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Crop Response to Gypsum Application to Subtropical Soils Under No-Till in Brazil: a Systematic Review

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ABSTRACT: The use of gypsum to improve the root environment in tropical soils in the southeastern and central-western regions of Brazil is a widespread practice with well-established recommendation criteria. However, only recently gypsum began to be used on subtropical soils in South of Brazil, so available knowledge of its effect on crop yield is incipient and mainly for soils under no-till (NT) systems. Avaiable studies span a wide range of responses, from a substantial increase to a slight reduction in crop yield. Also, the specific conditions leading to a favorable effect of gypsum application on crop yield are yet to be accurately identified. The primary objectives of this study were to examine previously reported results to assess the likelihood of a crop response to gypsum and to develop useful recommendation criteria for gypsum application to subtropical soils under NT in Brazil. For this purpose, we examined the results of a total of 73 growing seasons, reported in 20 different scientific publications that assessed grain yield as a function of gypsum rates. Four different scenarios were examined, by the occurrence or not of high subsurface acidity (viz., Al saturation >20 % and/or exchangeable Ca <0.5 $\text{cmol}_c\ \text{dm}^{-3}$ in the 0.20-0.40 m soil layer) and of water deficiency during the crop cycle. Based on the results, for grasses, 10 % Al saturation and/or 3 $\text{cmol}_c\ \text{dm}^{-3}$ exchangeable Ca in the soil subsurface layer (0.20-0.40 m) is more suitable than the current recommendation (Al saturation of 20 % and/or 0.5 $\text{cmol}_c\ \text{dm}^{-3}$ Ca) for subtropical NT soils in Brazil. Also, applying gypsum to NT soils with low subsurface acidity (Al saturation <10 %) and with an adequate Ca content (>3 $\text{cmol}_c\ \text{dm}^{-3}$) failed to increase crop yield, irrespective of the soil water status. Under these conditions, high gypsum rates (6-15 Mg ha^{-1}) may even reduce grain yield, possibly by inducing K and Mg deficiency. On the other hand, applying gypsum to soils with high subsurface acidity increased yield by 16 % in corn (87 % of cases) and by 19 % in winter cereals (83 % of cases), whether or not the soil was water-deficient. By contrast, soybean yield was only increased by gypsum applied in the simultaneous presence of high soil subsurface acidity and water deficiency (average increase 27 %, 100 % of cases).

Keywords: phosphogypsum, aluminum saturation, subsurface acidity, base saturation.

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INTRODUCTION

Soils under no-tillage (NT) in Brazil have expanded exponentially since the early 1990s, covering an area of more than 32 million hectares by 2012 (Febrapdp, 2012). Under this system, soils are not tilled, so the concept of "arable layer" was replaced by "chemical gradient", a result of differences in the soil surface content of nutrients and organic matter. Correcting soil acidity by surface liming creates an alkalizing front that gradually advances through the soil profile (Caires et al., 2004; Rampim et al., 2011). This results in a marked increase in pH in the soil surface layer, but also in a less marked decrease in Al^{3+}, and an increase in exchangeable Ca in the subsurface layer (Zoca and Penn, 2017). High soil acidity in the subsurface layer may restrict root growth and decrease water and nutrient uptake, thereby leading to low crop yields (Sousa et al., 2007; Dalla Nora and Amado, 2013; Zandoná et al., 2015).

Under these conditions, gypsum has been widely used in recent years to improve the soil subsurface environment and deepen rooting in NT soils. Gypsum for agricultural use is a byproduct of the phosphate fertilizer industry and broadly available in Brazil (Caires et al., 2011a). Gypsum is an excellent source of Ca (20 %) and S (15-18 %); also, it supplies small amounts of P (0.5-0.8 %). Gypsum is marketed not only as a fertilizer, but also as a soil conditioner on the grounds of being a highly soluble salt that rapidly increases Ca and sulfate contents in the soil subsurface layer. As a result, gypsum application may favor root growth in deep soil layers, both by supplying nutrients (Ca and S) and by causing a decrease in Al^{3+} activity in the soil subsurface and alleviating its phytotoxic effects (Caires et al., 2016). Aside from the chemical properties, gypsum can improve physical properties of soils by raising the ionic strength of the soil solution, improving soil aggregation and aggregate stability, and favoring biopore formation and soil water infiltration through increased plant root growth (Zoca and Penn, 2017). Gypsum can in fact improve a number of soil chemical and physical properties, resulting in increased crop yields. To what extent, however, depends on the particular soil type, crop, fertilizer rate, and rainfall regime (Zoca and Penn, 2017).

Gypsum application should be based on technical criteria (Sousa et al., 2007) to avoid unduly high production costs or unwanted effects such as leaching of exchangeable bases (e.g., Mg, K), nutrient deficiencies, and poor crop yields (Caires et al., 2011a; Fontoura et al., 2012; Pauletti et al., 2014). Also, supplying large amounts of S through gypsum may restrict Mo availability and uptake, and damage N-fixing crops such as soybean, the main cash crop in Brazil (Gelain et al., 2011).

Gypsum has been widely used on tropical soils under NT in Brazil, mainly in the Cerrado region (Sousa et al., 2007). The recommendation criteria for gypsum application to tropical soils are well defined, namely: Al saturation above 20 % and/or exchangeable Ca content below 0.5 $cmol_c$ dm^{-3} in the 0.20-0.40 m soil layer (Sousa and Lobato, 2004; Sousa et al., 2007). These criteria were recently adopted by the Nucleus of the Brazilian Society of Soil Science (SBCS/Nepar, 2017) for the state of Paraná. The specific gypsum rate to be used in each case is calculated as a function of the soil clay content. For the states of Rio Grande do Sul and Santa Catarina, no official recommendations or guidelines for gypsum (CQFS-RS/SC, 2016) are available, despite the widespread use by farmers. The current criteria for gypsum application to tropical soils in Brazil have to be re-evaluated for the subtropical soils that differ markedly from the former, particularly as regards organic matter content and cation exchange capacity (CEC).

In recent years, subtropical soils in Brazil have been the subject of much research on the ability of gypsum to promote a better environment for deep rooting and to increase crop yields in areas under NT. The results of research along this line, however, are contrasting and differ largely according to crop, climate, and initial conditions of the cropland. Thus, some authors reported a large increase in crop yield (Dalla Nora and Amado, 2013; Caires et al., 2016), whereas others observed no appreciable change (Vidigal et al., 2014; Somavilla et al., 2016) and still others found that gypsum reduced yields (Fontoura et al., 2012; Pauletti et al., 2014; Somavilla et al., 2016). Although the effects of gypsum on soil chemical properties are well known, the specific conditions for a favorable effect on crop yield and precise recommendations for usage, remain to be established (Caires et al., 2011b; Dalla Nora and Amado, 2013; Vicensi et al., 2016).

Therefore, our hypothesis is that soil critical levels used for the recommendation of gypsum in tropical soils must be different from those observed in subtropical soils under no-till system, and these soil critical limits may vary according to the crop and the occurrence of water deficit. This paper reports a systematic review of studies on the effect of gypsum on crop yield in South of Brazil. The study aimed to analyze the set of available data with a view to assessing the likelihood of crop response to gypsum application in different scenarios and to establish recommendation criteria for gypsum application to subtropical soils under no-till systems in Brazil.

MATERIALS AND METHODS

Data collection

We examined the grain yield data of crops of a total of 73 growing seasons in response to gypsum rates in agricultural areas under NT in three states of South of Brazil (Rio Grande do Sul, Santa Catarina, and Paraná). Data were obtained from different publications, i.e., a book, two dissertations, 16 scientific papers, and a conference paper. The publications were retrieved from the databases Science Direct, Scielo, and Google Scholar, using keywords in Portuguese (*gesso agrícola, gessagem, fosfogesso, plantio direto, produtividade de grãos*) and English (gypsum, no till, no tillage/no-till, crop yield, grain yield). The criteria for publication exclusion were as follows: (a) studies focused on biomass production only; (b) studies conducted in greenhouses and/or on soils under conventional tillage; and (c) studies not reporting the initial main chemical properties of the soils.

