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Soil Acidity Indicators for Liming in Tropical Acid Soils Cropped With Soybean Under Short- and Long-Term No-Tillage Systems

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Abstract

Although the movement of liming materials under no-tillage (NT) systems can intensify stratification of soil chemical properties and be deleterious to soybean growth, little is known regarding the soil acidity indicators used to predict lime requirement (LR) in Brazilian soils under NT. Thus, we hypothesize that the recommendation criteria used for predicting LR in soils under NT must be different from those adopted in soils under conventional tillage (CT), and the reference values for such liming indicators may vary according to the phase following the adoption of the NT system. The study aimed to obtain soil acidity indicators for soybean (*Glycine max* (L.) Merill) in tropical acid soils under no-tillage (NT) systems and their respective critical levels according to the phase of NT. Sites under NT were commercial soybean crop areas located in the Cerrado region, Brazil. Systems analyzed were NT_I (NT management from 0 to 5 years—initial phase), and NT_{TC} (NT management from 5 to 20 years—transition-consolidation phase). Soil samples were collected at the 0-5, 0-10, and 0-20 cm layers, and analyzed for chemical characteristics. Relationships between crop yield response of soybean to lime application and various soil acidity-related characteristics led to establishing soil acidiy indicators for liming in tropical acid soils under no tillage. Critical levels were approximately similar in both phases of NT for exchangeable Ca and Mg, and potential acidity, but varied greatly depending on the soil layer and phase of NT management for soil pH_{CaCl2}, $CEC_{pH7.0,}$ and base saturation. In general, for both phases of NT, the critical levels of soil acidity indicators were lowest for the 0-20 cm layer, moderate for the 0-10 cm layer, and highest for the 0-5 cm layer. Lime applied with incorporation in the NT_{TC} phase kept the soil with chemical attributes more favorable for plant growth than when surface liming was employed in the NT_I phase, which was verified by the soybean yield response. Our results indicate the differences on the soil acidity indexes between the top and bottom depths that would not have been realized in a soil sampling for conventional tillage. Hence, recommendation criteria for lime application considering distinct soil depths and NT systems will be helpful when making lime decisions. Further research should focus on the development of reliable methods for predicting LR according to the NT phase and consequently maximize soybean production under NT systems in Brazil.

Keywords: *Glycine max* L. Merrill, conservation tillage, critical limits, soil acidity indexes, soil layers

1. Introduction

In many areas of the world, soil acidity limits agricultural yield of field crops such as soybean (*Glycine max* (L.) Merill), which has high economic and social importance as a source for grain, bran, and oil production for human and animal food. The aluminum (Al^{3+}) toxicity and the deficiency of nutrients such as calcium (Ca^{2+}), magnesium (Mg^{2+}), phosphorous (P), and molybdenum (Mo) caused by soil acidification usually inhibit the growth of soybean, which leads to crop yield reduction (Brown et al., 2008; Fageria & Baligar, 2008).

Given the high degree of weathering, acid soils are mainly distributed in tropical and subtropical regions. In Brazil, most soils are acidic presenting pH values between 3.8 and 5.5 (Abreu Jr. et al., 2003). The surface application of lime [$CaCO_3$ or $CaMg(CO_3)_2$] is the traditional method for correcting soil acidity in weathered soils. Surface liming ameliorates topsoil acidity, enabling exchangeable Al neutralization, and Ca and Mg content increase in the superficial soil layer. However, due to the low solubility and mobility of carbonate through the soil profile, the benefits of surface-applied lime are usually limited to the lime incorporation sites

(Caires et al., 2005; Caires et al., 2006; Soratto & Crusciol, 2008) and hence is inefficient in ameliorating subsurface soil acidity (Tang et al., 2013). Thus, subsoil acidity is an important yield-limiting factor, especially in no-tillage (NT) systems where soil immobilization is not adopted.

In tropical and subtropical regions, NT systems with diversified crop rotations represent one of the most effective strategies to improve the sustainability of agriculture, contributing to minimizing the deleterious impacts of intensive farming such as soil and nutrient losses through erosion (Lal, 1995; Hobbs et al., 2008). The cultivated area under NT in Brazil has rapidly expanded over the years, currently taking up some 32.9 Mha (IBGE, 2017), which represents ~55% of the total grain production area. Additionally, more than 38.5 million hectares were planted with soybean in Brazil, with a production of 135.4 million of tones during the 2020/21 harvest (CONAB, 2022). Since the lime reaction in NT soils under commercial soybean cultivation is generally limited to the surface layers, there is a formation of an alkalizing gradient that moves vertically down into the soil profile (Rheinheimer et al., 2018), thereby leading to exacerbated stratification of pH and Al availability (Barth et al., 2018). This allows the re-acidification of deeper soil layers and compromises root penetration and plant nutrition.

Some soil acidity-related characteristics have been reported to be affected by NT practices, which may also influence plant development and yield. Caires et al. (2006) showed that the increase in soil CEC, caused by a higher OM content, provides sufficient concentrations of Ca^{2+} and Mg^{2+}, even in highly acidic soils. Other observed changes include decreased Al^{3+} toxicity through the formation of Al-organic complexes (Miyazawa et al., 2002). According to Alleoni et al. (2010), high organic matter contents found in the topsoil of NT systems can cause most Al in acid soil solution (pH < 5.5) to be complexed to dissolved organic C, thus decreasing its bioavailability.

