Environmental Research Communications

CrossMark

OPEN ACCESS

RECEIVED
28 April 2019

REVISED
15 October 2019

ACCEPTED FOR PUBLICATION
17 October 2019

PUBLISHED
29 October 2019

PAPER

Lime movement through highly weathered soil profiles

Márcio R Nunes[1], José E Denardin[2], Carlos M P Vaz[3], Douglas L Karlen[1] and Cynthia A Cambardella[1]

[1] United States Department of Agriculture, Agricultural Research Service, National Laboratory for Agriculture and the Environmental, Ames, IA, 50011, United States of America

[2] Embrapa Trigo, BR 285 Road, Passo Fundo, RS, 99001-970, Brazil

[3] Embrapa Agricultural Instrumentation, 741, São Carlos, SP, 13560-970, Brazil

E-mail: marcio_r_nunes@usp.br and marcio.nunes@usda.gov

Keywords: conservation tillage, aluminum toxicity, dolomitic lime, subsoil acidity, surface application, organic matter

Supplementary material for this article is available online

Abstract

Applying lime is a fundamental practice for abating acidity in highly weathered soil, but better management strategies for no-till systems are needed to prevent surface pH elevation with little to no subsurface effects. This study was conducted to quantify chemical changes within the soil profile in response to lime and straw applications under both greenhouse and field conditions. Four controlled environment experiments (soil columns) and one field study were conducted on soils classified as Rhodic Hapludox and Rhodic Eutrodox. The soil column experiments evaluated four lime rates (0, 3.9, 7.8, or 15.6 Mg ha^{-1}) and four straw rates (0, 4, 12 and 16 Mg ha^{-1}) either individually or in combination. Lime treatments were surface applied or incorporated in the top 5-cm, while straw treatments were incorporated in the top 5-cm. In the field, lime rates of 0, 8.3 and 33.2 Mg ha^{-1} were incorporated into the 0 to 10-cm depth in both a soybean [*Glycine max*] monoculture and diversified cropping system with white oat (*Avena sativa*), soybean, black oats (*Avena strigosa*), corn (*Zea mays*) and wheat (*Triticum aestivum*). Both field and soil columns studies showed minimal lime movement into the soil profile with chemical changes being limited to 2.5-cm below where it was applied or incorporated regardless of cropping system. Surface application of high lime rates promoted chemical stratification resulting in dramatic increases in topsoil pH and exchangeable Ca and Mg levels with minimal mitigation of subsurface soil acidity. Other studies also suggest that lime movement into the soil profile can vary depending on the experimental condition. Therefore, additional investigations across a wider geographic area, greater range of weather and climatic conditions, methods and rates of lime application need to be conducted to improve lime recommendation for high weathered soil managed using no-till practices.

1. Introduction

Most tropical and subtropical agricultural production occurrs on highly weathered soils that are acidic, with high toxic aluminum (Al) concentrations and low natural fertility. Thus, improving soil fertility and correcting soil pH are two of the greatest tropical soil fertility needs. Application of lime and fertilizer can increase nutrient concentrations and their availability for plants, and reduce concentrations of dissolved Al in soil solution which can restrict crop growth by competing with plant nutrients (Correia et al 2004, Seguel et al 2015). With conventional tillage (CT), lime and fertilizers are incorporated into the topsoil (i.e., 0 to 20 cm) by plowing and harrowing, but with no-tillage (NT) soil disturbance is restricted to the seeding row and lime is generally applied without incorporation on the soil surface. Quantifying and understanding interactions among lime and fertilizer management practices (i.e., rates, frequency, and application strategies) are among the greatest soil fertility needs in tropical agricultural regions.

Reduced- and no-tillage have been widely adopted to reduce soil erosion and are currently used worldwide on approximately 150 million hectares (Kassam et al 2015). No-tillage has also been incorporated into several

conservation practices, adapted to increase crop diversification, and shown to improve soil health and provide both environmental and economic benefits (Kassam et al 2015, Dairon et al 2017). It has also been identified (FAO (2016)) as an important soil management component of conservation agriculture, but NT is not without its challenges and improvements are needed to expand its adoption and capture its societal benefits.