Data analysis

Grain yields for different crops, regions, and seasons were compared by calculating a relative yield for each growing season, using the specific treatment that induced the highest yield as reference (Equation 1):

$$\text{Relative yield (\%)} = \frac{[\text{Yield of the gypsum treatment (Mg ha}^{-1})]}{\text{Maximum yield of the growing season (Mg ha}^{-1})} \times 100 \qquad \text{Eq. 1}$$

Crop data were divided according to two different criteria. One was crop response to gypsum application, classified as: (a) positive (yield increase) or (b) either negative (yield decrease) or absent (no response). The other criterion was the combination of the presence or absence of subsurface soil acidity with water deficiency, which led to four different possible scenarios, namely: (a) water deficiency and high subsurface acidity; (b) high subsurface acidity but no water deficiency; (c) water deficiency and low subsurface acidity; and (d) low subsurface acidity but no water deficiency. Soil subsurface acidity was graded in accordance with the fertilization and liming manuals for the Cerrado region (Sousa and Lobato, 2004) and Paraná (SBCS/Nepar, 2017), as follows: exchangeable Ca <0.5 $\text{cmol}_c\ \text{dm}^{-3}$ and/or Al^{3+} saturation >20 % in the 0.20-0.40 m soil layer. Water deficiency was determined from reported rainfall data and descriptions of the authors about occurrence or not of water deficiency, and whether crop yields decreased in relation to previous years.

The critical levels of Al^{3+} saturation and exchangeable Ca currently used as gypsum recommendation criteria in the Cerrado region (Sousa and Lobato, 2004) and Paraná

(SBCS/NEPAR, 2017) for subtropical soils under NT in South of Brazil were assessed for their adequacy, based on the crop response on soils with critical Al^{3+} saturation levels of 10, 20, 30, or 40 %, and exchangeable Ca contents of 0.5, 1.0, 2.0, or 3.0 $cmol_c\ dm^{-3}$ in the 0.20-0.40 m soil layer.

The gypsum rate resulting in the maximum economic efficiency (MEE), i.e., the rate leading to 95 % of the maximum possible yield, was also calculated in order to ascertain whether the methods currently used to establish gypsum rate recommendations (gypsum requirement, GR) were appropriate. This analysis assessed only data of 28 of the total 73 growing seasons, in which a positive response to gypsum application was observed. The GR values for MEE were then compared with those calculated by using (*a*) equation 2 (Sousa and Lobato, 2004), (*b*) equation 3 (Quaggio and van Raij, 1996), or (*c*) equation 4 (Caires and Guimarães, 2016). The former two equations are based on the clay content, whereas the latter considers effective CEC and exchangeable Ca content (0.20-0.40 m soil layer).

$$\text{GR (kg ha}^{-1}\text{)} = \text{clay content (\%)} \times 50 \qquad \text{Eq. 2}$$

$$\text{GR (kg ha}^{-1}\text{)} = \text{clay content (\%)} \times 60 \qquad \text{Eq. 3}$$

$$\text{GR (Mg ha}^{-1}\text{)} = [0.6 \times \text{CEC}_{\text{effective}} - \text{Ca (cmol}_c\text{ dm}^{-3}\text{)}] \times 6.4 \qquad \text{Eq. 4}$$

RESULTS AND DISCUSSION

Approximately 70 % of the 20 publications assessing crop response to gypsum application were published from 2011 and 2016 (Table 1). These sources reported 12 experiments comprising 73 growing seasons (Figure 1, Table 1). All studies were conducted on Oxisols (Soil Survey Staff, 2014), which corresponds to *Latossolos* according to Brazilian Soil Classification System (Santos et al., 2013). The Paraná state corresponded to 81 % of the crop data (n = 59) (Figure 2), mainly in the municipalities of Guarapuava and Ponta Grossa (Figure 1), which together accounted for 75 % (n = 44) of the studies in Paraná. The other studies were performed in Rio Grande do Sul (19 %, Figure 1). In half of the growing seasons (50 %, n = 37) soybean (*Glycine max* L.) was assessed and in 30 % (n = 22) corn (*Zea mays* L.). The other crops consisted of wheat (*Triticum aestivum*) (14 %, n = 10), barley (*Hordeum vulgare*) (3 %, n = 2), and black oat (*Avena strigosa*) (3 %, n = 2).

Scenario I: water deficiency and high soil subsurface acidity

Only 3 of the 73 growing seasons examined had high acidity in the soil subsurface with water deficiency. Soybean was cultivated in all three (Table 2). Under these conditions, gypsum application invariably increased crop yield.

The increased crop grain yields resulting from gypsum application have been ascribed to increased S availability (Caires et al., 1999; Caires et al., 2002; Somavilla et al., 2016), decreased Al^{3+} saturation, and increased Ca content and Ca saturation in the subsurface layer in response (Caires et al., 2004; Caires et al., 2011a; Caires et al., 2011b; Rampim et al., 2011; Dalla Nora and Amado, 2013; Trindade, 2013; Zandoná et al., 2015; Caires et al., 2016). The decreased Al^{3+} saturation in the deeper soil layers boosts root development (Caires et al., 2016), and hence water and nutrient uptake, thereby increasing grain yield. Based on these benefits, it is well-documented that gypsum application is most efficient in water-deficient years (Dalla Nora and Amado, 2013; Pauletti et al., 2014; Zandoná et al., 2015). However, the results obtained in this systematic review suggest that the actual effect of gypsum under these conditions is little known. In fact, less than 5 % of the studied growing seasons belong to this scenario.

Table 1. Grain yield (Mg ha^{-1}) of crops as a function of gypsum rates applied to subtropical soils under no-tillage in South of Brazil

Site	Clay	Crop	Season	Sign(1)	Gypsum rate							Reference
					0	1.5	3	4.5	6	9	12	
	%				Mg ha^{-1}							
Ponta Grossa, PR	58	Corn	2004/2005	*L	9.62	nd	9.67	nd	10.00	10.25	nd	Caires et al. (2011a)
Ponta Grossa, PR	62	Soybean	2005/2006	ns	3.30	nd	3.27	nd	3.09	3.08	nd	Caires et al. (2011a)
Ponta Grossa, PR	58	Soybean	2006/2007	ns	2.71	nd	2.60	nd	2.61	2.65	nd	Caires et al. (2011a)
Ponta Grossa, PR	62	Corn	2007/2008	*L	9.06	nd	9.29	nd	9.57	9.78	nd	Caires et al. (2011a)
Ponta Grossa, PR	58	Corn†	2001/2002	ns	8.54	nd	9.21	nd	8.37	8.89	nd	Caires et al. (2004)
Ponta Grossa, PR	62	Corn†a	2001/2002	*L	9.58	nd	9.90	nd	9.86	10.29	nd	Caires et al. (2004)
Ponta Grossa, PR	62	Soybean	1998/1999	ns	1.99	nd	1.90	nd	2.08	2.07	nd	Caires et al. (2003)
Ponta Grossa, PR	58	Soybean	1999/2000	ns	3.48	nd	3.49	nd	3.49	3.38	nd	Caires et al. (2003)
Ponta Grossa, PR	62	Soybean	2000/2001	ns	3.92	nd	4.02	nd	4.15	4.08	nd	Caires et al. (2003)
Ponta Grossa, PR	58	Soybean	2002/2003	ns	3.38	nd	3.45	nd	3.49	3.55	nd	Caires et al. (2006)
Ponta Grossa, PR	62	Soybean	2003/2004	ns	3.74	nd	3.72	nd	3.73	3.85	nd	Caires et al. (2006)
Ponta Grossa, PR	58	Wheat†	2000	*Q	3.42	nd	3.62	nd	3.84	3.81	nd	Caires et al. (2002)
Guarapuava, PR	70	Black oat(2)	2004, 2008	ns	10.42	nd	10.78	nd	10.81	10.33	nd	Fontoura et al. (2012)
Guarapuava, PR	70	Wheat(2)	2006, 2010	ns	8.76	nd	8.76	nd	8.99	9.18	nd	Fontoura et al. (2012)
Guarapuava, PR	70	Barley	2011	ns	5.02	nd	5.04	nd	5.13	5.13	nd	Fontoura et al. (2012)
Guarapuava, PR	70	Soybean(3)	2004-2012	*–L	18.97	nd	18.77	nd	18.44	18.46	nd	Fontoura et al. (2012)
Guarapuava, PR	70	Corn(2)	2005/2006, 2009/2010	ns	26.48	nd	27.05	nd	26.51	26.88	nd	Fontoura et al. (2012)
Guarapuava, PR	75	Corn†	2011/2012	*Q	10.33	nd	10.76	nd	10.91	10.77	10.39	Vicensi et al. (2016)
Guarapuava, PR	75	Wheat†	2012	*L	2.00	nd	2.22	nd	2.32	2.47	2.60	Vicensi et al. (2016)
Guarapuava, PR	75	Soybean†	2012/2013	ns	3.24	nd	3.24	nd	3.37	3.32	3.27	Vicensi et al. (2016)
Jaguariaíva, PR	16	Corn†	2005/2006	*Q	5.41	5.87	6.35	nd	7.38	nd	7.33	Pauletti et al. (2014)
Jaguariaíva, PR	16	Wheat†	2003	*L	5.07	5.66	5.69	nd	6.21	nd	6.31	Pauletti et al. (2014)
Jaguariaíva, PR	16	Soybean†a	2004/2005	*Q	2.08	2.32	2.66	nd	3.04	nd	2.97	Pauletti et al. (2014)
Jaguariaíva, PR	16	Soybean†	2004/2005	ns	2.40	2.90	2.62	nd	2.53	nd	2.73	Pauletti et al. (2014)
Jaguariaíva, PR	16	Soybean†a	2003/2004	ns	3.36	3.32	3.45	nd	3.39	nd	3.50	Pauletti et al. (2014)