Although the movement of liming materials under NT systems can intensify the stratification of soil chemical properties and be deleterious to soybean growth, little is known regarding the soil acidity indicators used to predict lime requirement in Brazilian soils under NT. This is because the liming criteria currently being used in NT areas were designed for conventionally tilled soils, allowing over predictions of lime rates for established NT systems in southern Brazil (Nola and Anghinoni 2007). Even less is known concerning the reference values for the liming criteria to be used in each phase of the NT system, that is, initial phase (0-5 years), transition phase (6-10 years), consolidation phase (11-20 years) and maintenance phase (> 20 years) (Sá, 2004).

Considering the predominance of acidic soils and the large area cropped with soybean under NT in Brazil, we hypothesize that (1) the recommendation criteria used for predicting lime rates in NT soils must be different from those adopted in soils under conventional tillage (CT), and (2) the reference values for such liming criteria may vary according to the phase following the adoption of the NT system. Thus, the objectives of this study were to obtain soil acidity indicators for soybean in soils under NT in the Cerrado region of Brazil and determine the critical levels for the liming criteria according to the phase of the NT system.

2. Materials and Methods

2.1 Study Area

The studied areas were selected from sites of the NT system located in the five mesoregions of the state of Goiás, in the Midwestern region of Brazil, between the parallels 12°30′ and 19°30′ S and the meridians 46°00′ and 53°00′ W, with an extension of approximately 345,965 square kilometers of land (Pena et al., 2016). The climate of the region is classified as Aw (seasonal tropical savanna), with a humid season from October to April and a dry one from May to September according to the Köppen climate classification. The average annual precipitation is 1500 mm, and the average air temperature ranges from 18 to 32 °C. The natural vegetation in the study area has been classified as Cerrado sensu stricto (tree dominated scrub of shrubs and trees of 3-8 m height with grass under story) and Cerradão (dry semi-deciduous woodland).

The soils occurring in all sites were classified as Red-Yellow Latossol according to the Brazilian System of Soil Classification (Santos et al., 2018), which was equivalent to a Typic Haplustox according to the USA Soil Taxonomy (Soil Survey Staff, 2014). The soils were all well-drained, with non-hydromorphic characteristics. In general, the clay content ranged from 130 to 570 g/kg soil for all sites and the mineral composition comprised variable charge minerals, primarily kaolinite, iron oxides, and gibbsite (data not shown).

2.2 Study Design

The study comprised three phases as described below.

2.2.1 Phase 1: Sites Selection

The sites under the NT system were selected at the five mesoregions of the state of Goiás (Site 1-North; Site 2-Northwest; Site 3-Center; Site 4-East; and Site 5-South), following divisions established by the Brazilian Institute for Geography and Statistics (IBGE, 2018). Each mesoregion corresponds to a subdivision that encompasses municipalities with similar levels of economic and social development.

In addition, the sites were selected according to the phase of the NT system: NT_I, agricultural sites under NT management ranging from 0 to 5 years (initial phase), and NT_{TC}—agricultural sites under NT management ranging from 5 to 20 years (transition-consolidation phase). No-tillage sites evaluated in the study were representative of the grain production area in Goiás, and were categorized by cropping technology level as a medium, and high. The medium and high cropping technology levels generated approximately 8-10 and 10-12 Mg/ha/year of aboveground biomass, respectively, with a predominance of both soybean in all rotations systems.

2.2.2 Phase 2: Field Survey

A field survey was conducted by applying a questionnaire to farmers and farm managers from each selected site under NT. The questionnaire was composed of 25 questions and focused on the current land management (cultivated area, crops used in rotation, use of fertilizers and other inputs), field characteristics, and the history of land use. The results from the field survey will be published separately. Here, we focused on the information about the crops used in the rotations, which included soybean (*Glycine max*, L. Merril), maize (*Zea mays*, L.), grain sorghum (*Sorghum bicolor*, L. Moench), ruzi grass (*Brachiaria ruziziensis*, Germain et Evrard), wheat (*Triticum aestivum*, L.), pearl millet (*Pennisetum glaucum*, L.), and sunn hemp (*Crotalaria juncea*, L.). Table 1 provides the location, phase of the NT management, and crop rotation for the five sites.

Table 1. Site location, phase of the no-tillage management, and crops in the studied areas

Site	Mesoregion	Phase	Crop sequence
1	North	NT_I	M-GS-PM-B/SH
		NT_{TC}	S-M-S
2	Northwest	NT_I	S-B
		NT_{TC}	S-B
3	Center	NT_I	S-B
		NT_{TC}	S-B
4	East	NT_I	S-M-W/PM
		NT_{TC}	S-M-B/PM/SH/W
5	South	NT_I	S-M-GS
		NT_{TC}	S-M-GS

Note. NT_I: initial phase (0-5 years of management under NT). NT_{TC}: transition-consolidation phase (5-20 years of management under NT). M: maize; GS: grain sorghum; PM: pearl millet; B: brachiaria; SH: sunn hemp; S: soybean; W: wheat.

2.2.3 Phase 3: Soil and Crop Measurements

Soil samples were collected in three different layers (0-5, 0-10, and 0-20 cm) from the selected sites under the NT system between 2020-2021. Each sample was composed of five subsamples randomly collected to represent the data of one plot. Samples at all sites were collected after lime application and before crop sowing and analyzed for soil textural class and chemical characteristics. In NT areas at the initial phase (NT_I), limestone was incorporated by farmers up to 0.20-0.25 m to alleviate subsurface soil acidity, while in NT areas at the transition-consolidation phase (NT_{TC}), liming was performed on the surface, without incorporation.

