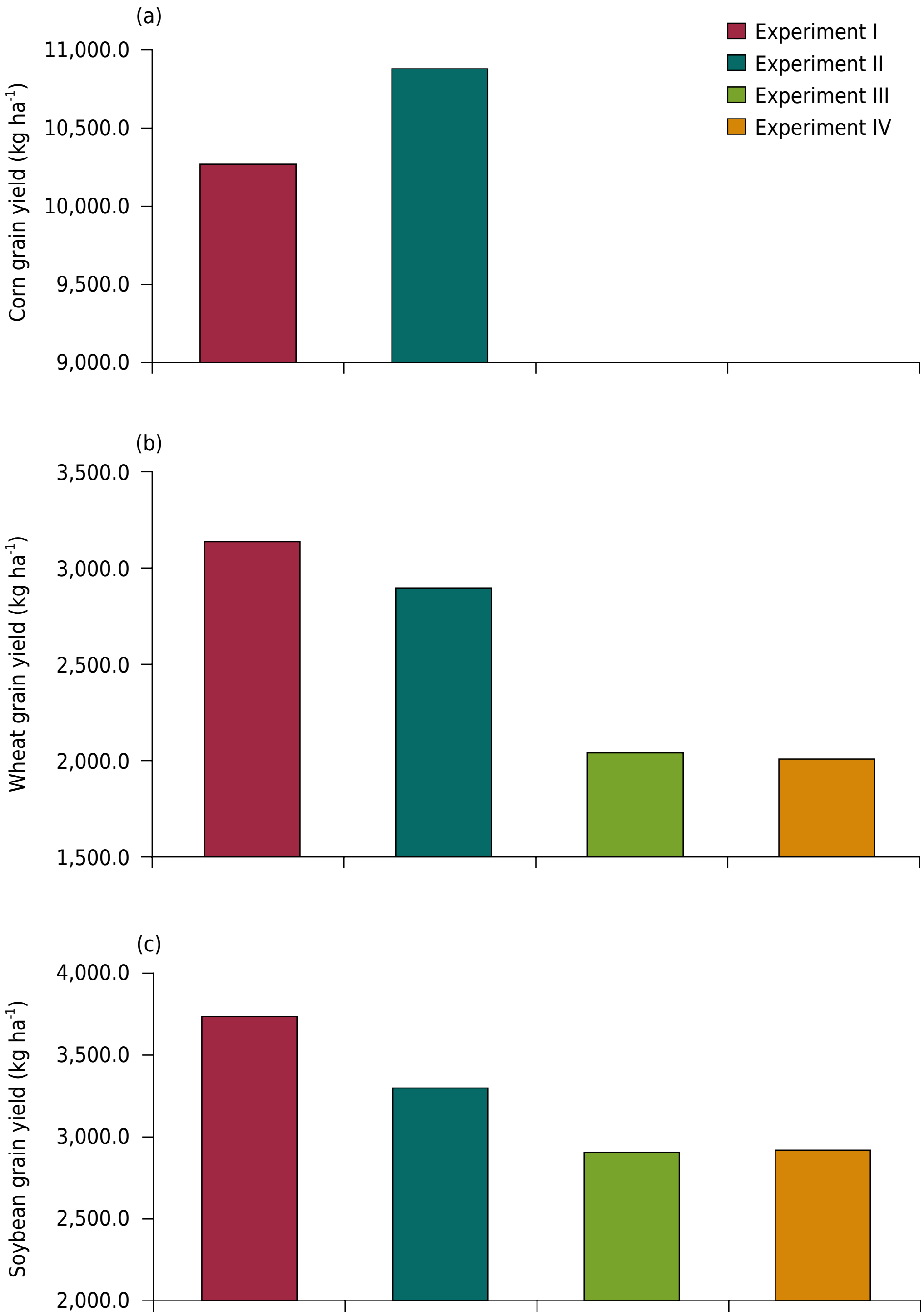

Figure 2. Average yield of the control plots of maize (a), wheat (b), and soybean (c).

The highest wheat yields in the control treatments (Figure 2b) were found in experiments I and II, which had satisfactory chemical quality in the RZ (Table 2). The average wheat yield in experiments III and IV was similar, however 49 % lower than in experiments I and II (Figure 2b). This result was associated with a low chemical quality [BS <65 % and Al^{3+} saturation >10 % (CQFS-RS/SC, 2004)] in the surface layer (0.00-0.10 m) in experiment III and the steep gradient in soil quality reduction from the topsoil layer to the lower layer (0.10-0.25 m) in experiment IV (Figure 2).

Similar to maize and wheat, the soybean yields were highest in experiments I and II, with on average 20.9 % higher yields than in experiment III (Figure 2c). The temporal analysis of grain yields in the soils with different chemical quality in the RZ indicated that in areas under crop rotation and with improved chemical quality in a thicker surface layer (experiments I and II) yields were higher, providing a higher yield stability over time than in experiments with low chemical quality (experiment III) or with improvements of the topsoil only (experiment IV).

Crop yield response to gypsum and lime inputs

Seventeen crop yields were evaluated during the study period (nine soybean, five wheat, and three maize harvests), in four experiments (Figure 3). In three (17 %) of these crops, no yield increase was observed in response to gypsum and lime inputs. The absence of responses in soybean in experiment I (2013/14) (Figure 3a), and II (2009/10) and of a wheat crop in experiment II (2013) (Figure 3b) was probably associated with the high and regular precipitation distribution during the cycle of these crops. In some experiments, the increase in soybean yield in response to gypsum input depended on the precipitation regime, usually with slight or no increases under high precipitation (Caires et al., 2011a; Rampim and Lana, 2011; Rampim et al., 2015). The discussion of the crop yield responses to inputs was ordered according to the initial soil chemical quality, to facilitate the interpretation of the results.