Continue

Continuation

Jaguariaíva, PR	16	Soybean†	2003/2004	*–Q	3.52	3.65	3.51	nd	3.58	nd	3.14	Pauletti et al. (2014)
Jaguariaíva, PR	16	Soybean	2006/2007	ns	3.23	3.23	3.23	nd	3.23	nd	3.23	Pauletti et al. (2014)
Jaguariaíva, PR	16	Soybean	2007/2008	ns	3.66	3.66	3.66	nd	3.66	nd	3.66	Pauletti et al. (2014)
Guarapuava, PR	75	Corn†	2009/2010	*Q	9.85	10.45	10.95	10.81	10.54	nd	nd	Michalovicz et al. (2014)
Guarapuava, PR	75	Barley†	2010	*L	4.35	4.53	4.79	4.73	4.84	nd	nd	Michalovicz et al. (2014)
					0	1	2	3	4	5	6	
Guaíra, PR	77	Soybean†	2006	ns	3.74	3.53	3.57	3.61	3.44	3.57	nd	Rampim et al. (2011)
Guaíra, PR	75	Soybean†	2006	ns	2.94	2.86	3.00	2.76	2.85	2.77	nd	Rampim et al. (2011)
Guaíra, PR	77	Wheat†	2006/2007	ns	2.30	2.03	2.27	2.03	2.01	1.92	nd	Rampim et al. (2011)
Guaíra, PR	75	Wheat†	2006/2007	*L	1.30	1.43	1.61	1.60	1.74	1.61	nd	Rampim et al. (2011)
Carazinho, RS	35	Soybean†	2010	ns	3.78	3.68	3.80	3.92	3.84	3.78	3.74	Dalla Nora and Amado (2013)
Carazinho, RS	50	Soybean†	2011	L*	4.49	4.54	4.71	4.72	4.65	4.76	4.71	Dalla Nora and Amado (2013)
Carazinho, RS	50	Corn†	2010	L*	10.69	10.74	11.13	11.28	10.97	11.36	11.19	Dalla Nora and Amado (2013)
Carazinho, RS	35	Corn†	2011	Q*	10.87	10.97	12.12	12.19	12.28	12.32	12.22	Dalla Nora and Amado (2013)
					0	5	10	15				
Tibagi, PR	71	Corn†d	2009/2010	*Q	8.33	10.37	11.69	10.47	nd	nd	nd	Caires et al. (2016)
Tibagi, PR	71	Corn†e	2009/2010	*L	8.75	11.47	11.44	12.38	nd	nd	nd	Caires et al. (2016)
Tibagi, PR	71	Corn†f	2009/2010	*L	11.21	10.60	12.03	12.92	nd	nd	nd	Caires et al. (2016)
					0	2	4	6	8	12		
Guarapuava, PR	70	Corn†	2005/2006	*Q	10.20	nd	11.07	nd	11.38	11.05	nd	Caires et al. (2011b)
Guarapuava, PR	70	Soybean†	2006/2007	ns	2.87	nd	3.13	nd	2.92	3.09	nd	Caires et al. (2011b)
Guarapuava, PR	70	Soybean†	2007/2008	ns	3.11	nd	3.13	nd	2.67	2.91	nd	Caires et al. (2011b)
Ponta Grossa, PR	45	Soybean	1993/1994	ns	2.87	nd	2.72	nd	2.82	2.76	nd	Caires et al. (1998)
Ponta Grossa, PR	45	Soybean	1995/1996	*–L	3.41	nd	3.29	nd	3.32	3.23	nd	Caires et al. (1998)
Ponta Grossa, PR	45	Corn†	1994/1995	*Q	9.62	nd	10.39	nd	10.70	10.70	nd	Caires et al. (1999)
Ponta Grossa, PR	45	Soybean†	1996	ns	2.60	nd	2.45	nd	2.37	2.37	nd	Caires et al. (1999)

Continue

Continuation

Ponta Grossa, PR	45	Wheat[†]	1996/1997	ns	1.10	nd	1.18	nd	1.17	1.11	nd	Caires et al. (1999)
Jaboticaba, RS	70	Soybean[†]	2009/2010	ns	3.50	3.57	3.46	3.50	nd	nd	nd	Somavilla et al. (2016)
Jaboticaba, RS	70	Soybean[†]	2011/2012	*Q	1.15	1.21	1.29	1.18	nd	nd	nd	Somavilla et al. (2016)
Jaboticaba, RS	70	Corn[†]	2010/2011	*ndQ	9.45	8.57	8.39	9.98	nd	nd	nd	Somavilla et al. (2016)
Jaboticaba, RS	70	Corn[†]	2012/2013	*L	9.80	9.92	10.10	11.20	nd	nd	nd	Somavilla et al. (2016)
Barra Funda, RS	66	Corn[†]	2012/2013	*P	10.39	10.98	11.04	11.44	11.42	nd	nd	Zandoná et al. (2015)
Barra Funda, RS	66	Soybean[†]	2012/2013	*P	2.65	2.86	2.86	3.06	2.97	nd	nd	Zandoná et al. (2015)
Barra Funda, RS	66	Soybean[†a]	2012/2013	*P	2.80	3.07	3.09	3.33	3.16	nd	nd	Zandoná et al. (2015)
Guarapuava, PR	70	Soybean	2013/2014	ns	4.20	4.09	4.28	nd	3.92	nd	nd	Vidigal et al. (2014)
Guarapuava, PR	70	Soybean[a]	2013/2014	ns	4.27	4.13	4.37	nd	4.32	nd	nd	Vidigal et al. (2014)
Guarapuava, PR	70	Corn[†]	2011/2012	*L	8.87	9.78	10.4	nd	11.1	nd	nd	Meert (2013)
Guarapuava, PR	70	Corn[†a]	2011/2012	*L	9.81	9.9	10.1	nd	10.3	nd	nd	Meert (2013)
Guarapuava, PR	70	Wheat[†]	2012	ns	1.9	2.02	1.94	nd	1.86	nd	nd	Meert (2013)
Guarapuava, PR	70	Wheat[†a]	2012	*L	1.9	1.93	2.05	nd	2.08	nd	nd	Meert (2013)
BVC, RS	51	Corn[b]	2011/2012	*Q	9.08	10.27	10.13	nd	10.53	nd	nd	Trindade (2013)
BVC, RS	51	Soybean[b]	2012/2013	ns	3.9	3.9	3.9	nd	3.9	nd	nd	Trindade (2013)
BVC, RS	51	Soybean[c]	2012/2013	ns	3.2	3.2	3.2	nd	3.2	nd	nd	Trindade (2013)

(1) Significance: ns = not significant; * = significant; Q = quadratic response; L = linear response; P = response with exponential increase tending to the maximum; negative values (-) indicate a significant response in the form of yield decrease; nd = not determined. (2) Cumulative for two seasons. (3) Cumulative for six seasons. [†] Data obtained from the figures. [a]: with liming. [b]: with irrigation. [c]: without irrigation. [d]: 60 kg ha^{-1} N. [e]: 120 kg ha^{-1} N. [f]: 180 kg ha^{-1} N. BVC = Boa Vista do Cadeado.

