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A Novel Phosphogypsum Application Recommendation Method under Continuous No-Till Management in Brazil

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ABSTRACT

Phosphogypsum (PG) is used in tropical and subtropical agriculture when subsoil acidity is an important yield-limiting factor. However, the conditions that increase crop yield under PG application in continuous no-till systems remain unclear. In addition, the methods used in Brazil to estimate the PG requirements are sometimes imprecise. Thus, to develop an accurate method for establishing PG recommendation, a dataset from experiments performed in southern Brazil and selected published papers involving PG application on various Oxisols under continuous no-till was analyzed by computational techniques of data mining using the M5-Rules algorithm to create regression models. Experimental areas consisted of annual crops managed under a long-term (≥10 yr) no-till system. These included maize (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], wheat (*Triticum aestivum* L.), and barley (*Hordeum distichum* L.). Results allowed the proposal of a new method for establishing the PG requirement to increase Ca^{2+} saturation to 60% in the effective cation exchange capacity (ECEC) at the 20- to 40-cm soil layer when this is lower than 54% using the following equation: PG (Mg ha^{-1}) = (0.6 × ECEC – exchangeable Ca^{2+} content in $cmol_c$ dm^{-3}) × 6.4. The PG rates indicated by this method agreed with those leading to the maximum economic yields obtained in most studies conducted on continuous no-till soils in Brazil. The proposed method might be efficiently used when subsoil acidity is an important growth-limiting factor.

Core Ideas

- Phosphogypsum application increases grain yield, particularly in acidic subsoils.
- Phosphogypsum rates can be based on Ca^{2+} saturation in the ECEC of the subsoil.
- We show a new method for phosphogypsum recommendation based on M5-Rules.

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No-till is defined as a system of seeding crops into untilled soil by opening a narrow slot, trench, or band with just the sufficient width and depth to confer proper seed coverage; no other soil tillage is performed in this system (Phillips and Young, 1973). Residues from previous cash crops or green manure cover crops should remain undisturbed on the soil surface after seeding. In this system, crop rotation and cover crops are essential practices (Derpsch et al., 2010). Continuous no-till systems have stood out as one of the most effective strategies to improve agricultural sustainability and minimize soil and nutrient losses due to erosion in tropical and subtropical regions (Hobbs et al., 2008; Lal, 1995). No-till systems are used across 111 million hectares worldwide (Derpsch et al., 2010).

In southern Brazil, the development of no-till conservation agriculture in the early 1970s contributed greatly to the increase in agricultural production. Currently, Brazil is a leading country regarding the adoption of the no-till system, which is used in more than 90% of the cash crop area in southern Brazil.

No-till systems are known to cause chemical stratification, including pH stratification, with high pH levels being found in the upper few centimeters of the soil profile (Caires et al., 2005). Subsoil acidity is a serious problem worldwide (Fageria and Nascente, 2014). The low content of base cations, especially calcium (Ca), and aluminum (Al) toxicity in the subsoil affect root growth, restricting the plant's capacity to access water and nutrients (Carvalho and van Raij, 1997). This issue is critical in Brazil because exchangeable Al is found in most cultivated soils within this country (Olmos and Camargo, 1976).

Phosphogypsum (PG), a by-product of the phosphoric acid industry, is largely available in several areas across the world. In Brazil, approximately 4.8 Tg of PG are produced each year (van Raij, 2008). When applied to the soil surface, PG moves down the soil profile during drainage, which increases Ca^{2+} supply and reduces the toxic levels of Al^{3+} (Sumner, 1995). As a result, root growth and the absorption of water and nutrients by plants roots improve (Caires et al., 2016; Carvalho and van Raij, 1997; Ritchey et al., 1980). In soils with very low Al^{3+} and low Ca^{2+} concentrations, calcium supply might be a limiting factor in root proliferation (Ritchey et al., 1982).

Positive effects of PG are expected when subsoil acidity is an important growth-limiting factor. Thus, the application of

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Abbreviations: ECEC, effective cation exchange capacity; MEY, maximum economic yield; PG, phosphogypsum

PG in Brazilian soils has been recommended when exchangeable Ca^{2+} content is lower than 0.4 $cmol_c\ dm^{-3}$ (Ribeiro et al., 1999; van Raij et al., 1996) or 0.5 $cmol_c\ dm^{-3}$ (Sousa and Lobato, 2002), when exchangeable Al^{3+} content is >0.5 $cmol_c\ dm^{-3}$ (Ribeiro et al., 1999), and/or when Al^{3+} saturation is higher than 20% (Sousa and Lobato, 2002), 30% (Ribeiro et al., 1999), or 40% (van Raij et al., 1996) in soil subsurface layers (20–40 cm or 30–50 cm). Although reasonable, these Ca^{2+} and Al^{3+} levels that are considered critical to root growth were based on only a few studies conducted in the western central and southeast regions of Brazil and thus might not be optimal for continuous no-till soils in southern Brazil.