Crop responses to gypsum and lime applications in soils with high chemical quality in the RZ

Experimental area I

According to the fitted equation for maize in 2009/10 (Figure 3a), a gypsum rate of 5.9 Mg ha^{-1} induced the highest yield (11,247 kg ha^{-1}), representing an increase of 8.0 % compared to the control, in spite of the high precipitation during the crop cycle (1,249 mm) (Figure 1). For the second maize crop (2012/13) in this experimental area, grain yield had a linear increase in response to the gypsum rates, reaching a yield of 10,406 kg ha^{-1} in response to the maximum gypsum rate (6.5 Mg ha^{-1}). This represents an increase of 8.0 % compared to the control, even though the control treatments already presented high maize yield (10,700 kg ha^{-1} in 2009/10 and 9,837 kg ha^{-1} in 2012/13). These results suggest that to explore the potential of modern maize hybrids, gypsum should be applied even in soils with satisfactory chemical soil quality in RZ (Table 2) and under favorable precipitation regime (Figure 1). Increases in maize yields with gypsum rates up to 12.0 Mg ha^{-1} were reported by Pauletti et al. (2014) even under normal precipitation. An increase in nitrogen use efficiency (NUE) associated to gypsum input, as reported by Torbert and Watts (2014) and Caires et al. (2015), may be an explanation for the maize yield increase, since a deeper root system provided by soil chemical improvement favors nitrate uptake in subsurface layers, in years with high precipitation. In a meta-analysis, Pittelkow et al. (2015) reported that continuous no-tillage management can decrease maize yields up to 7.6 % and in tropical regions this value could be even doubled. This result is partly attributed to insufficient plant N supply and other nutrient deficiencies under NTS in relation to conventional tillage (Rusinamhodzi et al., 2011; Ogle et al., 2012). Therefore, it is critical to enhance the NTS performance in tropical soils by developing strategies that allow improvements of NUE, e.g., gypsum input.