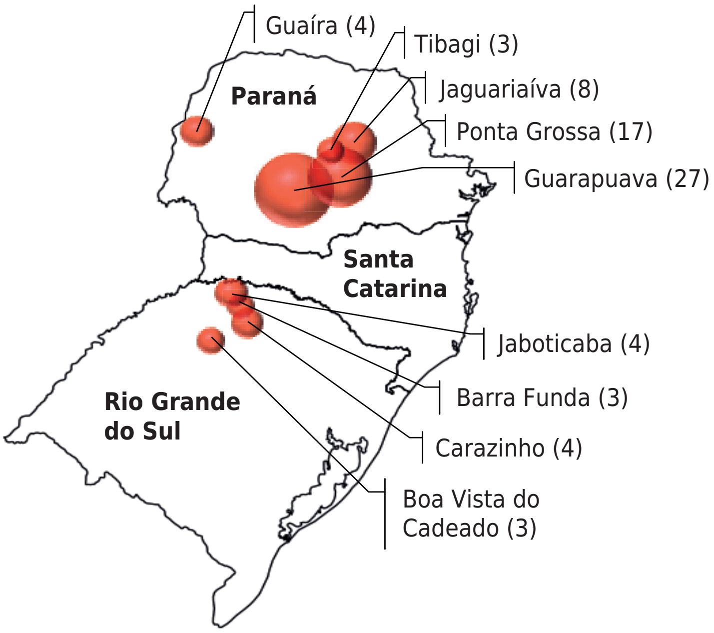

Figure 1. Geographic distribution and number of growing seasons in which crop grain yield was assessed as a function of gypsum rate in subtropical soils under no-tillage in South of Brazil.

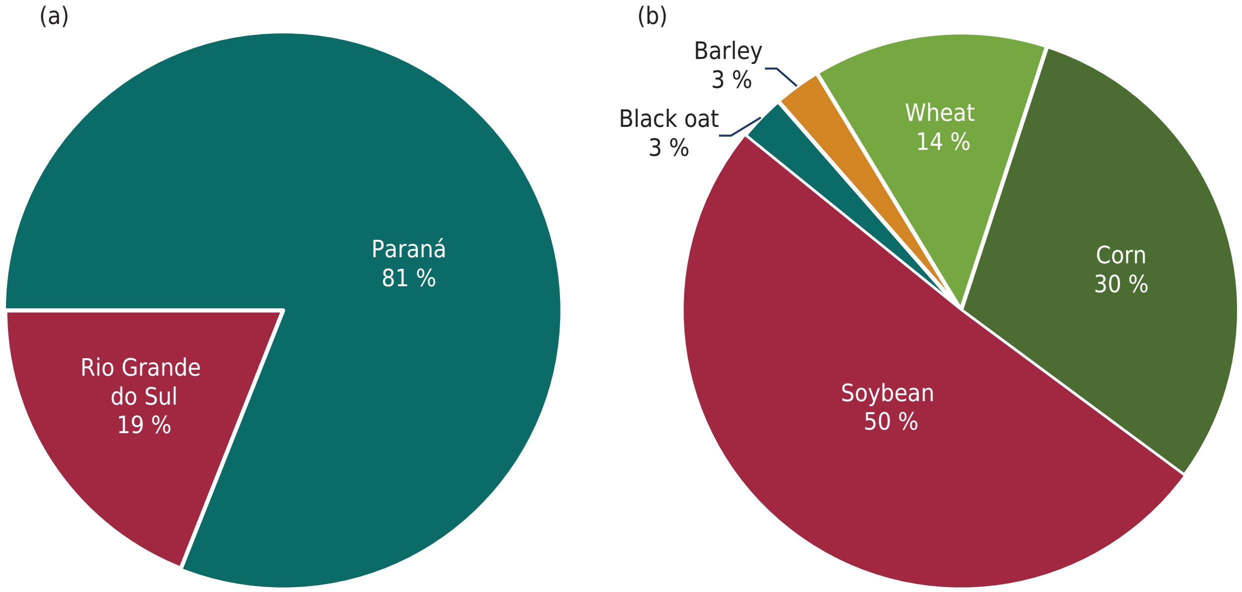

Figure 2. Relative frequency of growing seasons in each Brazilian state (a) and for each crop (b) studied with regard to yield response to gypsum in subtropical soils under no-tillage in Southern Brazil.

Scenario II: no water deficiency and high soil subsurface acidity

A total of 33 growing seasons corresponded to the scenario of high acidity in the soil subsurface layer in the absence of water deficiency (Scenario II). In 18 of the 33 seasons, soybean was cultivated, which responded positively to gypsum application in only one case (Table 2). This scenario also comprised 12 growing seasons with corn, of which 10 (83 %) exhibited an increase in grain yield in response to gypsum application. The absence of a response to gypsum on one corn crop season showed by Caires et al. (2011a) was ascribed to the low soil content of exchangeable bases (Mg and K). The authors claim that under these conditions, gypsum probably caused Mg and K to leach to subsurface layers and consequently a deficiency in these nutrients. In this case, leaf Mg contents and corn crop yield were highly significantly correlated ($r = 0.61$; $p<0.01$). These results indicate that soil with low Mg and K contents in its surface layers should be amended preferentially with Mg-rich (dolomite and magnesian) limestone and fertilized with K together with gypsum application (Caires et al., 2011a).

Wheat crops responded positively to gypsum in two of the three growing seasons of this scenario (Table 2). The absence of a positive response to gypsum in the third was ascribed to high rainfall in the harvest period resulting in high coefficients of variation for crop yield (Caires et al., 1999).

Scenario III: water deficiency and low soil subsurface acidity

Soils with low subsurface acidity associated to water deficiency (Scenario III) were studied in seven growing seasons. Five of them had a positive response to gypsum application and soybean was planted in only one (Somavilla et al., 2016). Although significant, the increase in soybean yield was very small (140 kg ha^{-1}); with a gypsum rate of 4 Mg ha^{-1}, the yield increased to only 1.29 Mg ha^{-1} from 1.15 Mg ha^{-1} in the control (without gypsum). The acidity of the soil in the said study was very low but its S content in the 0.20-0.40 m layer was only 10.5 mg dm^{-3}. This S content is very close to the critical level for soybean (10 mg dm^{-3}) (CQFS-RS/SC, 2016). Also, the soil had a low content of organic matter (1.9 %) (Basso et al., 2015), whose mineralization is the main S source for plants. Therefore, the increased S availability in the soil may have contributed to the observed response. In two wheat growing seasons (Rampim et al., 2011; Vicensi et al., 2016) and one barley crop (Michalovicz et al., 2014), in which

Table 2. Increase in grain yield of crops as a function of gypsum rates applied under different conditions of subsurface acidity and water deficiency in subtropical soils under no-tillage in Southern Brazil