For the analysis of the soil physical and chemical characteristics, samples were air-dried and sieved through a 2-mm mesh and then analyzed according to the methods described by Embrapa (2017). Particle size analysis was performed by using the pipette method after dispersing particles in 1 mol/L of NaOH. Then, the total clay fraction (Ø < 0.002 mm) of each soil sample was collected by sedimentation according to Stokes' law. Soil chemical analyses comprised pH_{CaCl2}, determined in a 1:2.5 (v/v) ratio; exchangeable Ca^{2+}, Mg^{2+}, and exchangeable Al^{3+}, extracted with KCl 1 mol/L; exchangeable K^+, extracted with Mehlich-1; and potential acidity (H + Al), extracted with $Ca(OAc)_2$ 0.5 mol/L buffered at pH 7.0. The cation exchange capacity at pH 7.0

[$CEC_{pH7.0}$ = SB + (H + Al)], sum of bases (SB = Ca^{2+} + Mg^{2+} + K^{+}), base saturation (BS = 100 × SB/$CEC_{pH7.0}$), and exchangeable Al^{3+} saturation [(m = Al^{3+}/(SB + Al^{3+})] were then calculated. Organic matter (OM) was calculated from the total carbon of organic compounds determined by oxidation with potassium dichromate using the Walkley-Black procedure (Nelson and Sommers 1996).

Grains of the soybean, which was used as the main crop in the rotation system at all sites, aswas machine-harvested from the full area at each site when the crop reached the maturity stage. The grain yield was then expressed as t/ha based on 130 g/kg H_2O.

2.3 Statistical Analysis

Soil acidity indicators for liming were obtained based on the relationship between the crop yield response of soybean to lime application and various soil acidity-related characteristics across sites under NT in the initial phase, as well as NT in the transition-consolidation phase. The soybean grain yield was used in the relationships because the soybean was the main crop in the cropping sequences of all studied sites under NT. Linear regression models were fit (Sigmaplot 11.0), and the reference values for the soil acidity indicators were then obtained by the first derivative of the yield response models (regression analysis), estimating the soil acidity indexes for the three sampling depths according to the phase of the NT system. The models with the highest level of significance were adopted.

3. Results

3.1 Soil Properties

Considering the properties of the soil layer (0-20 cm) sampled for characterization, the selected sites had a wide range of soil pH_{CaCl2}, clay, and OM content (Table 2). Low (≤ 4.4) and medium (4.5-4.8) pH_{CaCl2} values corresponding to strongly acidic soils were observed at site 2 (Northwest region) and site 4 (East region), whereas higher pH_{CaCl2} values (> 5.9) were observed at site 1 (North region) (Table 2). Site 3 (Center region) and site 5 (South region) showed adequate pH_{CaCl2} values (4.9-5.5) corresponding to moderately acidic soils (Table 2).

Table 2. Descriptive statistics of soil properties sampled for characterization at the 0-20 cm layer of the areas under no-tillage

Site	Phase	pH_{CaCl2}				Clay				Organic matter			
		Mean	Mi.	Ma.	CV	Mean	Mi.	Ma.	CV	Mean	Mi.	Ma.	CV
					%	---------- g/kg ----------			%	---------- g/kg ----------			%
1	NT_I	6.4	6.2	6.6	2.7	250	190	290	17	17	10	26	41
	NT_{TC}	6.5	6.2	6.7	3.2	308	290	340	7	13	10	18	27
2	NT_I	5.4	3.7	6.0	21.0	178	130	260	32	12	5	18	46
	NT_{TC}	5.6	5.1	5.8	6.0	220	130	260	28	11	3	20	85
3	NT_I	5.5	5.3	5.6	3.2	255	130	300	33	11	5	14	37
	NT_{TC}	6.2	5.6	6.7	9.4	285	260	320	11	10	7	14	31
4	NT_I	5.5	4.8	6.4	12.5	365	190	530	41	16	10	29	57
	NT_{TC}	5.9	5.5	6.2	5.1	353	300	400	12	25	20	30	18
5	NT_I	5.2	4.9	5.6	6.0	488	440	570	13	23	15	29	27
	NT_{TC}	5.6	5.4	5.8	3.7	410	400	420	3	18	7	26	45

Note. pH_{CaCl2}: 1:2.5 (v/v) ratio. Clay: pipette method. Organic matter: Walkley-Black method.

The clay content ranged from 130 to 570 g/kg for all locations, and it is composed of variable charge minerals, primarily kaolinite, iron oxides, and gibbsite. The dominant soil texture class was sandy loam (50% of NT soils), followed by medium loam (40%) and clay loam (10%). Fine-textured soils such as clay comprised only 1 soil.

Descriptive statistics of soil samples for each site in Table 2 also show substantial variation for the OM content, ranging from 3 to 30 g/kg across all locations. Low (≤ 20 g/kg) OM contents were found in 80% of the sites, whereas 20% of the sites presented medium (20-40 g/kg) OM contents.

With respect to the soil properties used to set the soil acidity indicators for distinct soil layers and phases of the NT management, they are shown in Table 3. A wide variation in soil properties was observed, with great differences among sites.