Surface lime application is suggested as the best practice to alleviate soil acidity under NT, but its effects throughout the soil profile are unclear. Several studies have shown that surface-applied lime can mitigate soil acidity to a depth of 20 cm or more, thereby maximizing crop productivity (Caires et al 2008, Joris et al 2013, Caires et al 2015), but others have shown very slow lime migration and minimal effects below 10 cm (Conyers et al 2003, Godsey et al 2007, Bortolanza and Klein 2016, Barth et al 2018). Factors influencing lime migration through the soil profile include the amount applied, time between application and planting, quantity of precipitation after liming, soil texture, soil mineralogy, lime type and particle size, and degree of soil compaction (Blevins et al 1978, Farina et al 2000, Godsey et al 2007, Caires et al 2015). In addition to those factors, organic substances accumulating on the soil surface under NT and anions arising from decomposition of plant residues, animal manure, or fertilizer may also retard Ca and Mg movement into the profile — a process needed to reduce subsurface Al activity (Miyazawa et al 2002, Zambrosi et al 2008).

Since lime is relatively insoluble, surface application may not be effective for ameliorating subsoil acidity (Shainberg et al 1989) and neutralizing Al toxicity (Ernani et al 2004, Godsey et al 2007, Kirkegaard et al 2014, Santos et al 2018, Barth et al 2018) in NT fields. If lime does not move downward into the soil profile under NT, continued surface applications can cause significant increases in pH and nutrient concentrations in the near-surface layer (i.e., 0 to 3 cm) over time (Kirkegaard et al 2014, Bortolanza and Klein 2016, Nunes et al 2017a, Barth et al 2018). Excessive accumulation of lime within the topsoil can promote chemical stratification, increase surface soil pH, and decrease availability of cationic micronutrients such as Cu, Mn, and Zn (Tahervand and Jalali 2017) within the soil profile. Such changes can impair soil microbiological activity (Barth et al 2018) and accelerate organic matter mineralization (Paradelo et al 2015). Stratification has also caused producers to question whether they should discontinue NT or at least rotate tillage practices.

Previous studies have shown that mechanical incorporation of lime before initiating NT, or even in established NT fields, can result in faster and more uniform amelioration of topsoil acidity (0 to 20 cm) than surface application (Farina et al 2000, Santos et al 2018). Shallow incorporation of lime can be achieved using subsoilers, chiselers or seeders equipped with shanks to disrupt the soil below furrow (Richards et al 1995, Klein et al 2007, Flower and Crabtree 2011, Nunes et al 2014) may improve subsoil chemical conditions, as compared to lime application on the surface.

Clearly, there are controversies and numerous questions regarding the effectiveness of surface-application versus shallow incorporation of lime for mitigating soil acidity in tropical soils. This study was conducted to determine how different lime application rates, with or without shallow incorporation and the addition of organic matter, affect soil chemical indicators under field and controlled conditions.

2. Material and methods

2.1. Experiments

This study consisted of four 50-week experiments conducted with soil incubated in polyvinyl chloride (PVC) cylinders under controlled conditions (greenhouse experiments), and one field experiment conducted to compare monoculture soybean versus a diversified crop rotation over a period of 130 weeks.

2.1.1. Greenhouse experiments

2.1.1.1. Soil characteristics

The greenhouse experiments used soil classified as Rhodic Hapludox [USDA (2014) soil taxonomy] or Latossolo Vermelho Distrófico (Brazilian soil classification system (Santos et al 2013)). The sampling site was under native vegetation from the 'Mata Atlântica' biome and had a humid subtropical (Cfa–Köppen classification) climate, with annual precipitation of 1560 mm that is distributed uniformly during the year. Soil was collected from the 0 to 20-cm depth (A horizon) near Passo Fundo, RS, Brazil (28°14′18″ S, 52°20′30″ W) in an area that had never been cultivated. The native soil had a particle density of 2.6 g cm^{-3}; sand, clay, silt, and organic matter concentrations of 580, 320, 100, and 30 g kg^{-1}, respectively; elevated potential acidity; and low base saturation (table 1). The soil mineralogy is dominated by kaolinite, hematite and hydroxyl-interlayered 2:1 minerals (Nunes et al 2017b). Soil characterization methods have been described elsewhere (Nunes et al 2017b), but briefly, texture and particle density were quantified as described by Gee and Or (2002) and (Donagema et al 2011), respectively, and clay mineralogy was quantified by: (1) using hydrogen peroxide (30% v/v; 1 h under room temperature and after 2 hours under 70 °C) to remove soil organic matter; (2) dispersing chemically with