Crop	n(1)	Positive response	No response(2)	Yield increase(3)		Clay	MEE(4)	Clay factor(5)	References(6)
				%	Mg ha^{-1}	%			
Scenario I: Water deficiency and high soil subsurface acidity									
Soybean	3	3	0	27 (15-46)	0.6 (0.4-1.0)	49 (16-66)	2.1 (0.4-5.4)	117 (6-338)	1, 2
Subtotal	3	3	0	27	0.6	49	2.1	117	-
Scenario II: No water deficiency and high soil subsurface acidity									
Corn	12	10	2	18 (6-42)	1.6 (0.6-3.6)	57 (16-71)	4.6 (0.4-10.2)	96 (8-170)	1, 2, 3, 4, 5, 6, 7, 8
Soybean	18	1	17	6	0.3	50	0.5	10	1, 4, 5, 6, 8, 9, 10, 11
Wheat	3	2	1	15 (12-19)	0.5 (0.4-0.5)	39 (16-62)	5.0 (2.6-7.4)	251 (41-461)	1, 6, 12
Subtotal	33	13	20	17	1.3	54	4.3	113	-
Scenario III: Water deficiency and low soil subsurface acidity									
Barley	1	1	0	11	0.5	75	2.9	38	13
Soybean	1	1	0	12	0.1	70	0.9	13	14
Wheat	5	3	2	24 (9-34)	0.4 (0.2-0.6)	75 (74-75)	5.6 (2.8-9.3)	745 (50-124)	15, 16, 17
Subtotal	7	5	2	19	0.4	74	4.1	55	-
Scenario IV: No water deficiency and low soil subsurface acidity									
Black oat	2	0	2	-	-	-	-	-	18
Barley	1	0	1	-	-	-	-	-	18
Corn	10	7	3	12 (5-25)	1.2 (0.5-2.2)	67 (35-75)	2.3 (0.0-6.2)	38 (0-87)	5, 13, 14, 15, 17, 18, 19
Soybean	15	0	15	-	-	-	-	-	5, 14, 15, 16, 18, 19, 20
Wheat	2	0	2	-	-	-	-	-	18
Subtotal	30	7	23	12	1.2	67	2.3	38	-
General summary									
Total	73	28	45	-	-	-	-	-	-
Minimum	-	-	-	5	0.1	16	0.0	0	-
Maximum	-	-	-	46	3.6	75	12.1	461	-
Median	-	-	-	12	0.7	68	2.8	45	-
Mean	-	-	-	17	1.0	60	3.5	84	-
SD(7)	-	-	-	12	0.9	19	3.2	115	-

(1) Number of growing seasons. (2) Yield maintenance or reduction. (3) Average yield increase: positive response in crop yield due to the gypsum application. (4) Maximum economic efficiency (95 % of the maximum yield). (5) Recommended value to be multiplied by the clay content to establish the MEE gypsum rate. (6) 1 = Pauletti et al. (2014); 2 = Zandoná et al. (2015); 3 = Caires et al. (2004); 4 = Caires et al. (2011a); 5 = Dalla Nora and Amado (2013); 6 = Caires et al. (1999); 7 = Caires et al. (2016); 8 = Trindade (2013); 9 = Caires et al. (2003); 10 = Caires et al. (2006); 11 = Caires et al. (1998); 12 = Caires et al. (2002); 13 = Michalovicz et al. (2014); 14 = Somavilla et al. (2016); 15 = Vicensi et al. (2016); 16 = Rampim et al. (2011); 17 = Meert (2013); 18 = Fontoura et al. (2012); 19 = Caires et al. (2011b); 20 = Vidigal et al. (2014). (7) Standard deviation.

a positive response was observed, the Al saturation in the subsurface (0.20-0.40 m) layer was higher than 15 %, which is very close to the boundary between the high and low acidity classes (20 % Al saturation). Therefore, water-stressed corn and barley on soils with lower acidity than those currently used as criteria for gypsum application in the Cerrado region (Sousa and Lobato, 2004) and Paraná (SBCS/Nepar, 2017) seem to respond positively to gypsum application.

Scenario IV: no water deficiency and low soil subsurface acidity

Scenario IV (viz., low acidity in the soil subsurface without water deficiency) comprised 30 growing seasons (41 % of all) (Table 2). Of these, 15 involved soybean, two black oat, two wheat, and one barley. No positive response to gypsum application was observed in any crop under these conditions. This result can be ascribed to: (a) low Al saturation and high exchangeable bases content of soils limed as per recommendations (especially when the 0.00-0.20 m layer is amended by lime incorporation prior to the establishment of no-tillage); (b) the amount of S present in the soil naturally or from atmospheric deposition (Tiecher et al., 2013), meeting the crop demands; and (c) an adequate amount of rainfall and distribution during crop development.

Ten of the growing seasons involved corn, of which 70 % responded to gypsum application (Table 2). Of these seven growing seasons, three were in 2009/2010 (Michalovicz et al., 2014), 2010/2011 (Dalla Nora and Amado, 2013), and 2011/2012 (Vicensi et al., 2016). The soil content of exchangeable Al exceeded 0.4 $cmol_c$ dm^{-3} in all three, and Al saturation was 9.5 % in the first and 15 % in the last. These results reinforce the previous conclusion for wheat and barley: a more rigorous decision criterion for gypsum recommendation than that currently used in the Cerrado region (Sousa and Lobato, 2004) should be adopted for grasses on subtropical soils under NT.

In the other four growing seasons, in which a positive response was observed even under theoretically unfavorable conditions (*viz.*, low acidity and no water deficiency), this effect was probably the result of the soil nutritional restrictions being overcome by gypsum application at high rates, raising crop yield by increasing P and S availability. The P contents of the surface soil layer (0.00-0.20 m) in 2011 and 2012, in the two corn seasons studied by Meert (2013), were very low (<2 mg dm^{-3}). On the other hand, the available P contents of the same layer in the corn season studied by Caires et al. (2011b) were medium (4.7 mg dm^{-3}), whereas those of S were very low (<4 mg dm^{-3}). Finally, the 0.20-0.40 m soil layer contained 10.5 mg dm^{-3} S in the last corn season with a positive response to gypsum (Somavilla et al., 2016); moreover, the soil exhibited low contents of S and organic matter (1.9 %), and a high grain yield (>10 Mg ha^{-1}) (Basso et al., 2015). The increased grain yield was not exclusively due to improved soil acidity, but also - and to a greater extent - to gypsum application, increasing the availability and uptake of P, Ca, and S. However, using gypsum as an alternative source of P is uneconomical owing to its low content of this element (0.5-0.8 %), so other, more concentrated fertilizers are to be preferred (Dalla Nora and Amado, 2013). Also, S deficiency can be corrected not only with gypsum (16 % S), but also with fertilizer formulas containing S, such as simple superphosphate (10-12 % S) or ammonium sulfate (22 % S).

Response of grass and legume crops to gypsum application

The results of this systematic review confirm that soybean, which is the main cash crop in South of Brazil, is less responsive to gypsum than grasses such as corn and wheat (Caires et al., 2011a; Fontoura et al., 2012; Vicensi et al., 2016). This is basically a consequence of the low CEC of grass roots (Caires et al., 2011a,b; Pauletti et al., 2014; Vicensi et al., 2016), adversely affecting cation uptake by plants in an environment of low ionic concentration; also, this reflects an increase in root cation contents above the levels of the aqueous solution surrounding the roots, altering the relative proportions of ions with a different valence in the rhizosphere. In other words, legume crops such as soybean are more efficient in absorbing Ca from the soil solution than grasses. As a result, the increased Ca content and Ca saturation following gypsum application are less likely to elicit a positive response in soybean than in grass yield in the absence of water. In addition, gypsum application can substantially increase the N use efficiency in grass crops due to greater root growth, boosting nitrate uptake by plants and hence reducing nitrate leaching losses (Caires et al., 2016). This process explains at least partly why grasses respond more markedly to gypsum application than soybean, which takes up most of its N by biological fixation (Caires et al., 2016; Zoca and Penn, 2017).