The methods currently used in Brazil to calculate PG requirement are based on the clay content in the subsoil. Therefore, two different formulas were proposed for the western central and southeast regions of Brazil, respectively: PG ($kg\ ha^{-1}$) = 5 × soil clay content in $g\ kg^{-1}$ (Sousa and Lobato, 2002) and PG ($kg\ ha^{-1}$) = 6 × soil clay content in $g\ kg^{-1}$ (van Raij et al., 1996). Although clay content is a soil attribute that can be used for estimating the PG application rate, such methods are incomplete because they do not consider the action depth of PG and the nature of the clay fraction (van Raij, 2008) and sometimes do not accurately estimate the PG rates that should be used. In a recent review on gypsum use in agriculture, Zoca and Penn (2017) reported that there is no single scientifically grounded method for determining suitable PG application rates that considers different soil environments and crop systems.

Most of the published literature has focused on the impacts of PG application on soil properties rather than crop yields (Zoca and Penn, 2017). Achieving maximum crop yields based on PG requirement estimates is a difficult and complex issue. Based on computational intelligence algorithms, data mining is emerging as a means to obtain useful information and knowledge from datasets in crop yield analysis in agriculture (Ramesh and Vardhan, 2013). Data mining for regression establishes consistent models that are hard to identify using classical statistical methods. M5-Rules is a rule-induction algorithm that generates a decision list for regression problems using a separate-and-conquer strategy (Holmes et al., 1999). A study conducted in southern Brazil using this algorithm found that Ca^{2+} saturation in the effective cation exchange capacity (ECEC) was the most important attribute to estimate PG requirement for no-till soils (Guimarães et al., 2015). To accurately establish PG recommendations for continuous no-till systems, we hypothesized that the PG application rate could be based on the Ca^{2+} saturation in the ECEC at the subsoil layer (20–40 cm) as estimated through the M5-Rules algorithm applied to calculate the increase in subsoil exchangeable Ca^{2+} content with PG application.

MATERIALS AND METHODS

Dataset and Description of Soils, Sites, and Experiments

Our dataset was based on field experiments and selected papers involving PG application on continuous no-till Oxisols in southern Brazil. Six field experiments were performed at contrasting times using various PG rates (Table 1). Table 2 shows the results of chemical and particle-size distribution analyses of topsoil (0–20 cm) and subsoil (20–40 cm) before the establishment of the six field experiments. X-ray diffractograms performed on the clay fraction in the subsoil (Embrapa, 1997) indicated dominance of gibbsite and kaolinite in Experiments 1, 2, and 3; kaolinite and hematite in Experiment 4; kaolinite and goethite in Experiment 5; and kaolinite, gibbsite, and goethite in Experiment 6. Also found were, to a lesser degree, hematite and goethite in Experiments 1, 2, and 3; goethite and gibbsite in Experiment 4; gibbsite and lepidocrocite in Experiment 5; and hematite in Experiment 6.

We only considered papers reporting field studies using various PG rates and those that allowed obtaining the exchangeable Ca^{2+} content at the 20- to 40-cm soil layer up to 12 mo after application. Only three studies met the established criteria (Table 3): Dalla Nora and Amado (2013), Michalovicz et al. (2014), and Rampim et al. (2011).

All experimental areas of both field experiments and selected papers consisting of annual crops that had been managed under a long-term no-till system (≥10 yr). The main cash crops were maize (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and winter cereals [wheat (*Triticum aestivum* L.) and barley (*Hordeum distichum* L.)]. Phosphogypsum used in all studies contained 205 ± 7 $g\ kg^{-1}$ Ca, 158 ± 10 $g\ kg^{-1}$ sulfur (S), and 134 ± 28 $g\ kg^{-1}$ water. Further details regarding Experiments 1, 2, 3, and 4 (Table 1) can be found in Caires et al. (1999, 2002, 2011, 2016), respectively. Experiments 5 and 6 (Table 1) were performed on two Oxisols with different clay contents (Table 2). In both experiments, the plot size was 10.0 × 4.5 m, and PG was broadcast on the soil surface 15 d before sowing. Soybean ('Nidera 5909') was sown during spring 2013 (October in Experiment 6 and November in Experiment 5) at a seeding rate of 14 seeds m^{-1} (inoculated with *Bradyrhizobium japonicum*) with a row spacing of 0.45 m. Soybean received fertilizers at 13 $kg\ ha^{-1}$ phosphorous (P) and 83 $kg\ ha^{-1}$ potassium (K). Wheat ('Supera') was sown during winter 2014 (June) at a seeding rate of 60 seeds m^{-1} with a row spacing of 0.17 m in Experiment 6 only. Wheat received 100 $kg\ ha^{-1}$ nitrogen (30 $kg\ ha^{-1}$ at sowing and 70 $kg\ ha^{-1}$ as top dressing), 13 $kg\ ha^{-1}$ P, and 83 $kg\ ha^{-1}$ K. Soybean grain was harvested from a 9 m^2-plot (middle four rows by 5 m in length), and wheat grain was harvested from an 8.5-m^2 plot (middle 10 rows by 5 m in length). Grain yields were expressed at a 130 $g\ kg^{-1}$ moisture content.

According to the Köppen–Geiger system (Peel et al., 2007), the climate at the experimental sites is categorized as humid subtropical, with mild (Cfb) or slightly warmer (Cfa) summer and frequent frosts during the winter. Annual average temperature and rainfall are 17.5°C and 1550 mm in Ponta Grossa (Paraná, PR), 16.7°C and 1710 mm in Guarapuava (PR), 18.7°C and 1335 mm in Tibagi (PR), 21.7°C and 1600 mm in Guaíra (PR), and 18.4°C and 1730 mm in Carazinho (Rio Grande do Sul, RS).