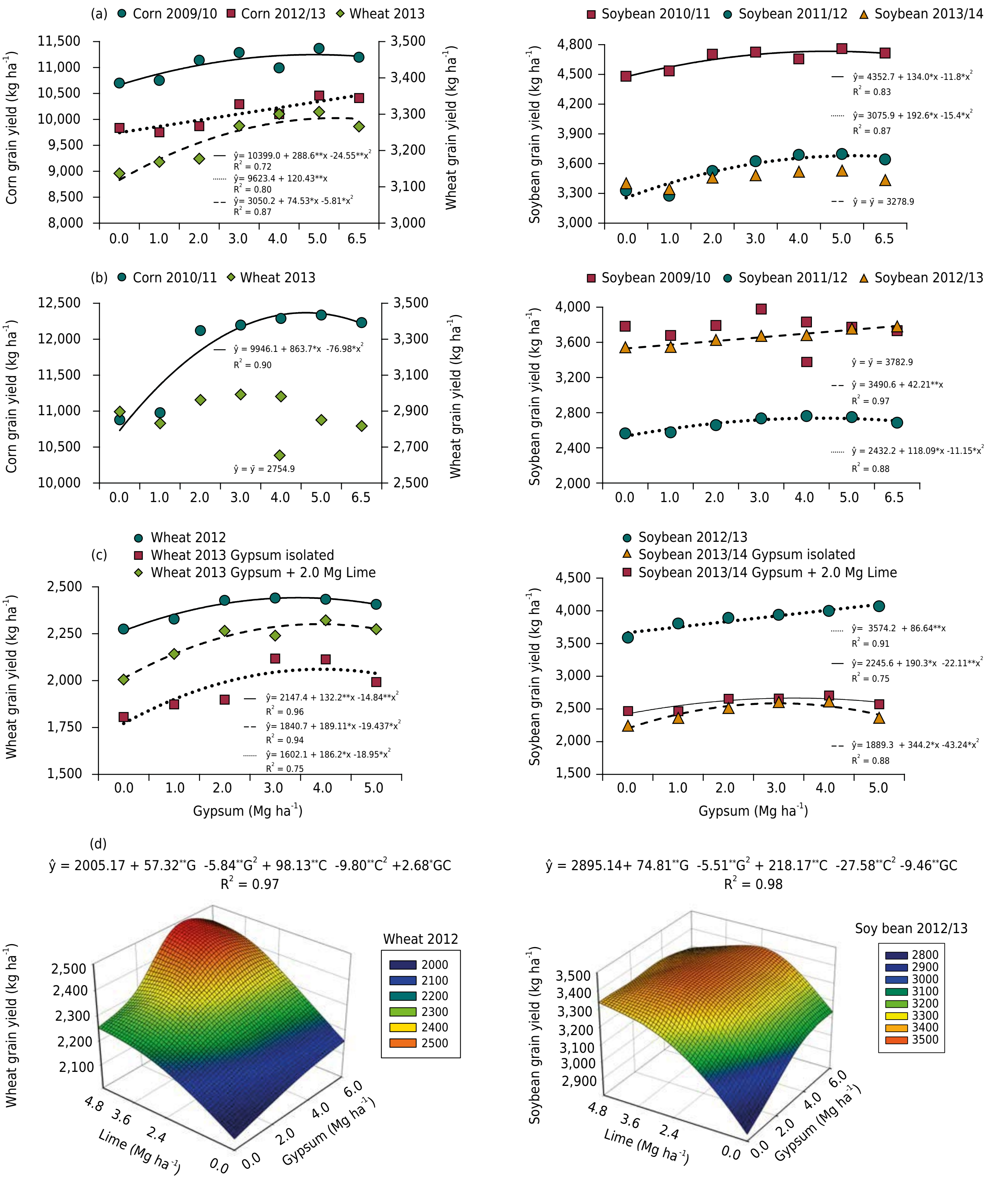

Figure 3. Yield of soybean, maize, and wheat for experiment I (a), experiment II (b), experiment III (c), and experiment IV (d) in relationship to the separately gypsum rates or combined with the lime. * and **: significant at 5 and 1 % error probability, respectively.

For wheat crop (2013), based on the fitted equation, the highest yield was 3,288 kg ha^{-1}, under a gypsum rate of 6.4 Mg ha^{-1}, representing an increase of 7.8 % compared to the control (Figure 3a). Similar results were observed by Caires et al. (2002), who found an increase in wheat yield in response to gypsum rates of up to 9.0 Mg ha^{-1}, even in a year with no water stress.

For soybean, an increase in grain yield was observed in response to gypsum input in two of the three years evaluated (Figure 3a). In 2010/11, soybean yield increased 8.8 % (4,733 kg ha^{-1}) in response to gypsum rates of 5.7 Mg ha^{-1} compared to the control, according to the fitted equation. This yield was the highest of all four experimental areas, exceeding the RS state average by approximately 82.0 %. This result confirms the high yield potential (≈ 5.0 Mg ha^{-1}) of the transgenic genetic plant material and excellent crop management on the selected farms (reference farms with high technology input). In a recent soybean yield contest in Brazil, aiming at soybean yields >6 Mg ha^{-1}, the use of gypsum was frequently reported as one of the management strategies used to develop a thicker Ca^{2+}-rich, Al^{3+} -free layer with high BS (CESB, 2015). In the second soybean crop year (2011/12), the relative yield (19.0 %) was even higher than in the previous year, in response to gypsum rate of 6.2 Mg ha^{-1}, compared to the control, reaching a yield of 3,678 kg ha^{-1} (22 % lower than in the first year). This higher relative increase in the second soybean year was related with the lower precipitation during the crop cycle (401 mm) compared to precipitation observed in the previous crop season (808 mm) (Figure 1). Under water stress, the plants invest more photoassimilates in roots to use water stored in deeper soil layers (Shainberg et al., 1989). Thus, the increase in Ca^{2+} content and the lower activity of Al^{3+} in the RZ in treatments with gypsum input probably enhanced root development, mitigating the water stress. Increases in soybean yield by applying gypsum rates in an Oxisol in the state of Paraná were reported by Pauletti et al. (2014). In a study with modern soybean cultivars, Bender et al. (2015) reported that a total Ca^{2+} uptake as high as 120 kg ha^{-1} for a yield of 3,500 kg ha^{-1}. The quantity of Ca^{2+} demanded by modern soybean is only exceeded by N and K uptake. In addition, the S demand of modern soybean was close to 20 kg ha^{-1} (Bender et al., 2015). These results may explain the marked soybean yield response to gypsum input.

Experimental area II

The first maize crop (2010/11) in this experimental area had a quadratic yield response to gypsum rates, reaching an increase of 24 % (2,413 kg ha^{-1}) over the control. The gypsum rate of 5.6 Mg ha^{-1} enabled a grain yield of 12,360 kg ha^{-1} (Figure 3b), based on the fitted equation. This maize yield was the highest of all experimental areas and was 2.6 times higher than the RS state average. Thus, maize yield was positively affected by gypsum input, even when the yield in the control treatment was high (≈10 Mg ha^{-1}), as a result of the satisfactory initial chemical quality of the RZ (Table 2). A similar relative increment in maize yield was reported by Fageria (2001), who observed an increase of 23.0 % in relation to the control. For wheat (2013), no significant increase in yield was observed in response to gypsum (Figure 3b).

The treatment provided significant increase in the first soybean harvest (2009/10) (Figure 3b). For the second soybean crop (2011/12), a yield increase of 13.0 % was observed in response to a gypsum rate of 5.3 Mg ha^{-1}, reaching a yield of 2,744 kg ha^{-1}, according to the fitted equation. The high relative increase in soybean yield was probably related to the low precipitation during the crop cycle (401 mm) (Figure 1), which resulted in a lower average yield than in the other years in the same experimental area (Figure 3b). In the third soybean crop (2012/13), there was a linear yield increase to the gypsum rates, with a relative yield increase of 7.8 % at the highest gypsum rate (6.5 Mg ha^{-1}) compared to the control, reaching 3,764 kg ha^{-1}. In addition, the maximum effect on soybean yield was observed after 44 months of gypsum application.