Table 3. Soil chemical properties in different soil layers of the sampled areas under no-tillage

Soil depth (cm)	Site 1		Site 2		Site 3		Site 4		Site 5	
	NT_I	NT_{TC}	NT_I	NT_{TC}	NT_I	NT_{TC}	NT_I	NT_{TC}	NT_I	NT_{TC}
pH_{CaCl2}										
0-5	6.5	6.8	6.1	6.2	5.9	6.4	6.1	6.2	5.9	6.0
0-10	6.4	6.7	6.2	6.0	5.6	6.1	5.8	6.2	5.4	5.8
0-20	6.4	6.5	5.4	5.6	5.5	6.2	5.5	5.9	5.2	5.6
Exchangeable Ca ($cmol_c/dm^3$)										
0-5	1.4	2.7	2.4	2.4	2.9	3.9	2.7	5.4	4.9	5.0
0-10	1.3	2.4	2.0	2.0	2.7	3.7	2.4	4.8	3.4	3.9
0-20	1.3	1.9	1.5	1.6	2.3	3.4	1.9	4.1	2.6	3.4
Exchangeable Mg ($cmol_c/dm^3$)										
0-5	0.9	1.0	0.9	1.0	1.4	1.5	1.1	1.5	1.7	1.3
0-10	0.8	0.9	0.7	0.9	1.3	1.4	0.9	1.5	1.3	1.1
0-20	0.8	0.7	0.7	0.7	1.1	1.2	0.8	1.3	1.1	1.0
Potential acidity ($cmol_c/dm^3$)										
0-5	6.9	7.4	6.7	6.8	2.1	1.9	2.5	2.2	2.2	1.9
0-10	6.8	7.3	6.8	6.6	2.4	1.9	3.0	2.5	3.5	2.4
0-20	6.7	7.0	6.7	6.3	2.7	2.1	3.2	3.3	3.8	2.8
$CEC_{pH7.0}$ ($cmol_c/dm^3$)										
0-5	9.4	11.5	10.3	10.9	6.7	7.5	6.6	9.9	9.2	8.5
0-10	9.1	10.9	9.9	9.9	6.6	7.3	6.5	9.5	8.5	7.7
0-20	8.9	9.8	9.1	8.9	6.3	7.0	6.1	9.2	7.7	7.3
Base saturation (%)										
0-5	26.5	35.9	34.5	37.3	68.5	75.4	63.0	78.2	76.1	77.5
0-10	25.0	33.0	31.3	33.3	63.9	74.0	56.0	73.7	58.3	68.9
0-20	24.7	28.5	26.6	29.1	57.5	69.6	48.7	64.6	50.1	62.5
Organic matter (g/kg)										
0-5	14.3	20.5	18.5	12.3	12.5	10.3	23.3	42.8	36.5	23.3
0-10	10.5	14.0	14.0	12.8	16.5	9.5	27.8	34.5	27.5	17.0
0-20	16.8	13.3	11.8	11.3	10.8	9.8	15.8	25.0	22.8	17.5

Note. NT_I: initial phase (0-5 years of management under NT). NT_{TC}: transition-consolidation phase (5-20 years of management under NT). pH_{CaCl2}: 1:2.5 (v/v) ratio. $CEC_{pH7.0}$: cation exchange capacity at pH 7.0.

3.2 Soybean Grain Yield and Soil Properties

The soybean grain yields ranged from 3.23 to 4.56 t/ha in the NT_I sites, and 3.71 to 5.04 t/ha in the NT_{TC} sites (Figure 1). The large range in grain yields across sites can be partly explained by the wide range of soil properties occurring in the evaluated areas of this study together with variation in soil moisture regimes.

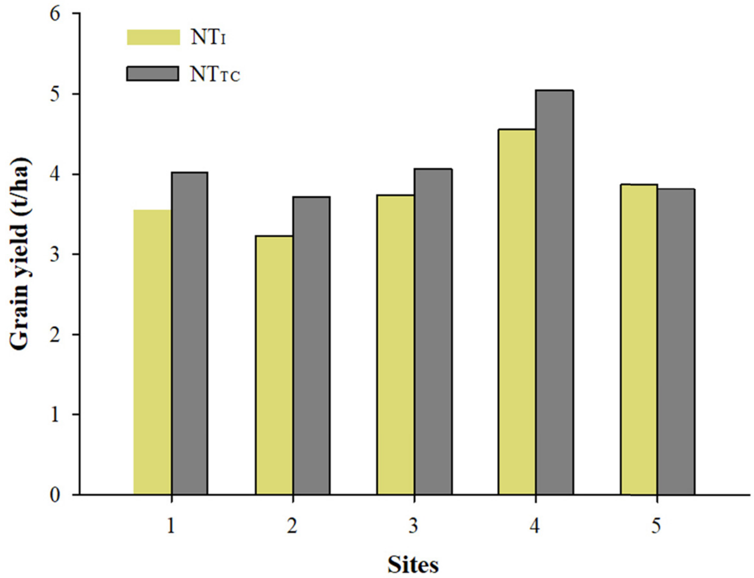

Figure 1. Soybean grain yield in the sites under no-tillage for 0-5 years (NT_I: initial phase) and for 5-20 years (NT_{TC}: transition-consolidation phase)

Figures 2 and 3 summarize the relationship between soybean grain yield response from lime application and between soybean grain yield response and soil acidity-related properties for each soil layer across sites under NT for, respectively, for 0-5 years (initial phase) and 5-20 years (transition-consolidation phase). The R^2 values of significant quadratic models ranged from 0.10 to 0.91 across sites under NT in the initial phase (Figure 2), and from 0.10 to 0.93 across sites under NT in the transition-consolidation phase (Figure 3). In both NT systems, the lowest R^2 values were found in the 0-5 cm layer, which often encompassed the soil pH_{CaCl2}. Exchangeable Ca, potential acidity, and $CEC_{pH7.0}$ exhibited relatively low R^2 values in their relationships with the soybean grain yield ($R^2 < 0.30$) (Figures 2 and 3).