Recommendation criteria for gypsum in no-till areas in Southern Brazil

This systematic review shows that the criteria currently used for gypsum application in the Cerrado region (Sousa and Lobato, 2004) and Paraná (SBCS/Nepar, 2017) (viz., Al saturation >20 % and/or 0.5 $\text{cmol}_c\ \text{dm}^{-3}$ Ca) are not valid for grasses on subtropical soils (Figure 3). Of the 22 growing seasons in which Al saturation was lower than 20 % - conditions under which gypsum application is not recommended -, 12 responded positively (Figure 3a). Also, of the 14 seasons with high soil subsurface acidity (Al saturation >20 %, condition under which gypsum application is recommended), 3 exhibited no response (Figure 3a). Therefore, the reliability of the existing criterion was 58 % but increased to 75 % when replaced by Al saturation >10 % (Figure 3b). Similarly, raising the Ca critical level from 0.5 to 3.0 $\text{cmol}_c\ \text{dm}^{-3}$ increased the reliability from 42 to 86 %. These results are consistent with those of Guimarães et al. (2015), who found that Ca saturation of the effective CEC in the 0.20-0.40 m soil layer was more influential on crop yield than Al saturation. Based on the previous results, we propose the following criteria for gypsum application to soils under grass cultivation: Al saturation >10 % and/or exchangeable Ca content <3.0 $\text{cmol}_c\ \text{dm}^{-3}$ in the 0.20-0.40 m layer. This combined criterion increased the reliability of the recommendations to 89 %. Owing to the small number of seasons with a positive response, no similar criterion for legume crops on subtropical soils could be established. Moreover, the positive legume response was mainly due to water-deficient conditions. Therefore, farmers should rely on the particular crop rotation they use when making decisions about gypsum application to subtropical soils. Thus, for legume–grass rotations, the criterion should be adjusted to the requirements of the most demanding crop (i.e. grass). Adopting this criterion may have a favorable effect on soybean in water-deficient years, which are very frequent in South of Brazil.

When the response to gypsum application was positive, grain yields above 95 % of the maximum relative yield were generally obtained, even at the lowest rates (2-3 Mg ha^{-1}) (Figure 4a). Table 2 shows the average maximum economic efficiency (MEE) rate with positive effect of gypsum application for each crop. Considerable differences in MEE were observed among seasons (0.0-12.1 Mg ha^{-1}; standard deviation = 3.2 Mg ha^{-1}). The average MEE rate was 3.5 Mg ha^{-1}; however, we recommend using the median value (2.8 Mg ha^{-1}) to offset the high data dispersion.

A multiplying factor for the clay content was calculated from the results for the 28 growing seasons with a positive response to gypsum in order to identify the gypsum rate corresponding to MEE (MEE rate/clay content). Considering the mean of the crops, the gypsum rate for MEE can be obtained by multiplying the clay content by a factor of 84 ± 115. In terms of the median, which was more representative of the data set owing to its high variability, the MEE gypsum rate was calculated by multiplying the clay content by 45 (Table 2). This value is smaller than that for soils under conventional tillage, 60 (Quaggio and van Raij, 1996), but close to that recommended by Sousa and Lobato (2004) for production systems under NT: 50. However, none of these recommendations exhibited good correlation with MEE rates (Figure 5b). Also, the recommendation of Caires and Guimarães (2016), which considers Ca saturation of the effective CEC, led to no substantial correlation with MEE rates when a positive crop response to gypsum was observed (Figure 5a). This result can be ascribed to the high variability of MEE rates among crops and seasons, and confirms that the current recommendations, based on clay content, Ca saturation, and CEC, are severely limited. Further research is therefore needed to accurately determine the appropriate gypsum rate for application.

Effect of gypsum application on grain yield

Figure 6b shows the average increase in grain yield in the different scenarios under the assumption of 10 % Al saturation and/or 3.0 $\text{cmol}_c\ \text{dm}^{-3}$ exchangeable Ca as thresholds for high soil subsurface acidity. Only those growing seasons in which a positive response to gypsum application was observed are included in the figure. The average increase in grain

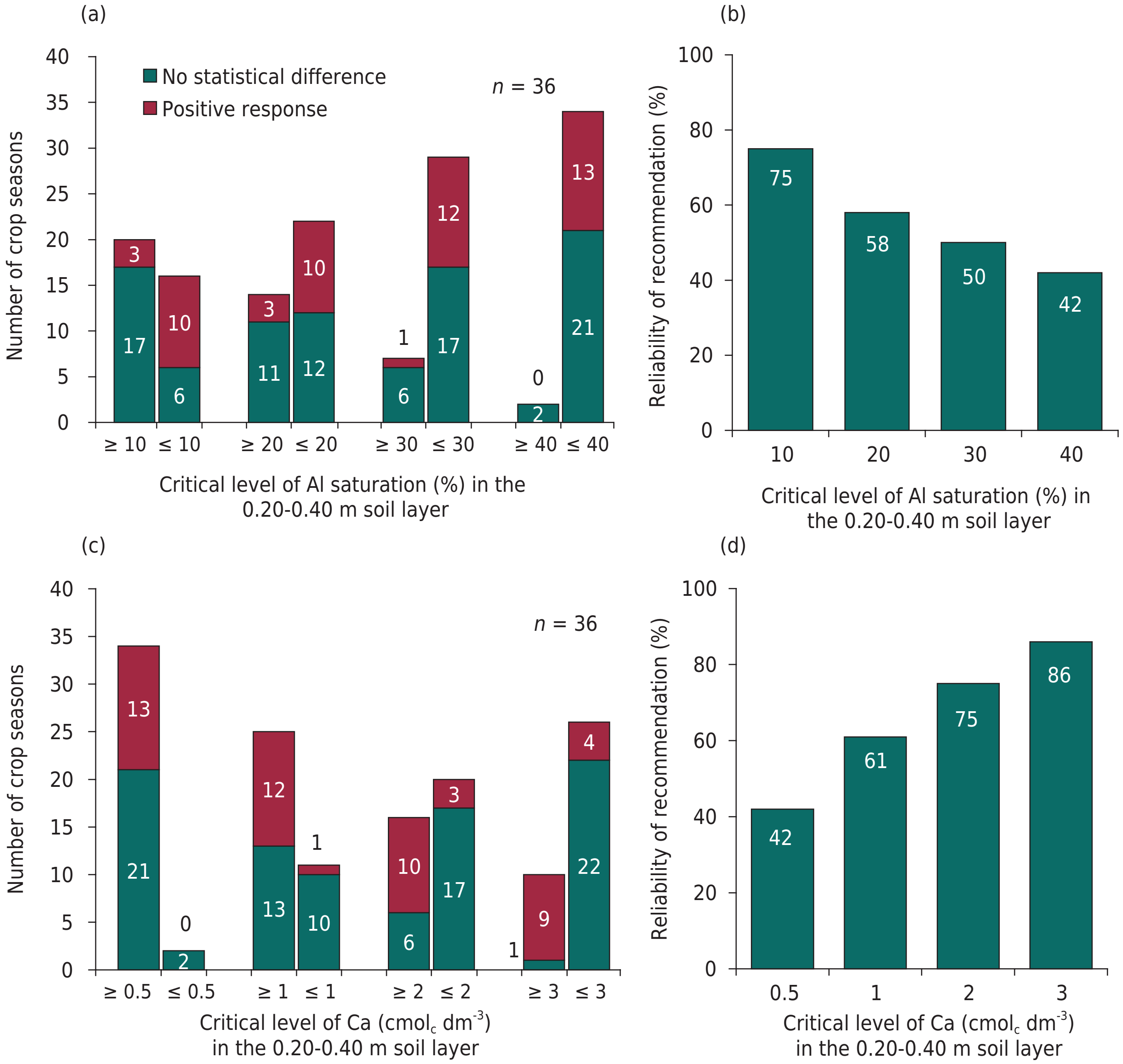

Figure 3. Response of grass crops (36 growing seasons) to gypsum application as a function of different critical Al saturation (a) and exchangeable Ca contents (c), and reliability of recommendations (b, d), in studies of subtropical soils under no-tillage in South of Brazil. Reliability was calculated from the number of growing seasons with a positive yield response to gypsum application when Al saturation and exchangeable Ca content (0.20-0.40 m soil layer) were above and below, respectively, the critical level, and the number of growing seasons in which no response to gypsum was observed when Al saturation and exchangeable Ca content (0.20-0.40 m soil layer) were above and below, respectively, the critical level.

yield for soybean in soils with high subsurface acidity was 23 % (9-35 %) in the presence of water deficiency and 6 % in its absence. For corn, which responded positively to gypsum in a greater number of growing seasons (17), representing more consistent results with regard to yield, the average increase from the control treatment in soils with high subsurface acidity was 14 % (6-42 %). Despite the relative scarcity of studies on winter cereals, wheat and barley exhibited a medium response potential to gypsum application. Thus, in a scenario of high subsurface acidity and water deficiency, gypsum increased wheat yield by 24 % (average of three growing seasons). In the other scenarios, the average yield increase in winter cereals was 14 %.