Crop responses to gypsum and lime applications in soils with low chemical quality or abrupt quality drop in the RZ

Experimental area III

The soil of this experiment differed from the others by presenting high acidity and low BS still in upper layers (0.00-0.05 and 0.05-0.10 m) (Table 2). Furthermore, the low Ca^{2+}

saturation in the 0.25-0.40 m layer indicated that this cropland would have the highest probability of responding to gypsum input. In fact, as expected, yield increases were observed in all crop types and years evaluated in response to gypsum rates applied separately or in combination with lime (Figure 3c). For wheat, the two years evaluated had a quadratic response to gypsum input. In the first wheat harvest (2012) (Figure 3c), the gypsum rate responsible for the highest yield (2,448 kg ha^{-1}) was 4.5 Mg ha^{-1}, with a yield increase of 14.0 % in relation to the control treatment, according to the fitted equation.

In the second year of wheat (2013), after plot subdivision for lime input, the yield of 2,060 kg ha^{-1} at a gypsum rate of 4.9 Mg ha^{-1} applied separately, promoted an increase of 28.0 % over the control. Gypsum in combination with lime resulted in a maximum yield of 2,301 kg ha^{-1} in response to gypsum rates of 4.9 Mg ha^{-1} combined with 2.0 Mg ha^{-1} lime, resulting in an increase of 25.5 % over the control. This gypsum + lime was 12.0 % higher than the plot with only gypsum input at same rate (4.9 Mg ha^{-1}). This result reinforces the interaction effect provided by the combination of these inputs. On the other hand, a lime rate of 2.0 Mg ha^{-1}, applied separately, enabled an increase of 15.0 % compared to control. The yield obtained by lime applied separately (2.0 Mg ha^{-1}) was equivalent to the yield resulting from 2.5 Mg ha^{-1} gypsum applied separately. The same yield (2,060 kg ha^{-1}) achieved with separately applied gypsum at 4.9 Mg ha^{-1} was achieved with 1.4 Mg ha^{-1} gypsum together with 2.0 Mg ha^{-1} lime, with lower cost (Figure 3c).

The first soybean harvest (2012/13) had a linear yield response to gypsum rates, with a maximum yield (4,007 kg ha^{-1}) achieved with the rate of 5.0 Mg ha^{-1}, representing an increase of 12.0 % compared to the control (Figure 3c). The higher response of modern soybean cultivars to Ca^{2+} (Bender et al., 2015) and S (Broch et al., 2011) helped to explain these results.

The second soybean harvest (2013/14) induced a quadratic yield response to gypsum input (Figure 3c). The highest yield (2,574 kg ha^{-1}) was achieved with a rate of 4.0 Mg ha^{-1}, representing an increase of 36.5 % compared to the control. Combined gypsum + lime application obtained the highest yield (2,655 kg ha^{-1}) with rates of 4.3 Mg ha^{-1} gypsum and 2.0 Mg ha^{-1} lime, i.e., an increase of 18.2 % over the control. Lime applied separately increased soybean yield by 19.0 % compared to the control. The response to lime was expected considering the low chemical quality in the beginning of the experiment (Table 2). According to the fitted equation, the combination of 2.0 Mg ha^{-1} lime with 2.3 Mg ha^{-1} gypsum reached the highest experimental yield (2,574 kg ha^{-1}), which was also obtained with 4.0 Mg ha^{-1} gypsum applied separately. In addition, the response curve to gypsum + lime application was higher than the curve of gypsum applied separately. The combination of gypsum with lime, especially applied to acid soils, induced a positive interaction effect compared to the separately applied inputs (Raij, 2008). Similar results were reported by Caires et al. (2004, 2011a), Souza et al. (2012), Dalla Nora et al. (2014a), and Pauletti et al. (2014).

Experimental area IV

The experiment at this fourth site was arranged in a 4 × 4 factorial design, thus enabling further assessments of the interaction effect of gypsum and lime inputs (Figure 3d). Interactions ($p<0.01$) were observed between the lime and gypsum rates and the soybean and wheat yields. According to the fitted binomial equation, for the first wheat harvest (2012), the highest yield of 2,454 kg ha^{-1} was obtained with the combination of 4.7 Mg ha $^{-1}$ of lime with 4.9 Mg ha^{-1} of gypsum (Figure 3d), representing an increase of 18.0 % compared to the control. Gypsum applied separately induced a maximum wheat yield of 2,149 kg ha^{-1} at 4.9 Mg ha^{-1}, representing an increase of 7.2 % compared to the control. On the other hand, lime applied separately obtained a maximum yield of 2,251 kg ha^{-1} at 4.7 Mg ha^{-1}, i.e., an increase of 12.2 % compared to the control. Therefore, the yield response to lime was 4.7 % higher than that of gypsum, although the rate for maximum yield was similar for both inputs.

In the first soybean harvest (2012/13) (Figure 3d), the maximum yield was 3,350 kg ha^{-1} in response to 4.0 Mg ha^{-1} of lime combined with 6.0 Mg ha^{-1} of gypsum, resulting in a yield increase of 15.7 % compared to control, according to the fitted binomial equation. The maximum yield obtained with separately applied gypsum was 3,146 kg ha^{-1} at a rate of 6.0 Mg ha^{-1}, representing an increase of 8.7 % compared to the control. On the other hand, lime applied separately obtained a maximum yield of 3,326 kg ha^{-1} at 4.0 Mg ha^{-1}, representing an increase of 14.9 % compared to the control. This yield response to separately applied lime was 5.7 % higher than that found with separate gypsum, even at a 50 % higher rate of gypsum than lime. The result of higher soybean and wheat yield responses to lime than to gypsum in this experimental area, reinforce that in cases of acid subsoil, the application of amendment only in the surface layer (0.00-0.10 m) is not enough to ensure high yields. In addition, this soil would not require lime input based on the current recommendation criteria of CQFS-RS/SC (2004) [pH(H_2O) <5.5; BS <65 %; and Al^{3+} saturation >10 % for the 0.00-0.10 m layer], although yield responses were observed up to 4 Mg ha^{-1} for soybean and 4.7 Mg ha^{-1} for wheat.