Soil Sampling and Exchangeable Ca^{2+} Analysis

In both field experiments and selected papers, soil samples were taken at the 20- to 40-cm depth up to 12 mo after PG application to determine the increase in the exchangeable Ca^{2+} content in the subsoil. In field experiments (Table 1) and to obtain a composite sample, five soil cores were collected in each plot using a soil probe at 8 (Experiments 1 and 2), 9 (Experiment 3), 6 (Experiments 4 and 5), and 6 and 12 mo (Experiment 6)

Table 1. Details of the field experiments involving phosphogypsum (PG) application on various Oxisols from southern Brazil under continuous no-till management.

Experiment	Site	Climate†	Soil texture	Beginning of experiment	Experimental design	PG rates‡	Number of replications
						$Mg\ ha^{-1}$	
1	Ponta Grossa (PR)	Cfb	Loamy	1993	RCB§	0.0, 4.0, 8.0, and 12.0	3
2	Ponta Grossa (PR)	Cfb	Clayey	1998	RCB	0.0, 3.0, 6.0, and 9.0	3
3	Guarapuava (PR)	Cfb	Clayey	2005	RCB	0.0, 4.0, 8.0, and 12.0	4
4	Tibagi (PR)	Cfa	Clayey	2009	RCB	0.0, 5.0, 10.0, and 15.0	12¶
5	Ponta Grossa (PR)	Cfb	Loamy	2013	RCB	0.0, 2.0, 4.0, and 6.0	3
6	Ponta Grossa (PR)	Cfb	Clayey	2013	RCB	0.0, 2.0, 4.0, and 6.0	3

† According to the Köppen–Geiger System (Peel et al., 2007).

‡ Phosphogypsum was applied on the soil surface in the beginning of experiment.

§ Randomized complete block.

¶ In this experiment, three N rates in top dressing (60, 120, and 180 kg N ha^{-1}) were considered as replications.

Table 2. Results of soil chemical and particle-size distribution analyses of the topsoil (0–20 cm) and subsoil (20–40 cm) before the establishment of the experiments under continuous no-till in southern Brazil.

Attributes	Experiment 1	2	3	4	5	6
			0–20 cm depth			
pH (1:2.5 soil:0.01 M $CaCl_2$ suspension)	4.5	4.6	5.9	5.6	5.1	4.8
Total acidity pH 7.0 (H + Al), $cmol_c\ dm^{-3}$	5.8	7.8	4.5	5.4	4.7	6.9
Organic C, g dm^{-3}	19	31	28	32	11	25
P (Mehlich–1), mg dm^{-3}	9.0	0.3	4.7	5.0	15.9	10.6
Exchangeable cations, $cmol_c\ dm^{-3}$						
Ca^{2+}	1.6	2.5	4.8	5.8	2.1	3.4
Mg^{2+}	1.0	2.0	2.2	3.0	1.2	0.9
K^{+}	0.14	0.36	0.42	0.38	0.30	0.20
Al^{3+}	0.6	0.3	0.0	0.0	0.1	0.2
ECEC, $cmol_c\ dm^{-3}$†	3.34	5.16	7.42	9.18	3.70	4.70
CEC (pH 7.0), $cmol_c\ dm^{-3}$‡	8.54	12.66	11.92	14.58	8.30	11.40
Base saturation, %§	32	38	62	63	43	39
Al^{3+} saturation, %¶	18	6	0	0	3	4
Particle-size distribution, g kg^{-1}						
Clay	295	580	655	680	170	490
Silt	240	130	270	240	60	122
Sand	465	290	75	80	770	388
			20–40 cm depth			
pH (1:2.5 soil/0.01 M $CaCl_2$ suspension)	4.4	4.2	5.2	4.4	4.4	4.4
Total acidity pH 7.0 (H + Al), $cmol_c\ dm^{-3}$	5.8	9.7	6.2	9.7	5.9	9.4
Organic C, g dm^{-3}	18	21	20	22	6	22
P (Mehlich-1), mg dm^{-3}	4	0.1	1.8	1.5	2.2	2.0
Exchangeable cations, $cmol_c\ dm^{-3}$						
Ca^{2+}	1.6	0.7	2.3	2.3	0.6	1.2
Mg^{2+}	1.0	0.8	2.9	1.1	0.4	0.5
K^{+}	0.15	0.22	0.24	0.12	0.13	0.09
Al^{3+}	0.6	0.8	0.0	0.9	0.8	0.9
ECEC, $cmol_c\ dm^{-3}$†	3.35	2.52	5.44	4.42	1.93	2.69
CEC pH 7.0, $cmol_c\ dm^{-3}$‡	8.55	11.42	11.64	13.22	7.03	11.19
Base saturation, %§	32	15	47	27	16	16
Al^{3+} saturation, %¶	18	32	0	20	41	33
Particle-size distribution, g kg^{-1}						
Clay	335	600	720	740	200	580
Silt	192	100	216	191	61	110
Sand	473	300	64	69	739	310

† Effective cation exchange capacity (ECEC) = $Al^{3+} + Ca^{2+} + Mg^{2+} + K^{+}$.

‡ Cation exchange capacity (CEC) pH 7.0 = $Ca^{2+} + Mg^{2+} + K^{+}$ + total acidity (H + Al).

§ Base saturation = $100(Ca^{2+} + Mg^{2+} + K^{+}/CEC\ pH\ 7.0)$.