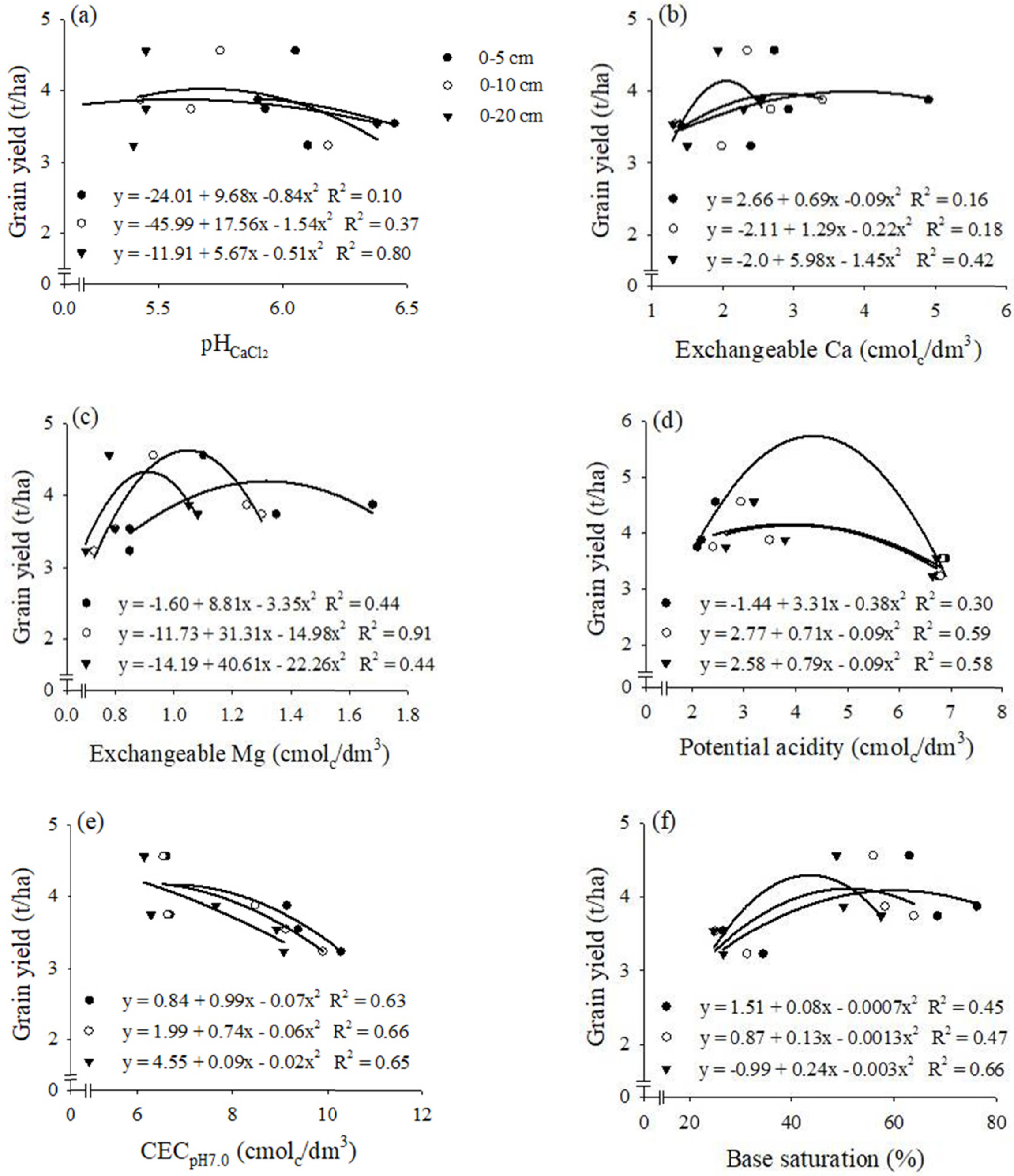

Figure 2. Relationship between soybean grain yield and pH_{CaCl2} (a), exchangeable Ca (b), exchangeable Mg (c), potential acidity (d), cation exchange capacity at pH 7.0 (e), and base saturation (f) in three layers of soil under no-tillage for 0-5 years (initial phase)