Table 1. Physical and chemical attributes of the Rhodic Hapludox soil (Latossolo) in the controlled environment column experiment and the Rhodic Eutrodox soil (Nitossolo) in the field trial.

Soil attribute	Unit	Latossolo	Nitossolo
Clay	$g\,kg^{-1}$	320	590
Silt	$g\,kg^{-1}$	100	200
Sand	$g\,kg^{-1}$	580	210
Particle density	$g\,cm^{-3}$	2.67	2.70
Organic matter	$g\,kg^{-1}$	26	30
SMP index		5.6	5.2
Phosphorus	$mg\,dm^{-3}$	20	22
Exchangeable K	$mmol_c\,dm^{-3}$	1.5	1.3
Exchangeable Ca	$mmol_c\,dm^{-3}$	17	20
Exchangeable Mg	$mmol_c\,dm^{-3}$	10	12
Exchangeable Al	$mmol_c\,dm^{-3}$	12	27
Potential acidity	$mmol_c\,dm^{-3}$	96	135
Sum of bases	$mmol_c\,dm^{-3}$	28	34
Cation exchangeable capacity	$mmol_c\,dm^{-3}$	124	169
Base saturation	%	28	20

10-ml of sodium hydroxide (0.1 $mol\,l^{-1}$); (3) dispersing mechanically with a Wagner type shaker TE-160/24 rotated 360º and engaged at 25 rpm for 16 hours; and (4) sieving to remove the sand fraction. The clay fraction was then separated from the silt fraction by siphoning after allowing the silt to settle for an appropriate amount of time-based on Stokes' law. The clay fraction was characterized by x-ray diffraction (powder method), utilizing an XRD 6000 (Shimadzu, Japan), with a Cu tube operated at 30 mA, 30 kV, equipped with theta-compensate slit. Samples were scanned from 3 to 60 (2θ), at 0.5° step size and count time of 1/step.

2.1.1.2. Experimental set up and design

Potential soil acidity was determined by the Shoemaker–McLean–Pratt (SMP) method (Shoemaker et al 1961), modified by Tedesco et al (1995). The SMP method is one of the most common soil fertility tests used to estimate potential acidity in soils from this region. The SMP solution contains four chemicals that act as weak bases to buffer the pH, along with calcium chloride to control the ionic strength. Based on the test, 7.8 $Mg\,ha^{-1}$ of lime (100% relative power of total neutralization) was required to efficiently raise soil pH in water to 6.5. PVC cylinders with an internal diameter of 14.5 cm and a height of 30 cm were constructed (supp. material 1 is available online at stacks.iop.org/ERC/1/115002/mmedia), and after determining the lime requirement, each was filled with 6 kg of air-dried soil (2.2% gravimetric moisture) and carefully packed to create a bulk density of 1.2 $g\,cm^{-3}$. Each week, 547 ml of water (equivalent to 1/52 of the site's annual precipitation or 33.6 mm of water) was applied to each cylinder.

The experimental design for each of the four greenhouse experiments was a completely randomized block with four treatments and three replicates. In Experiment I, lime application equivalents of 0 (L1s), 0.5 (L2s), 1 (L3s) and 2 times (L4s) the SMP index (0, 3.9, 7.8, and 15.6 $Mg\,ha^{-1}$, respectively) were added to the soil surface. Experiment II utilized the same application rates, but lime was incorporated into the top 5-cm of each PVC cylinder (L1i = 0 SMP, L2i = 0.5 SMP, L3i = 1 SMP and L4i = 2 SMP). For Experiment III, *Brachiaria brizantha* (a tropical grass) straw that had been ground into 5-mm pieces was incorporated into the top 5-cm soil layer at rates equivalent to 0, 4, 12 and 16 $Mg\,ha^{-1}$ (S1i = 0, S2i = 4, S3i = 12 e S4i = 16 $Mg\,ha^{-1}$). In Experiment IV, four lime rates (0, 0.5, 1 and 2 times the SMP recommendation) and straw (16 $Mg\,ha^{-1}$) were combined and incorporated in the top 5-cm of each cylinder (L1i/S4i, L2i/S4i, L3i/S4i e L4i/S4i). Table 2 provides a treatment description for the four experiments.