¶ Al^{3+} saturation = $100(Al^{3+}/ECEC)$.

Table 3. Details of the experimental areas used in the papers involving phosphogypsum (PG) application on various Oxisols from southern Brazil under continuous no-till management that were selected for the present study.

Reference	Site	Climate†	Soil texture	Beginning of experiment	Experimental design	PG rates‡	No. of replications
						Mg ha^{-1}	
Rampim et al. (2011)	Guaíra (PR)	Cfa	Clayey	2006	RCB§	0.0, 1.0, 2.0, 3.0, 4.0, and 5.0	6
Michalovicz et al. (2014)	Guarapuava (PR)	Cfb	Clayey	2009	RCB	0.0, 1.5, 3.0, 4.5, and 6.0	4
Dalla Nora and Amado (2013)	Carazinho (RS)	Cfa	Clayey	2010	RCB	0.0, 1.0, 2.0, 3.0, 4.0, 5.0, and 6.5	3

† According to Köppen–Geiger System (Peel et al., 2007).

‡ Phosphogypsum was applied on the soil surface in the beginning of experiment.

§ Randomized complete block.

after PG application. In selected papers (Table 3), soil sampling procedures were as described by Dalla Nora and Amado (2013), Michalovicz et al. (2014), and Rampim et al. (2011), and soil samples were taken at 6 mo (Michalovicz et al., 2014; Rampim et al., 2011) and at 12 mo (Dalla Nora and Amado, 2013) after PG application. Before chemical analysis, soils were air-dried, ground, and sieved through a 2-mm sieve. Exchangeable Ca^{2+} was extracted with neutral 1 mol L^{-1} KCl in a 1:10 (v/v) soil/solution ratio, and its determination followed the standard methods used in southern Brazil (Pavan et al., 1992; Tedesco et al., 1995). Thus, our dataset consisted of 142 data points, which were used to estimate the increase in exchangeable Ca^{2+} content at the 20- to 40-cm soil layer after PG application.

Using the M5-Rules Algorithm to Estimate the Increase in Exchangeable Ca^{2+} Content

The exchangeable Ca^{2+} content dataset was analyzed by data mining computational techniques using the M5-Rules algorithm to create regression models. This algorithm estimates the value of a goal attribute by calculating regression models using predictive attributes. The resulting model establishes the correlation between the predictive and goal attributes. In our study, the increase in exchangeable Ca^{2+} content at the 20- to 40-cm soil layer after PG application was considered the goal attribute. Phosphogypsum rates and soil sampling times after PG application were used as the predictive attributes. Weka 3.8 (Frank et al., 2016), which is a collection of machine learning algorithms for data mining tasks, was used for estimations.

Analysis of the Relationship between Ca^{2+} Saturation in the Effective Cation Exchange Capacity and Crop Grain Yields

Data from the six experiments and the papers published by Dalla Nora and Amado (2013) and Michalovicz et al. (2014) were used to evaluate the relationship between grain yields (maize, soybean, wheat, and barley) and Ca^{2+} saturation in the ECEC at the 20- to 40-cm soil layer. The following criteria were used to select data from the experiments and papers: (i) studies with PG application under a continuous no-till system, (ii) variable crop yields with increasing PG rates, and (iii) soil analysis results that allowed calculating Ca^{2+} saturation in the ECEC at the 20- to 40-cm depth and crop yield in the same year. The ECEC was calculated by adding the contents of exchangeable cations ($Ca^{2+} + Mg^{2+} + K^{+} + Al^{3+}$), and Ca^{2+} saturation was calculated as 100 × (Ca^{2+}/ECEC). The criterion adopted for choosing the regression model was the magnitude of the determination coefficients significant at $P < 0.05$.

Proposal and Validation of a New Method for Establishing Phosphogypsum Application Recommendations

A new method for PG application recommendation was proposed based on the increase in Ca^{2+} saturation in the ECEC at the subsoil layer (20–40 cm). For its validation, the PG application rates used when maximum economic yields (MEYs) of maize, soybean, wheat, and barley were obtained in field studies on continuous no-till soils in southern Brazil were compared with PG application rates recommended by the proposed method and by methods based on the clay content (g kg^{-1}) in the subsoil, which are in use in different regions in Brazil: 5 × soil clay content and 6 × soil clay content. We first considered all papers that reported field studies using various PG rates under a continuous no-till system and that allowed obtaining crop yields over a 4-yr period. In these papers, we selected the results in which there was no indication of PG application by any method of PG recommendation and no crop response to the PG rates applied and results in which there was indication of PG application by at least one of the methods of PG recommendation and that allowed obtaining a positive crop response to the PG rates applied. To define a PG rate for MEY, data on crop grain yields obtained for PG application rates were adjusted to the Linear Response Plateau model. When model adjustment was significant ($P < 0.05$), we considered that MEY was achieved by the PG rate in which the grain yield stabilized. When data were not adjusted, MEY was defined by the PG rate that provided 95% of maximum yield for quadratic models and by the maximum yield PG rate for linear models. In studies involving various PG and lime rates in which there was no significant lime × PG interaction, we considered the average responses obtained with the PG application rates; when there was a significant lime × PG interaction with a single rate of lime applied, we considered the effects of PG rates only on liming treatment. To avoid confusion in crop responses, results on significant lime × PG interactions and various lime rates were disregarded. The same procedure was applied to studies involving various rates of PG and other nutrients (e.g., nitrogen, phosphorus). Because one-third of dataset used to validate the model consisted of data used to build the model, a model validation disregarding the data used to build the model was also performed.