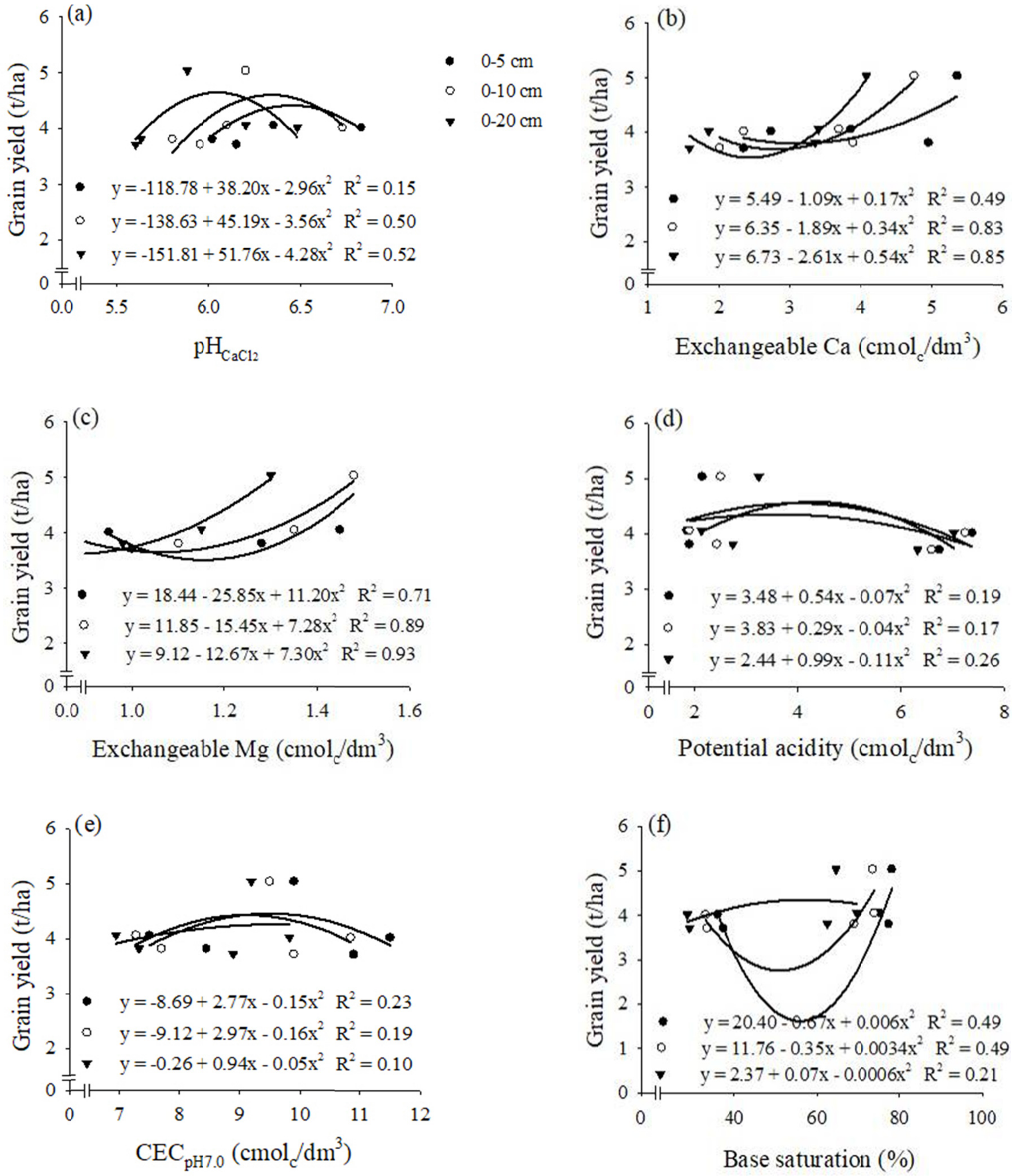

Figure 3. Relationship between soybean grain yield and pH_{CaCl2} (a), exchangeable Ca (b), exchangeable Mg (c), potential acidity (d), cation exchange capacity at pH 7.0 (e), and base saturation (f) in three layers of soil under no-tillage for 5-20 years (transition-consolidation phase)

3.3 Critical Levels of Soil Acidity Properties

The critical levels of soil acidity properties in different soil layers at NT sites managed for 0-5 years (NT_I) and 5-20 years (NT_{TC}) are shown in Tables 4 and 5, respectively. Critical levels were approximately similar in both phases of NT for some soil properties such as exchangeable a, exchangeable Mg and potential acidity, but varied greatly depending on the soil layer and phase of NT management for soil pH_{CaCl2}, $CEC_{pH7.0,}$ and base saturation. In general, for both phases of NT, the critical levels of soil acidity properties were lowest for the 0-20 cm layer, moderate for the 0-10 cm layer, and highest for the 0-5 cm layer. Exceptions were found for the potential acidity,

$CEC_{pH7.0}$, and base saturation. As such, the potential acidity levels were similar in the 0-5 cm and 0-20 cm layers of the NT_I sites, and highest in the 0-20 cm layer of the NT_{TC} sites as well as the soil CEC and base saturation.

Among soil layers of the NT_I sites, there was a great change in the levels of exchangeable Ca, $CEC_{pH7.0}$, base saturation, and OM content, and slight changes in the soil pH_{CaCl2}, exchangeable Mg, and potential acidity. In contrast, at the NT_{TC} sites, soil pH_{CaCl2}, base saturation, and OM content changed greatly whereas exchangeable Mg, potential acidity, and $CEC_{pH7.0}$ changed little across soil layers.

Table 4. Soil acidity indicators and corresponding reference values for three layers of soil with soybean under no-tillage management ranging from 0 to 5 years (initial phase)

Soil acidity indicators	0-5 cm	0-10 cm	0-20 cm
pH_{CaCl2}	5.8	5.7	5.6
Exchangeable Ca ($cmol_c/dm^3$)	3.8	2.9	2.0
Exchangeable Mg ($cmol_c/dm^3$)	1.3	1.0	0.9
Potential acidity ($cmol_c/dm^3$)	4.4	3.9	4.4
$CEC_{pH7.0}$ ($cmol_c/dm^3$)	7.1	6.2	2.3
Base saturation (%)	57	50	40

Note. pH_{CaCl2}: 1:2.5 (v/v) ratio. $CEC_{pH7.0}$: cation exchange capacity at pH 7.0.