2.1.2. Field experiment

This study was conducted at the Brazilian Agricultural Research Corporation (EMBRAPA) near Coxilha, RS, Brazil (28º11'20″S, 52º19'62″W). The experimental site has gently rolling relief and the soil which has a clay texture is classified as Rhodic Eutrodox [Soil Taxonomy (USDA 2012) or Nitossolo Vermelho Distrófico latossólico (Brazilian Soil Classification System (Santos et al 2013)). The A horizon (0 to 35-cm) has 187 $g\,kg^{-1}$ SiO_2, 135 $g\,kg^{-1}$ Fe_2O_3, 190 $g\,kg^{-1}$ Al_2O_3, a particle density of 2.68 $g\,cm^{-3}$, and Ki and Kr ratios of 1.67 and 1.20, respectively (Nunes 2014). Ki values ≥ 2.2 suggest a predominance of kaolinite, Ki values ≤ 1.7 suggest the dominance of oxides, and Ki values ≥ 1.7 indicate the presence of equal amounts of kaolinite and 2:1 minerals (Soares et al 2005). The regional climate is humid subtropical (Cfa—Köppen classification) with annual precipitation of 1560 mm that is uniformly distributed throughout the year.

Table 2. Description of the four greenhouse experiments.

Exp.	Applied	Lable	Lime Rate[a]	Straw Rate
			Mg/ha	Mg/ha
1	Surface	L1s	0	0
		L2s	3.9	0
		L3s	7.8	0
		L4s	15.6	0
2	Incorporated	L1i	0	0
		L2i	3.9	0
		L3i	7.8	0
		L4i	15.6	0
3	Incorporated	S1i	0	0
		S2i	0	4
		S3i	0	12
		S4i	0	16
4	Incorporated	L1i/S4i	0	16
		L2i/S4i	3.9	16
		L3i/S4i	7.8	16
		L4i/S4i	15.6	16

[a] Lime rate equivalent to 0; 0.5, 1 and 2 times the SMP.

The experimental site was under natural vegetation until 1960 after which it was converted to an agricultural area. Soil fertility deficiencies (i.e., acidity and macronutrient concentrations) in the topsoil (0 to 20-cm) were corrected by addition and incorporation of lime and chemical fertilizers. From 1960 to 2004, the field was managed under conventional tillage practices (i.e., moldboard ploughing and harrowing). The cropping system during this period included wheat (*Triticum aestivum*) and other cereal grains in the winter season, and soybean (*Glycine max*) and corn (*Zea mays*) in the summer season. From 2004 to 2014, until the initiation of the current experiment, the field was kept fallow, with only spontaneous natural vegetation.

Prior initiating the experiment, samples were taken from the 0 to 20-cm depth increment and analyzed for potential soil acidity using the SMP method (Shoemaker *et al* 1961), modified by Tedesco *et al* (1995). It was determined that 8.3 Mg ha^{-1} of lime (100% relative power of total neutralization) was required to efficiently raise soil pH in water to 6.5.

The experiment started in August 2014 with two cropping system treatments (monoculture versus diversified crop rotation) and three lime rates in sub-plots with four replications. The three lime rates were equivalent to 0 SMP, 1 SMP (8.3 Mg ha^{-1}), and 4 SMP (33.2 Mg ha^{-1}). To facilitate discussion, the treatments are referred to as: monoculture without lime (0 SMP-Mono), monoculture with addition of 1 SMP lime rate (1 SMP-Mono), monoculture with addition of 4 SMP lime rate (4 SMP-Mono), diversified crop rotation without lime (0 SMP-Rot), diversified crop rotation with addition of 1 SMP lime rate (1 SMP-Rot) and diversified crop rotation with addition of 4 SMP lime rate (4 SMP-Rot). Lime was incorporated to a depth of 10 cm using a rotary hoe (rotary tiller). Monoculture was simply soybean in the summer followed by winter fallow. The diversified cropping system consisted of white oat (*Avena sativa*) in the winter of 2014; soybean in the summer of 2014; black oats (*Avena strigosa*) in the winter of 2015; corn in the summer of 2015; and wheat in the winter of 2016. The five-crop field study was conducted over a period of 130 weeks.