These results suggest that the high performing transgenic soybean and modern wheat are more responsive to lime than the traditional cultivars, which were used to establish the response curves to this input. The characteristics of higher yield potential, short cycle, lower soil acidity tolerance, and less developed root system were among the factors contributing to this result. Similarly, the response of these genetic materials to gypsum should be further evaluated since this input is not recommended for soils in the south of Brazil. The interaction effect between gypsum and lime found in this experiment was similar to that observed in experiment III and to results reported previously by Raij (2008) and Caires (2013). The results of this experimental area highlight the need of amending a deeper layer than the topsoil to explore the yield potential of modern cultivars in Oxisols.

Cumulative yield of grain crops in response to gypsum and lime applications

Crop rotation is preconized management to NTS aiming to sustain high crop yields (Pittelkow et al., 2015). In addition, lime and gypsum inputs have relevant residual effects. Thus, an analysis of the cumulative grain yield over time at the same site would be required to accurately assess the impacts of gypsum and lime on crop yields

For the cumulative yield in all experimental areas quadratic yield responses were observed for experiments I, II, and IV ($p<0.05$) and for experiment III ($p<0.01$) (Table 3). For experiment I, the maximum cumulative production of 36,826 kg ha^{-1} was obtained with a gypsum rate of 5.8 Mg ha^{-1} in an experimental period of 54 months (evaluation of six harvests). This rate induced a cumulative yield increase of 7.0 % (2,223 kg ha^{-1}) compared to the control, according to the fitted equation. Experiment II had a maximum cumulative yield of 25,626 kg ha^{-1} at a gypsum rate of 4.6 Mg ha^{-1} throughout the 54-month experimental period (evaluation of five harvests), representing an increase of 9.5 % (2,230 kg ha^{-1}) compared to the control, according to the fitted equation. The grain yield increase in response to gypsum was near 495 kg ha^{-1} yr^{-1} in both experiments. For experiment III, the maximum cumulative yield was 11,225 kg ha^{-1} at a gypsum rate of 3.8 Mg ha^{-1}, representing an increase of 12.0 % (1,158 kg ha^{-1}) over the control (evaluation of four harvests). The grain yield increase (386 kg ha^{-1} yr^{-1}) obtained with gypsum application to this acid soil was marked, although this input is not an acidity corrector. According to Farina et al. (2000), gypsum application induced increases of 135 kg ha^{-1} yr^{-1} (average of 10 harvests). Linear and significant increases in maize yields ($p<0.01$) 10 years after gypsum applications between 0.0 and 9.0 Mg ha^{-1} in an Oxisol under NTS were reported by Caires et al. (2011b).

Table 3. Cumulative yields of six, five, four, and two harvests for experiment I, II, III, and IV, respectively

Experiment I		Experiment II		Experiment III+		Experiment IV				
Gyp	C_{yield}	Gyp	C_{yield}	Gyp	C_{yield}	Gyp	Lime			
Mg ha^{-1}										
0.0	34,882	0.0	23,673	0.0	10,107		0.0	2.4	3.6	4.8
1.0	34,825	1.0	23,620	1.0	10,537		C_{yield}			
2.0	35,871	2.0	25,165	2.0	10,972		Mg ha^{-1}			
3.0	36,682	3.0	25,578	3.0	11,172	0.0	4,927	5,433	5,534	5,586
4.0	36,255	4.0	25,550	4.0	11,292	2.0	5,083	5,647	5,730	5,651
5.0	37,120	5.0	25,469	5.0	11,061	4.0	5,252	5,711	5,837	5,824
6.5	36,663	6.5	25,254			6.0	5,289	5,742	5,770	5,726
Effect										
$\hat{y}$ =34,603.0+771.8*x -7.0*x^{2} R^2=0.85		$\hat{y}$ = 23,396.0+967.1*x-105.4*x^{2} R^2=0.86		$\hat{y}$ = 10,068.0+614.7**x-81.6**x^{2} R^2=0.98		$\hat{y}$ =4,900.3+132.1**G-11.4**G^{2}+316.3**L-37.4**L^{2}-6.8GxL* R^2=0.98 (Experiment IV)				

Gyp: gypsum; C_{yield}: cumulative yield; +For experiment III, the yield was averaged between the treatments of separate gypsum application and gypsum combined with lime. * and **: significant at 5 and 1 % error probability, respectively. &: there was a significant interaction between gypsum and lime rates with yield, at 5 % error probability. G = gypsum; L = lime.