Table 5. Soil acidity indicators and corresponding reference values for three layers of soil with soybean under no-tillage management ranging from 5 to 20 years (transition-consolidation phase)

Soil acidity indicators	0-5 cm	0-10 cm	0-20 cm
pH_{CaCl2}	6.5	6.4	6.0
Exchangeable Ca ($cmol_c/dm^3$)	3.2	2.8	2.4
Exchangeable Mg ($cmol_c/dm^3$)	1.2	1.1	0.9
Potential acidity ($cmol_c/dm^3$)	3.9	3.6	4.5
$CEC_{pH7.0}$ ($cmol_c/dm^3$)	9.2	9.3	9.4
Base saturation (%)	56	51	58

Note. pH_{CaCl2}: 1:2.5 (v/v) ratio. $CEC_{pH7.0}$: cation exchange capacity at pH 7.0.

4. Discussion

4.1 Variability of the Selected Sites Under No-tillage

Soil pH and clay content showed relatively low to moderate variation, whereas the OM content revealed considerable variation as indicated by the coefficient of variation values (Table 2). In general, the pH variability was relatively higher in site 2 (CV = 21%) and site 4 (CV = 13%) under NT in the initial phase, followed by site 3 (CV = 9%) under NT in the transition-consolidation phase, where differences between the maximum and minimum pH values were as high as 1.1 to 2.3 pH units.

According to the soil pH reference values established by Sousa and Lobato (2004) in the Cerrado region of Brazil, most of the sampled sites fall in the acidic range. In acid soils of Cerrado, liming is recommended for soybean when the soil pH varies between 5.5 and 6.0, where the maximum availability of nutrients such as P, K, S, and N generally occurs (Sousa & Lobato, 1996). The high within-field pH_{CaCl2} values in site 1, for example, would result in no lime recommendation, but the high variation in the other four regions would result in varying lime requirements within the fields. This kind of variation justifies site-specific management for soil pH and lime in different fields.

However, the variability of clay content was, in absolute terms, higher than for pH_{CaCl2}, being highest in site 2 (CV = 28-32% in both NT phases), site 3 (CV = 33% in NT_I) and site 4 (CV = 41% in NT_I). This soil texture variation, which is useful to estimate lime requirement, is due to natural soil formation causes, whereas the pH variation likely resulted from soil management practices since the fields had been cultivated for many years and lime had been applied in the past crop season.

The OM variability was, in absolute terms, extremely high in site 2 (CV = 46-85% in both NT phases), followed by site 4 (CV = 57% in NT_I), and site 5 (CV = 45% in NT_{TC}). The differences in OM content between the locations were mainly associated to the type of soil management. These contents of OM found in our study are typical in Oxisols of the Brazilian Cerrado and were due to higher temperatures and precipitation, since the interaction between these factors regulates the organic carbon content in soils (Neufeldt et al., 2002). With high temperatures and precipitation events, carbon content in the soil decreases because of more intense organic matter mineralization. It is widely accepted that OM is a very important indicator of soil fertility and crop productivity (Korschens et al., 2013; Lal, 2013). Organic matter is essential for improving soil chemical properties, given that adding OM probably increases the CEC of weathered, and clayey (1:1, kaolinite) soils.

4.2 Soil Acidity Indicators for No-tillage Sites

Critical levels of soil acidity-related properties can be defined as the soil status below which crop yield response is restricted due to soil acidity and above which a large yield response can be obtained with an adequate supply of liming. In the present study, soil acidity indicators were set for soybean in NT at the initial phase (0-5 years) and transition-consolidation phase (5-20 years) considering three soil layers.

The critical levels of soil pH_{CaCl2} ranged from 5.6 to 5.8 in NT_I sites, and 6.0 to 6.5 in NT_{TC} sites, whereas base saturation ranged from 40 to 57% in NT_I sites, and 51 to 58% in NT_{TC} sites (Tables 4 and 5). In both sites, the values of soil pH_{CaCl2} and base saturation were above the reference values for soils under NT in the Brazilian Cerrado region ($pH_{CaCl2} \geq 5.4$, base saturation ≥ 50%) as proposed by Sousa and Lobato (2004). The critical levels of soil pH_{CaCl2} and base saturation obtained here are higher and lower, respectively than the critical levels established in previous studies for soybean in consolidated NT systems in Brazil.

Nolla and Anghinoni (2006) showed that critical soil pH_{CaCl2} and base saturation for NT soils with soybean were 4.6 and 62% for the 0-10 cm layer, and 4.4 and 61% for the 0-15 cm layer. In a study conducted with six grain crops, Nicolodi et al. (2008) found critical soil pH_{CaCl2} ranging from 5.2 to 5.0, whereas the base saturation recorded were 65 and 60% in the 0-10 cm and 0-20 cm layers, respectively. However, the above-mentioned studies were performed in soils of southern Brazil, where climatic conditions and soils are different from those of the Cerrado region.

In fact, soils of southern Brazil have a high capacity of Al complexation by functional groups of OM (Alleoni et al., 2010), resulting in lower Al saturation and higher base saturation in topsoil layers (Santos et al., 2018). Considering the natural chemical conditions of the soils of the Cerrado region, with low CEC due to their mineralogy (Yamada, 2005) and low exchangeable bases and OM contents, the lower base saturation levels recorded here at both NT sites compared to the soils of southern Brazil were expected.