Based on the subsurface acidity conditions suggested by our systematic review, gypsum application increased yields only at high subsurface acidity. Also, grasses (particularly corn) exhibited a large increase even in the absence of water deficiency, which was not the case with soybean (Figure 6).

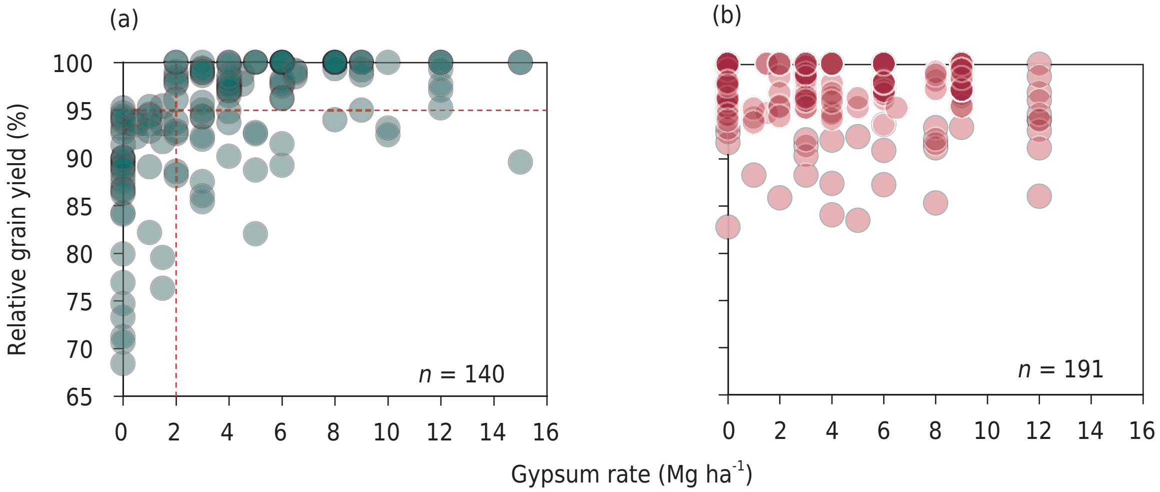

Figure 4. Relative grain yield for growing seasons with positive response (a) and no response (no statistical difference) (b) to gypsum application to subtropical soils under no-tillage in Southern Brazil. Graphs constructed from data in table 1.

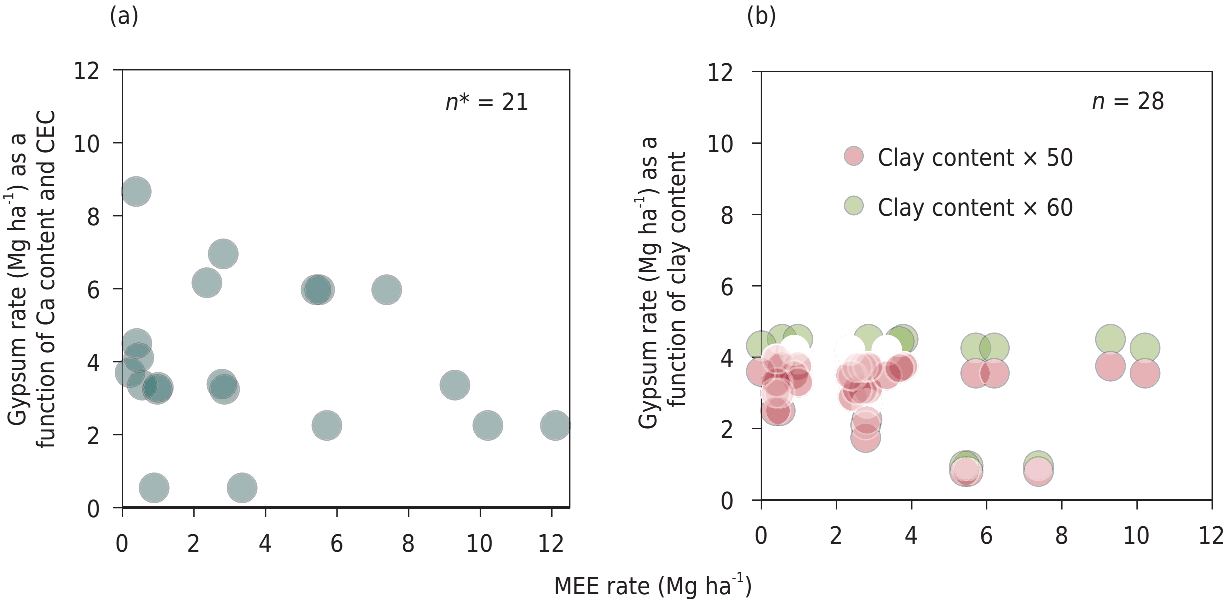

Figure 5. Comparison between the gypsum rate of maximum economic efficiency (MEE) (95 % of yield) obtained in growing seasons with positive response to gypsum application, and gypsum rates calculated according to different recommendations based on soil exchangeable Ca content and CEC (a: Caires and Guimarães, 2016) or on clay contents [b: clay × 50 (Sousa and Lobato, 2004) and clay × 60 (Quaggio and van Raij, 1996)] for subtropical soils under no-tillage in South of Brazil. *: only 21 growing seasons with a positive response were studied (for which Ca contents and CEC of the soil subsurface were available).

Negative effects of high gypsum rates

Many studies with a significant crop response to gypsum application indicated a quadratic relation of gypsum rate to grain yield in corn (Caires et al., 1999; Caires et al., 2011b; Trindade, 2013; Michalovicz et al., 2014; Caires et al., 2016; Vicensi et al., 2016), soybean (Caires et al., 1998; Pauletti et al., 2014; Somavilla et al., 2016), and wheat (Caires et al., 2002). Also, in nine growing seasons, soybean yield was significantly decreased by gypsum relative to the control treatment (Caires et al., 1998; Fontoura et al., 2012; Pauletti et al., 2014; Somavilla et al., 2016). The decreased yield in response to very high gypsum rates (6-15 Mg ha^{-1}) may have resulted from excessive K and Mg leached through the soil profile, as previously hypothesized by Caires et al. (1998), who found the Mg content of soybean leaves to decrease with increasing gypsum rate. These authors