The maximum cumulative yield in experiment IV was 5,786 kg ha^{-1} in response to the combination of 4.2 Mg ha^{-1} lime and 5.8 Mg ha^{-1} gypsum, representing an increase of 18.0 % (886 kg ha^{-1}) compared to the control (Table 3). This relative yield increase was the highest in the four experimental areas. The annual yield increase was 443 kg ha^{-1} yr^{-1} (two harvests). Gypsum applied separately induced a maximum production of 5,283 kg ha^{-1} at 5.8 Mg ha^{-1}, representing an increase of 7.0 % (383 kg ha^{-1}) compared to the control. The annual yield increase was 192 kg ha^{-1} yr^{-1}. On the other hand, the treatments with separately applied lime at 4.2 Mg ha^{-1} induced an increase of 12.0 % (669 kg ha^{-1}) over the control. The annual yield increase was 334 kg ha^{-1} yr^{-1}. This result reinforces the need to alleviate the abrupt drop of chemical quality in the RZ to stabilize crop yields. The interaction between rates of 3.0 Mg ha^{-1} lime and 2.0 Mg ha^{-1} gypsum (experience-based rates frequently used by farmers) would achieve a cumulative grain yield of 5,690 kg ha^{-1} (97.0 % of the maximum grain yield in the experiment), representing an increase of 14.0 % (790 kg ha^{-1}) compared to the control, according to the fitted binomial equation. The annual yield increase was 395 kg ha^{-1} yr^{-1}, confirming the adequacy of the famer' strategy.

As expected, the chemical improvement in the RZ had very strong effects on crop yield increases in experiments III and IV (Table 3), where the chemical restrictions of the subsurface soil were most limiting than experiments I and II (Table 2). These results reinforce the importance of chemical amendment in the subsoil layers of Oxisols to facilitate water and mobile nutrient uptake by roots (Coleman and Thomas, 1967; Reeve and Sumner, 1972; Shainberg et al., 1989; Sumner, 1995; Farina et al., 2000; Caires et al., 2011b; Dalla Nora et al, 2014a).

Relative yield of grain crops affected by gypsum rates

In order to identify the yield response of each crop separately (Figure 4a, 4b, and 4c) and all crops together (Figure 4d) to gypsum input, the experimental areas were analyzed separately and the yield of each treatment in relation to the highest yield obtained was calculated. Thus, a quadratic relative yield response ($p<0.05$) to the gypsum rates was found (Figure 4). This result is relevant considering that the chemical quality of the experimental areas differed largely in the beginning.

Soybean had a maximum relative yield (MRY) of 98.8 % in response to gypsum rates of 4.7 Mg ha^{-1}, while the control treatment reached 92.2 % (Figure 4a). The MRY of wheat was also 98.8 % at a gypsum rate of 4.5 Mg ha^{-1}, while the control treatment reached 90.1 %,

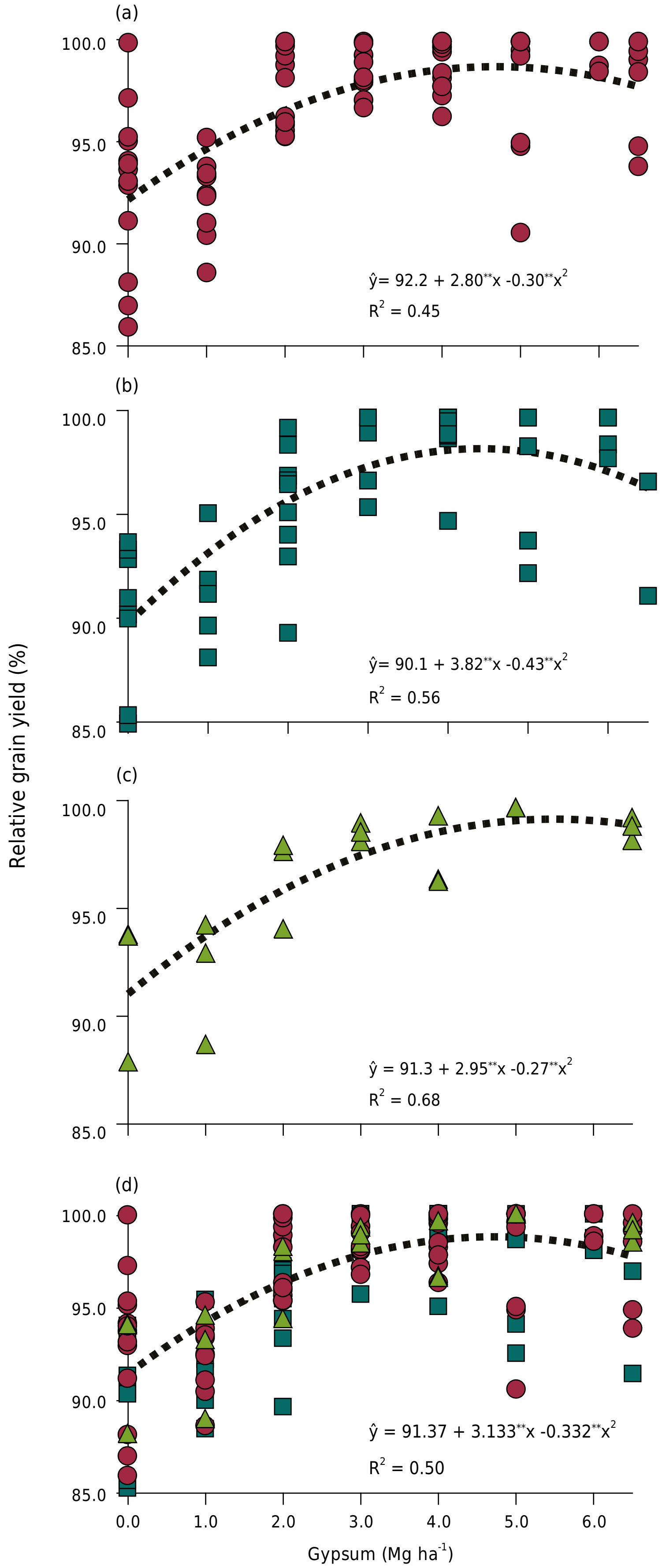

Figure 4. Relationship between relative soybean yield (a), wheat (b), maize (c), and all harvests together (d) for all experiments together treated with separate gypsum rates or gypsum combined with lime. **: significant at 1 % error probability.