Regarding the excessive pH_{CaCl2} values reaching the three soil layers, they are likely due to the high lime rates applied in addition to the recent surface application of lime since soils of all sites were sampled between one- and two-month following liming. The rate of reaction of a lime material with soil and the maximum pH increase depends on several factors, including initial soil pH, application rate, OM, and clay content (Costa et al., 2016). Alleoni et al. (2005), and Neto et al. (2019) reported fast lime reaction in the soil to a depth of 20 cm under NT. Therefore, the high pH increase observed up to 20-cm depth was proportional to the application rate and reaction time of lime agree with published results. Additionally, it is important to highlight that since the pH_{CaCl2} was higher than 5.0 over the entire sampling depth, exchangeable Al^{3+} was not detected.

The exchangeable Ca and Mg decreased throughout the profile, reaching the lower levels in the 0-20 cm layer of all NT sites (Table 3). The critical levels of exchangeable Ca ranged from 2.0 to 3.8 $cmol_c/dm^3$ at NT_I sites, and 2.4 to 3.2 $cmol_c/dm^3$ NT_{TC} sites, whereas the exchangeable Mg ranged from 0.9 to 1.3 $cmol_c/dm^3$ at NT_I sites, and 0.9 to 1.2 $cmol_c/dm^3$ at NT_{TC} sites (Tables 4 and 5). At both sites, the sum of Ca^{2+} and Mg^{2+} was above the 2.2-7.4 $cmol_c/dm^3$ considered adequate by Sousa and Lobato (2004) for 0-2.5, 2.5-5, 5.10, and 10-20 cm topsoil layers under NT in the Brazilian Cerrado region. Therefore, as expected, the beneficial effects of lime application were higher in the topsoil than in the subsoil of the NT sites.

At NT_I sites, changes in potential acidity occurred only in the 0-10 cm soil layer, being 0.5 units lower than the uppermost and deepest soil layers (Table 4). At NT_{TC} sites, potential acidity increased up to a depth of 20 cm, ranging from 3.9 to 4.5 $cmol_c/dm^3$ (Table 5). Consequently, these changes can cause differences in plant growth. Crusciol et al. (2016) also found increased potential acidity levels with depth after 3 months from the surface application of lime to NT soil, which varied from 3.2 to 4.3 $cmol_c/dm^3$ between the 0-5 cm and 10-20 cm layers. Despite the increase with soil depth, the critical levels of potential acidity were low in the three depths, allowing to neutralize Al^{3+} as deeply as possible and the plant roots to grow in a less toxic environment.

The cation exchange capacity at pH 7.0 ($CEC_{pH7.0}$) increased with soil depth at NT_{TC} sites (Table 5), indicating higher retention capacity for base cations due to increased exchangeable Ca and Mg replacing exchangeable acidity and/or Al^{3+} in the soil. The high $CEC_{pH7.0}$ in the NT_{TC} sites suggests an effect of the increased potential acidiy because the $H^+ + Al^{3+}$ content is added to the other measured cations in the equation used to calculate CEC. By contrast, decreasing levels of soil $CEC_{pH7.0}$ with depth were found in the N_{TI} sites (Table 4), reducing Ca and Mg availability to soybean. This decrease in CEC is attributed to the depletion of OM with depth, since the continuous input of organic carbon from plant and animal residues that increases the mineralization and accumulation of OM occurs on the surface. Except for the 0-20 cm layer of N_{TI} sites, all soil layers and sites showed critical $CEC_{pH7.0}$ levels (6.2 to 7.1 $cmol_c/dm^3$ at NT_I sites and 9.2 to 9.4 $cmol_c/dm^3$ at NT_{TC} sites) classified as high for sandy loam and medium loam soils of the Cerrado region in Brazil according to Sousa and Lobato (2004).

For some soil properties such as exchangeable Ca, potential acidity, and $CEC_{pH7.0}$, the distribution of the data points does not fit a continuous model well (Figures 2 and 3). These results indicate a poor capacity of these soil properties to predict a reasonable crop yield response. Further, the distribution of points indicates that the large variability in the soybean grain yield across sites (Figure 1) tended to weaken the strength of the relationships between grain yield and soil properties.

Based on the above results, it is considered that the criteria for determining the amount of lime needed to correct the soil acidity to levels that are suitable for cultivation in the Brazilian Cerrado region are not valid for NT soils. Therefore, recommendation criteria for lime application to the soils studied considering distinct soil depths and NT systems will be helpful when making liming decisions.

5. Conclusions

Relationships between crop yield response of soybean to lime application and various soil acidity-related characteristics led to establishing soil acidiy indicators for liming in tropical acid soils under no tillage. Critical levels were approximately similar in both phases of NT for exchangeable Ca and Mg, and potential acidity, but varied greatly depending on the soil layer and phase of NT management for soil pH_{CaCl2}, $CEC_{pH7.0,}$ and base saturation. In general, for both phases of NT, the critical levels of soil acidity indicators were lowest for the 0-20 cm layer, moderate for the 0-10 cm layer, and highest for the 0-5 cm layer. Lime applied with incorporation in the NT_{TC} phase kept the soil with chemical attributes more favorable for plant growth than when surface liming was employed in the NT_I phase, which was verified by the soybean yield response. Our results indicate the differences on the soil acidity indexes between the top and bottom depths that would not have been realized in a soil sampling for conventional tillage. Hence, recommendation criteria for lime application considering distinct soil depths and NT systems will be helpful when making lime decisions. Further research should focus on the development of reliable methods for predicting LR according to the NT phase and consequently maximize soybean production under NT systems in Brazil.

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