RESULTS AND DISCUSSION

Data analysis revealed that the highest grain yields of maize, soybean, wheat, and barley occurred for Ca^{2+} saturation in the ECEC in the subsoil (20–40 cm) ranging from 52 to 65% (Fig. 1).

The use of the M5-Rules algorithm on the exchangeable Ca^{2+} content dataset resulting from the soil samples taken from the

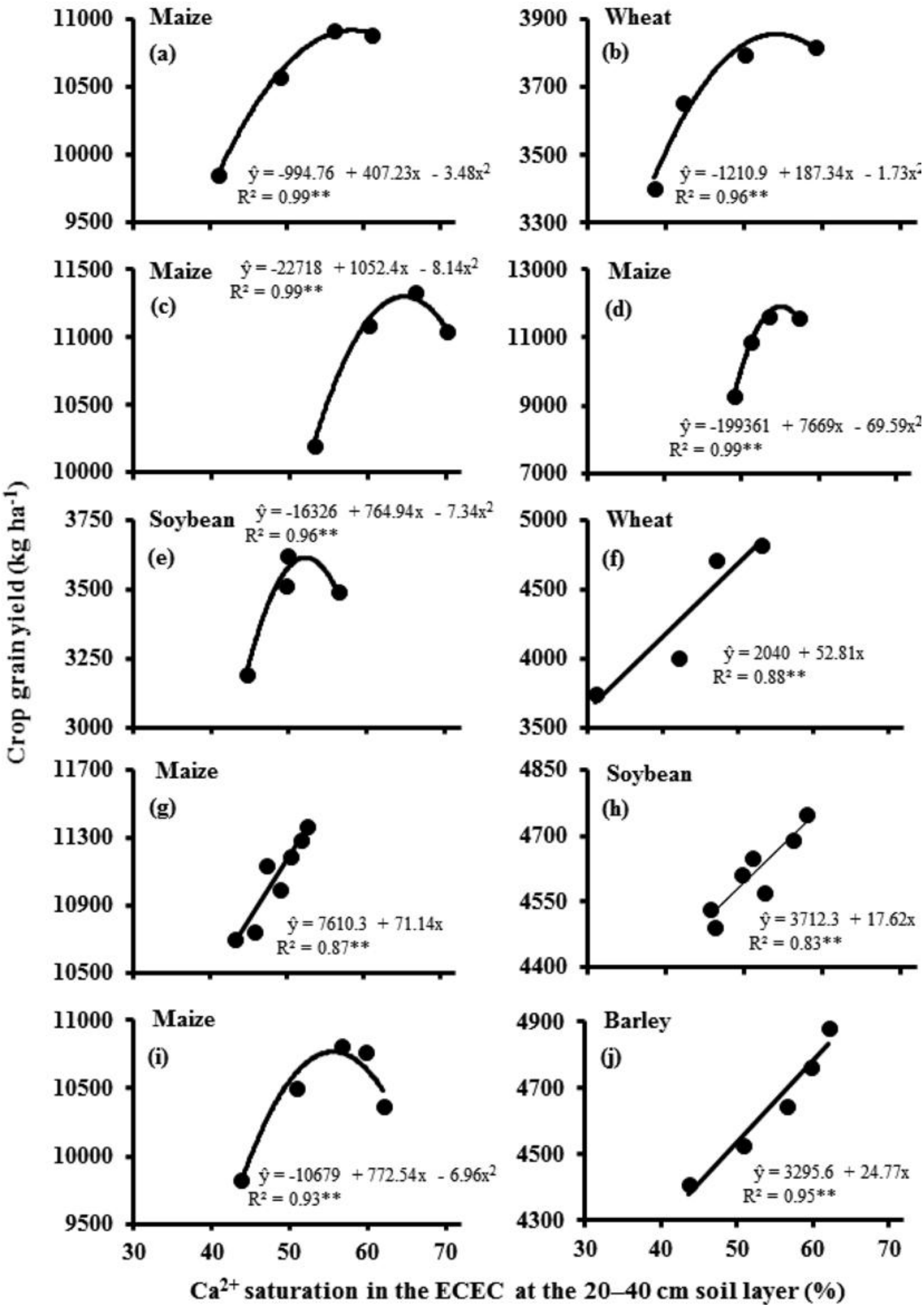

Figure 1. Crop yields of maize, wheat, soybean, and barley affected by Ca^{2+} saturation in the effective cation exchange capacity (ECEC) at the 24-40 cm soil layer in field experiments on no-till Oxisols in southern Brazil: (a) Exp. 1: Cargill 901 maize, (b) Exp. 2: OR 1 wheat, (c) Exp. 3: Pioneer 30R50 maize, (d) Exp.4: Dekalb 240 maize, (e) Exp. 5: Nidera 5909 soybean, (f) Exp. 6: Supera wheat, (g and h) Dalla Nora and Amado (2013): Pioneer 3069 maize and Nidera 5909 soybean, respectively, and (i and j) Michalovicz et al. (2014): Premium Flex maize and BRS Cauê barley, respectively. ** $P < 0.01$.