according to the fitted equation (Figure 4b). Maize had a MRY of 99.5 % at a gypsum rate of 5.5 Mg ha^{-1}, while the control treatment reached 91.3 % (Figure 4c). Therefore, maize (8.2 %) and wheat (8.7 %) had a higher increase in relative yield than the control, while soybean had the lowest (6.6 %). The higher gypsum response of maize and wheat are probably due to the fact that Poaceae have roots with a lower cation exchange capacity (CEC) than legumes. Thus, maize and wheat plants have roots with CEC between 100 and 200 mmol (+) kg^{-1} of root dry matter, while soybean has a root CEC between 400 and 800 mmol (+) kg^{-1} (Fernandes and Souza, 2006). Roots with high CEC accumulate bivalent ions, different from the roots with low CEC, which take up monovalent ions more efficiently (Broyer and Stout, 1959). Thus, maize and wheat are less efficient than soybean in taking up Ca^{2+} from the soil solution, justifying the higher response to gypsum (Caires et al., 2004). Another possible explanation for these results is the improvement in NUE for wheat and maize associated with the deeper growth of the root system in the soil.

In the combined analysis of the crop types (Figure 4c), the gypsum rate of 4.7 Mg ha^{-1} obtained a maximum relative yield of 98.8 %, while the control reached 91.4 %. Similar results that showed the positive effect of gypsum on increasing grain yields were reported in several studies (Farina et al., 2000; Caires et al., 2004, 2005; Souza et al., 2012; Caires, 2013; Dalla Nora and Amado, 2013; Pauletti et al., 2014). Considering an average regional cost of 1.0 Mg gypsum of US$ 48.54 and an average value of 1.0 kg soybean of US$ 0.345, an amount of 661.0 kg soybean would be required to compensate the expenses of the rate that reached the MRY (4.7 Mg ha^{-1}). In this study, the soybean harvests of 2010/11 and 2011/12 in experiment I accumulated 981 kg ha^{-1} for the rate that reached the maximum yield in relation to the control. Thus, despite the high initial investment with gypsum input, the first harvests would already achieve positive economic results. These results are even more evident in the described experiments where the residual effect of gypsum was verified in the long term.

Relationships between soil layer and crop yield and critical soil chemical properties

The accumulated relative yield of soybean, maize, and wheat of each experimental area and the soil layers and their critical chemical properties were significantly correlated ($p<0.05$ and $p<0.01$) (Figure 5). The properties BS and Al^{3+} saturation of each soil layer and experimental area shown in this figure were the ones that best explained the crop yields.

In experiment I (Figure 5a), a positive linear relationship between the relative yield and BS ($p<0.01$) and a negative linear relationship with Al^{3+} saturation ($p<0.01$) were found in the 0.25-0.40 m layer. In this experimental area, this soil layer had a decrease in BS and an increase in Al^{3+} saturation in relation to the adjacent surface layer (Table 2). Thus, the major chemical restrictions to root growth at this site occurred below a depth of 0.25 m. The maximum cumulative relative yield had critical values of BS and Al saturation of approximately 60.0 and 3.0 %, respectively, in the 0.25-0.40 m layer. Similar results were found by Dalla Nora and Amado (2013), who reported maximum yield of maize and soybean, in two Oxisols in RS, when Al^{3+} saturation decreased to less than 10.0 % and BS increased to values above 50.0 % in the 0.25-0.40 m layer.

The soil of experiment II presented a positive quadratic relationship between relative yield and BS ($p<0.01$) and a negative linear relationship with Al^{3+} saturation ($p<0.01$) in the 0.00-0.40 m layer (averages of the 0.00-0.05; 0.05-0.10; 0.10-0.15; 0.15-0.25; and 0.25-0.40 layers) (Figure 5b). Thus, the relative yield was highest at BS close to 70 % and Al^{3+} saturation near zero. This result indicates the need to amend a thicker soil layer to achieve high yields for modern cultivars under NTS in dystrophic Oxisols.

The soil of experiment III had a positive and linear relationship between relative yield and BS ($p<0.01$) and a negative linear relationship with Al^{3+} saturation ($p<0.01$) in the 0.00-0.10 m layer (averages between the layers 0.00-0.05 and 0.05-0.10) (Figure 5c).