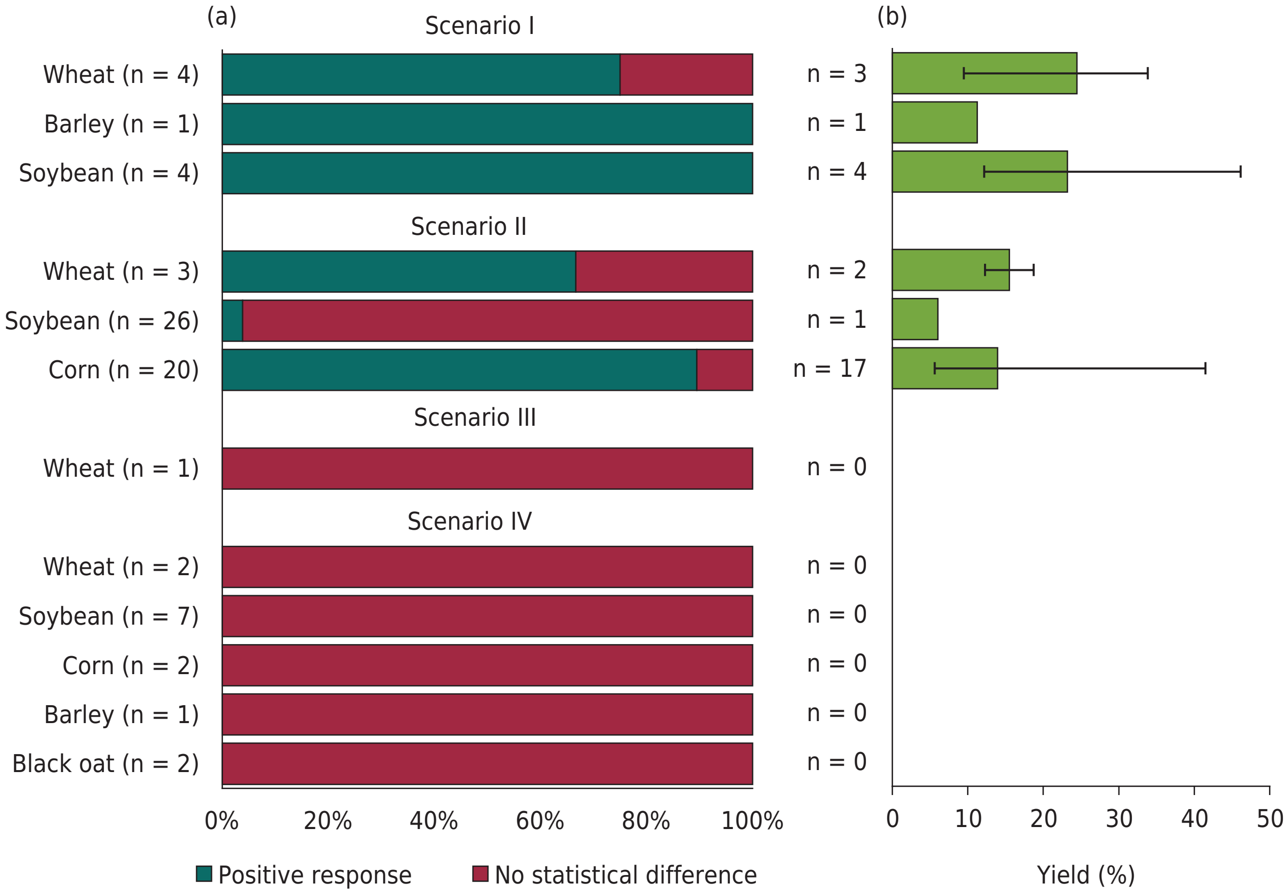

Figure 6. Crop response to gypsum application in different scenarios considering a critical level of Al saturation of 10 % and/or of exchangeable Ca content of 3.0 $cmol_c$ dm^{-3} (a). Average increase in grain yield in response to gypsum in subtropical soils under no-tillage in South of Brazil (b). Scenario I: water deficiency and high soil subsurface acidity; Scenario II: no water deficiency and high soil subsurface acidity; Scenario III: water deficiency and low soil subsurface acidity; and Scenario IV: no water deficiency and low soil subsurface acidity.

also found a positive correlation (r = 0.80) between Mg leaf content and grain yield. According to Pauletti et al. (2014) and Fontoura et al. (2012), the Mg deficiency induced by higher gypsum rates resulted in lower yields.

Suggestions for further research on gypsum application to NT soils

Further research into the effects of gypsum application to subtropical soils under no-tillage in Brazil is required, especially as regards soil and crop types. In fact, all existing studies involved Oxisols and most (80 %) examined the crop response of soybean or corn. Sixty-one (76 %) of the 73 growing seasons examined in this systematic review corresponded to a period shorter than three years after gypsum was applied. However, long-term trials have shown that the effects of gypsum on crop yield may persist for up to seven years (Caires et al., 2002, 2004, 2011b). The persistence of benefits of gypsum in soil should be studied in more detail to assess the economic viability of applying gypsum in each situation. Studies using lower rates of gypsum (<1 Mg ha^{-1}) as S source are also needed because high rates prevent the distinction of whether a positive response is due to the S supplied or to decreases in soil subsurface acidity - an effect only apparent at gypsum rates ≥2 Mg ha^{-1}. Finally, recommendation criteria for gypsum application to subtropical soils in South of Brazil should take three factors into account that affect the probability of a crop response, namely: (a) acidity in the soil subsurface, (b) crop type, and (c) water deficiency (Figure 7).

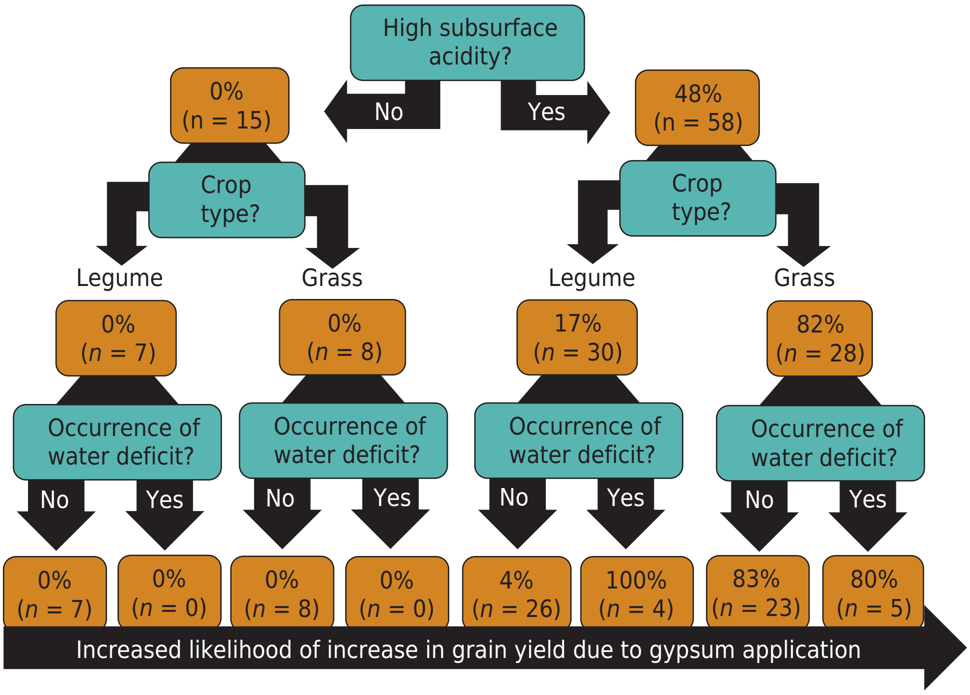

Figure 7. Decision tree to increase grain yield by applying gypsum to subtropical soils under no-tillage in South of Brazil. High subsurface acidity means Al saturation >10 % and/or exchangeable Ca content <3.0 $cmol_c$ dm^{-3}.

CONCLUSIONS

Soil critical levels used for the recommendation of gypsum in tropical soils are not the same observed in subtropical soils under no-till system, and it may be different for legumes and grasses crops. For grasses grown on subtropical Oxisol under no-till soils, the use of 10 % Al saturation and/or 3.0 $cmol_c$ dm^{-3} exchangeable Ca in the soil subsurface layer (0.20-0.40 m) is more suitable than the current recommendation (Al saturation of 20 % and/or 0.5 $cmol_c$ dm^{-3} Ca) for tropical soils.

Irrespective of water deficiency, applying gypsum to soils with high subsurface acidity increased the average yield by 14 % in corn (85 % studied cases) and by 20 % in winter cereals (75 % of cases). Soybean only responded positively to gypsum in the simultaneous presence of high soil subsurface acidity and water deficiency (average increase 23 %, 100 % of cases).

Gypsum applied to soils with low subsurface acidity (Al saturation <10 %), adequate exchangeable Ca content (>3.0 $cmol_c$ dm^{-3}), available P and S contents failed to increase crop yield; rather, they decreased crop yields when applied at very high rates (6-15 Mg ha^{-1}), probably by inducing K and Mg deficiency.

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