20-40-cm layer up to 12 mo after PG application revealed that the goal attribute (i.e., the increase in exchangeable Ca^{2+} content at the 20- to 40-cm soil layer after PG application) was not influenced by the different sampling times. The best resulting regression model showed an increase in exchangeable Ca^{2+} content at the 20- to 40-cm soil layer (ΔCa, in $cmol_c\ dm^{-3}$) with PG addition (PG > 0, in Mg ha^{-1}) according to the equation $\Delta Ca = 0.062PG + 0.602$ ($r = 0.63$). Thus, the model revealed that 6.4 Mg ha^{-1} of PG would be required to increase the exchangeable Ca^{2+} content by 1 $cmol_c\ dm^{-3}$ at the 20- to 40-cm soil layer.

The results led us to propose a new method for estimating PG application recommendations based on the increase in Ca^{2+} saturation in the ECEC at the subsoil layer (20–40 cm). This new method is based on the amount of PG required to increase

Table 4. Comparisons between the phosphogypsum (PG) application rates recommended by the different methods and the PG rates associated with the maximum economic yield (MEY) of several crops, adjusted to the data obtained in field experiments on no-till soils in southern Brazil.

Clay	ECEC	Ca^{2+}	Al^{3+}	m	PG				Source
					5 × clay	6 × clay	Proposed method	MEY (Model)†	
g kg^{-1}	cmol$_c$ dm^{-3}			%	Mg ha^{-1}				
								Maize	
335	3.35	1.6	0.6	18	1.7	2.0	2.6	2.8 (Q)	Caires et al. (1999)
600	2.52	0.7	0.8	32	3.0	3.6	5.2	4.5 (LRP)	Caires et al. (2004)
720	5.44	2.3	0.0	0	0.0	0.0	6.2	4.9 (LRP)	Caires et al. (2011)
570	5.14	1.7	0.8	16	2.85	3.4	8.9	6.5 (L)	Dalla Nora and Amado (2013)
480	3.81	1.8	0.4	10	0.0	0.0	3.1	2.5 (LRP)	Dalla Nora and Amado (2013)
790‡	2.65‡	1.1‡	0.4‡	15‡	0.0	0.0	3.1	2.2 (LRP)	Michalovicz et al. (2014)
168	1.89	0.2	1.4	74	0.85	1.0	6.0	5.7 (LRP)	Pauletti et al. (2014)
680	4.19	2.0	0.9	21	3.4	4.1	3.3	1.6 (LRP)	Zandoná et al. (2015)
780‡	2.65‡	1.1‡	0.4‡	15‡	0.0	0.0	3.1	1.1§ (Q)	Vicensi et al. (2016)
700¶	5.94¶	2.5¶	0.8¶	13¶	3.5	4.2	6.8	6.5 (L)	Dalla Nora et al. (2017)
								Soybean	
800	6.11	3.8	0.4	7	0.0	0.0	0.0	0.0	Rampim et al. (2011)
803	7.58	5.9	0.0	0	0.0	0.0	0.0	0.0	Rampim et al. (2011)
570	5.14	1.7	0.8	16	2.85	3.4	8.9	6.5 (L)	Dalla Nora and Amado (2013)
168	1.89	0.2	1.4	74	0.85	1.0	6.0	4.7 (LRP)	Pauletti et al. (2014)
680	5.10	2.7	0.9	18	3.4	4.1	2.3	1.2 (LRP)	Zandoná et al. (2015)
500¶	4.45¶	2.5¶	0.4¶	9	2.5	3.0	1.1	1.7 (LRP)	Dalla Nora et al. (2017)
								Barley	
600	2.52	0.7	0.8	32	3.0	3.6	5.2	9.0 (L)	Caires et al. (2001)
790¶	2.65‡	1.1‡	0.4‡	15‡	0.0	0.0	3.1	3.3 (LRP)	Michalovicz et al. (2014)
								Wheat	
600	2.52	0.7	0.8	32	3.0	3.6	5.2	5.2 (LRP)	Caires et al. (2002)
168	1.89	0.2	1.4	74	0.85	1.0	6.0	5.0 (LRP)	Pauletti et al. (2014)
780‡	2.65‡	1.1‡	0.4‡	15‡	0.0	0.0	3.1	2.9§ (LRP)	Vicensi et al. (2016)

The contents of soil clay, Ca^{2+}, and Al^{3+}, Al^{3+} saturation (m), and effective cation exchange capacity (ECEC) refer to the 20- to 40- cm depth. Al^{3+} saturation (m) = 100 × (Al^{3+}/ECEC).

† L, linear (maximum yield); LRP, Linear Response Plateau (stabilized yield); Q, quadratic (95% of maximum yield).

‡ Soil sample taken from the 30- to 50-cm depth.

§ One-third of the PG rate applied per year on the soil surface for 3 yr.

¶ Soil sample taken from the 25- to 40-cm depth.

Ca^{2+} saturation in the ECEC at the 20- to 40-cm soil layer to 60% when this is lower than 54%, and it is calculated as follows:

$$\text{PG (Mg ha}^{-1}) = (0.6 \times \text{ECEC} - \text{exchangeable Ca}^{2+} \text{ content in cmol}_c \text{ dm}^{-3}) \times 6.4.$$

Because the highest crop grain yields were obtained for a confidence interval of Ca^{2+} saturation in the ECEC at the 20- to 40-cm soil layer of 57% ± 3% ($P < 0.05$) and because some relationships between crop grain yields and Ca^{2+} saturation were linear (Fig. 1), we only fixed a value for Ca^{2+} saturation at the greater range of variation (60%) when saturation was below the minimum range of variation (54%).