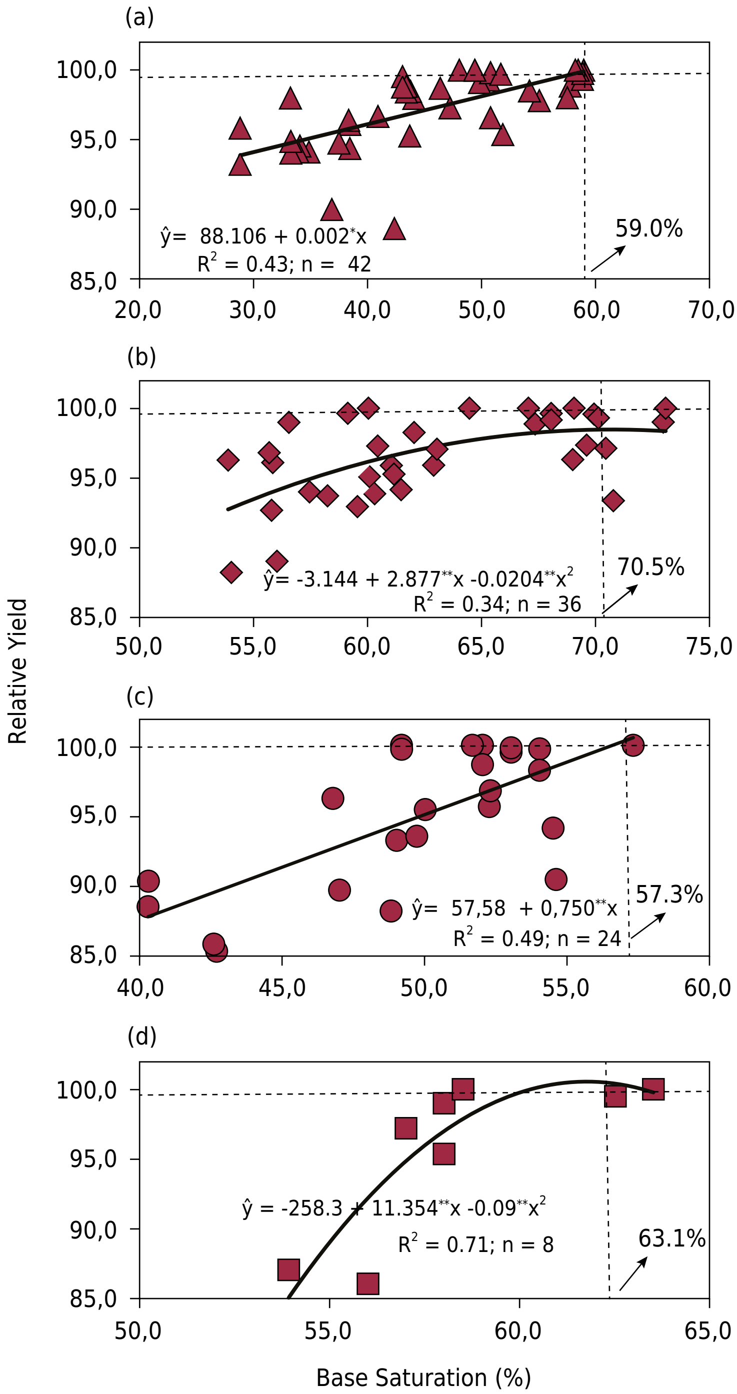

Figure 5. Relationship between the relative yield of soybean, maize and wheat with base saturation (BS) and Al saturation in the 0.25-0.40 m layer for experiment I (a); between the relative yield of soybean, maize and wheat, with BS and Al saturation in the 0.00 to 0.40 m layer for experiment II (b); between the relative yield of soybean and wheat with BS and Al saturation in the 0.00 to 0.10 m layer for experiment III (c); between the relative yield of soybean and wheat with BS and Al saturation in the 0.00 to 0.25 m layer for experiment IV (d). * and **: significant at 5 and 1 % error probability, respectively.

The highest yields in this experiment were achieved with BS of about 57.0 % and Al^{3+} saturation of 5.5 %, and due to the linear effect, values that would ensure maximum yields could not be found.

The soil of experiment IV (Figure 5d) had a positive quadratic effect ($p<0.01$) on relative yield and BS, and a negative linear effect ($p<0.05$) on Al^{3+} saturation in the 0.00-0.25 m layer (averages between the layers 0.00-0.05; 0.05-0.10; 0.10-0.15; and 0.15-0.25). The base and Al^{3+} saturation that induce the maximum relative yield were about 63 and 5 %, respectively, in that layer.

Based on the results in this study, to extend a BS content of 65 %, currently proposed for the 0.00-0.10 m layer, to the 0.00-0.25 m layer, and to decrease the Al^{3+} saturation from 10 to 5 %, could represent an important improvement in the criteria used for lime requirement for modern grain cultivars under NTS in RS. Evaluating soybean and maize crops in an Oxisol under NTS in Paraná, Vieira et al. (2013) observed that the critical BS content of 60 % in the 0.00-0.20 m layer enabled a maximum economic return.

The critical BS saturation suggested in this study is coherent with that reported by Raij et al. (1997), for the state of São Paulo, and Nicolodi et al. (2008), for the state of RS, for which the authors suggested a BS of 60 % in the 0.00-0.20 m layer for NTS. Studying soybean, maize and wheat cultivated for five years on an Oxisol in Paraná, Caires et al. (1999) reported that the economic return was highest when BS was 65 % in the 0.00-0.20 m layer. In another study, Caires et al. (2005) observed that by extending the return period to 10 years, BS would be as high as 70 %.

CONCLUSIONS

Soybean, wheat, and maize on Oxisols were positively affected by gypsum, applied separately or in combination with lime in most crops investigated. The positive effect of gypsum on grain yield increase was enhanced when combined with lime, with a stronger impact in years with dry spells.

In general, there was a positive yield response to lime input even in soils with satisfactory chemical quality in topsoil, indicating that the modern cultivars are more responsive to lime and less tolerant to aluminum than the traditional ones. The yield response to gypsum was also high, particularly when the subsoil had a poor chemical quality.

The amendment of a thicker layer in the root zone in NTS is needed to maximize the yield of modern grain cultivars.

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