Comparisons between the PG rates recommended by the different methods and those associated with the MEY obtained in field experiments on no-till soils in southern Brazil are shown in Table 4. Large divergences were observed between the PG rates recommended by the proposed method and those indicated by the methods based on clay content. Because these methods have different fundamentals to estimate the required PG application rates, the new method for PG application recommendation estimated both higher (e.g., Dalla Nora and Amado, 2013; Pauletti et al., 2014) and lower (e.g., Zandoná et al., 2015) PG rates than methods based on clay content. Based on these results, there seems to be no maximum PG rate that could be applied on the soil surface. However, because leaching of exchangeable Mg^{2+} has often been observed in studies of PG application (Caires et al., 2004; Dalla Nora and Amado, 2013; de Oliveira and Pavan, 1996; Farina et al., 2000; Michalovicz et al., 2014; Pauletti et al., 2014), PG application should only be recommended to soils with high exchangeable Mg^{2+} content in their surface layers. The combination of dolomitic lime and PG has been an appropriate amendment for Oxisols with toxic Al^{3+} levels (Dalla Nora et al., 2014; Pavan et al., 1984).

Although Dalla Nora et al. (2017) conducted four field experiments, we only used some data from Experiments I and II and no data from Experiments III and IV. In Experiment I, PG rates were applied on the soil surface in 2009, and soybean (2011/2012) and wheat (2013) yields were not considered. The authors adjusted the grain yields of these crops to PG application rate according to the quadratic model. However, because the adjusted curves showed no inflection and maximum crop yields were obtained with PG rates (6.25 Mg ha^{-1} for soybean and 6.4 Mg ha^{-1} for wheat) close to the maximum applied PG

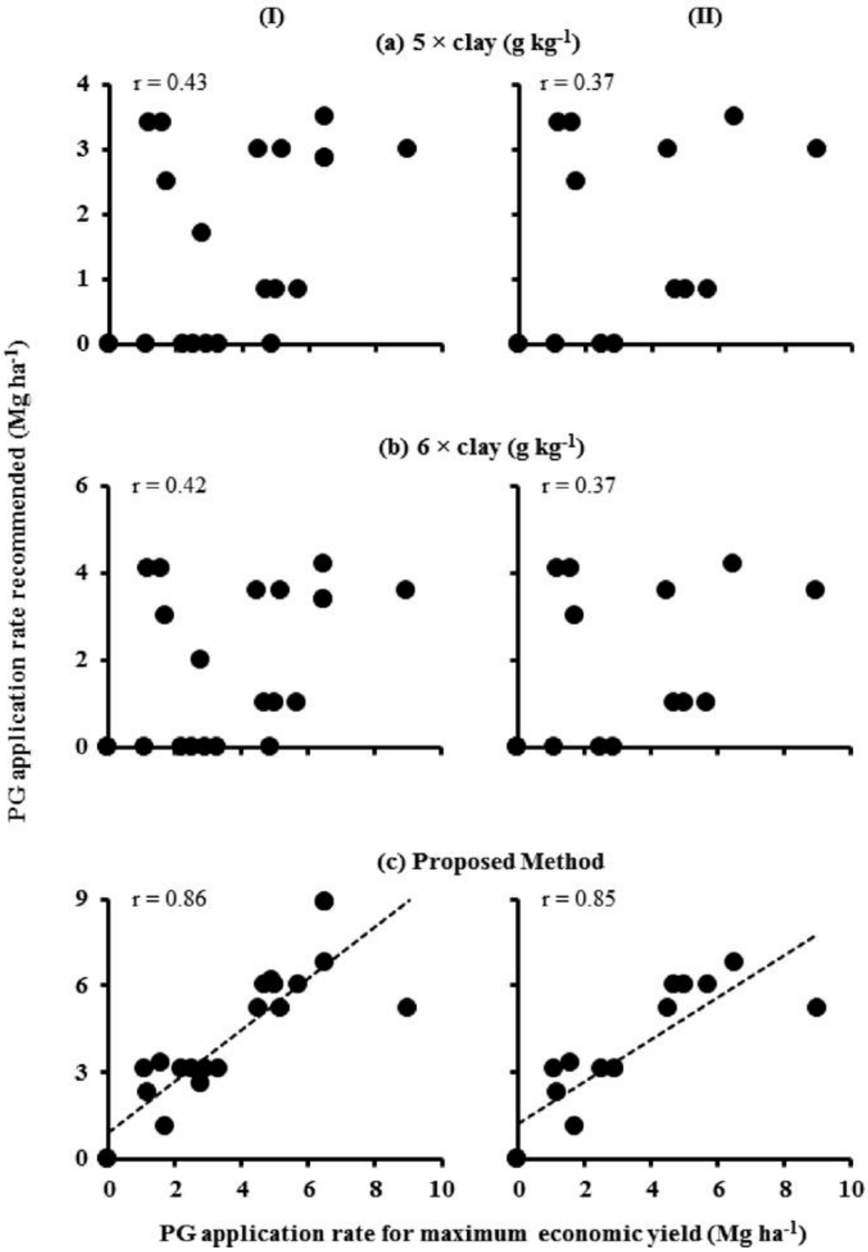

Figure 2. Relationship between phosphogypsum (PG) application rate for maximum economic yields of maize, wheat, soybean, and barley on no-till Oxisols in southern Brazil, and the PG application rate recommended by different methods: (a) 5 × soil clay content in g kg^{-1}, (b) 6 × soil clay content in g kg^{-1}, and (c) the method proposed to increase Ca^{2+} saturation to 60% in the effective cation exchange capacity (ECEC) at the 20-40 cm soil layer, and with (I) and without (II) comprising the data used to build the model.

rate (6.5 Mg ha^{-1}), these results were not used for suggesting linear response. In Experiment II, PG rates were also applied on the soil surface in 2009, and soybean yield (2012/2013) was not considered. In this case, there was a very low increase in soybean yield with increasing PG rates (42.2 kg grain per Mg PG), which was insufficient to estimate a PG rate for MEY. In addition, the soil in this study was analyzed at the 25- to 40-cm layer, not at the 20- to 40-cm layer. Because the exchangeable Al^{3+} content (0.4 $cmol_c$ dm^{-3}) and Ca^{2+} saturation in the ECEC (56%) at the 25- to 40-cm layer were close to the limit for PG application, the PG rates recommended by the different methods were compared. The cumulative yields of the five harvests performed in Experiment II increased according to the quadratic model with increasing PG rates. Based on the regression equation obtained (Dalla Nora et al., 2017), the MEY (95% of maximum yield) would be obtained using 1.3 Mg ha^{-1} of PG, which is very close to that estimated by our method (1.1 Mg ha^{-1}). Data from Experiment III were not used because PG rates were applied in a soil with high acidity at the surface layers, which most likely affected PG action regarding subsoil improvement. In Experiment IV there was a significant interaction among the surface-applied lime and PG rates, which did not allow an accurate interpretation of the results with varying PG rates; therefore, this experiment was not considered.

Some studies found a linear increase in crop grain yield with increasing PG rate, which did not allow obtaining an accurate PG rate for maximizing crop yield (Table 4). For example, Dalla Nora and Amado (2013) found a linear increase in the grain yields of maize and soybean up to a maximum PG application rate of 6.5 Mg ha^{-1}, and therefore the proposed method recommended a higher rate of PG application (8.9 Mg ha^{-1}). A similar result was obtained by Dalla Nora et al. (2017) for maize, with a linear increase in grain yield up to a maximum PG application rate of 6.5 Mg ha^{-1}; similarly, the new method presented here recommended a higher PG application rate (6.8 Mg ha^{-1}). Caires et al. (2001) also verified a linear increase in barley yield with an increasing PG application rate of up to 9.0 Mg ha^{-1}; however, the new method proposed here estimated a lower recommended rate for PG application (5.2 Mg ha^{-1}). The greater barley yield obtained by Caires et al. (2001), using a higher rate of PG application, might have been due to the severe water deficit that occurred at a critical stage, during crop flowering. Nevertheless, the PG application rate recommended by the new proposed method was closer to the PG application rate associated with higher barley yield than that suggested by the methods based on soil clay content.

The best performance of the method proposed in our study is shown in Fig. 2. The relationships obtained between the PG rates for the maximum crop yield and the PG rates recommended by the different methods leave no doubt that the proposed method is promising. The correlation coefficient obtained for the proposed method was higher than those of the methods based on soil clay content (5 and 6 × clay content), both including (r = 0.86 versus 0.43 and 0.42) and not including (r = 0.85 versus 0.37 and 0.37) the data used to build the model. The correlation obtained for the new proposed method was not higher because the PG application rate recommended by the new method was higher than that for maximum crop yield obtained in some studies; however, due to the linear increase in crop yield with increasing PG rates, the MEY was not effectively achieved.

Because the PG rates increasing Ca^{2+} saturation in the ECEC at the 20- to 40-cm soil layer to 60% corresponded with those leading to the MEY in most of the studies conducted on continuous no-till soils in southern Brazil, this method might be efficiently used when subsoil acidity is an important growth-limiting factor.

Because the residual effect of PG application varies according to soil and climatic conditions, reapplication of PG should be performed when the Ca^{2+} saturation in the ECEC at the 20- to 40-cm soil layer is below 54%. Over time, this PG application strategy will improve the deep soil profile, allowing greater plant root growth in deep layers and greater capacity of plants to mitigate stress caused by drought. The progress achieved with PG use under no-till soils in southern Brazil should serve as a reference standard for other tropical and subtropical agricultural regions.

CONCLUSIONS

Our study found that the PG application recommendation for crop grain production under continuous no-till systems can be based on the Ca^{2+} saturation in the ECEC at the subsoil layer (20–40 cm). The method proposed herein is based on the PG rate required to increase Ca^{2+} saturation to 60% in the ECEC at the 20- to 40-cm soil layer when it is less than 54%, calculated as PG (Mg ha^{-1}) = (0.6 × ECEC – exchangeable Ca^{2+} content in $cmol_c$ dm^{-3}) × 6.4. The PG rates recommended by this method were closer to the PG rates associated with MEY than the PG rates obtained by methods based on subsoil clay content, which are currently used in Brazil. Thus, the new proposed method can be efficiently used when subsoil acidity is an important growth-limiting factor.

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