2.2. Soil sampling and analyses

After incubating for 50 weeks, the soil in each greenhouse cylinder was fractionated into 0 to 2.5-, 5 to 7.5-, 12.5 to 15-, 17.5 to 20- and 25 to 27.5-cm depth increments (Supp. material 1) and sampled. Following the field trial (130-weeks), field were sampled at five positions: P_1 = soil surface; P_2 = 5 cm from the soil surface; P_3 = maximum depth of lime incorporation; P_4 = immediately below the maximum depth of the lime incorporation; and P_5 = 20 cm from the soil surface (figure 1). Samples from controlled and field trials were submitted to the soil fertility laboratory of the University of São Paulo, Piracicaba, SP, for soil chemical analysis (fertility indicators).

The soil samples were analyzed for chemical properties using techniques described by Donagema *et al* (2011): concentrations of exchangeable calcium (Ca), magnesium (Mg), potassium (K) and aluminum (Al), phosphorus (P - extracted using the Melich-I solution) and potential acidity ($H^+ + Al^{3+}$). Soil pH was quantified in 1:1 soil: $CaCl_2$ ratio (only for the trials conducted under controlled conditions), and in 1:1 soil: water ratio and 1:1 soil:KCl ratio (only for the trials under field conditions). From these, the base sum

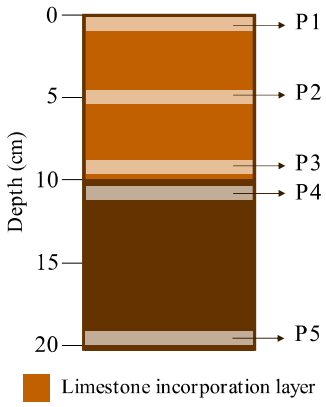

Figure 1. Soil profile schematic showing positions where soil samples were taken in the field experiment: P1 (near surface; P2 (5 cm below the surface; P3 (maximum depth of lime incorporation; P4 (immediately below maximum depth of incorporation; and P5 (10 cm below the surface.

(Σ B (K + Ca + Mg), the cation exchange capacity (CEC (H + Al + ΣB), and the base saturation of CEC (%BS (ΣB/CEC) were calculated. Soil organic matter (SOM) was determined by the Walkley-Black method.

2.3. Data analysis

2.3.1. Greenhouse experiments

One-way analysis of variance (ANOVA) was applied to assess significant differences in terms of lime rates. Treatment effects were assessed separately for each soil depth and each of the four experiments conducted under controlled condition.

2.3.2. Field experiment

Data were analyzed based on a split-plot design. ANOVA was applied to evaluate the influence of cropping system (monoculture and diversified crop rotation), lime rate and their interaction on the studied soil chemical properties. Cropping system (factor 1), lime rates (factor 2) and cropping system versus lime rate interaction were assumed as fixed effects, and block, replicate and their interactions were assumed as random. Treatment effects were assessed separately for each soil depth. The statistical analyses were performed using the R software version 3.1.1 (R Core Team 2014). Moreover, the standard deviation for each soil chemical attribute was calculated for each soil layer.

3. Results

3.1. Greenhouse experiments

Surface application of lime (Experiment I) at 3.9, 7.8, or 15.6 Mg ha^{-1} resulted in migration to a depth of ~2.5 cm into the soil profile, as documented by changes in several chemical attributes within that layer (figure 2; table 3). The measurements also showed that applying lime at the equivalent of 0.5 SMP was sufficient to elevate soil pH in $CaCl_2$ to values higher than 6.0 (figure 2 (a)). This was sufficient to eliminate Al toxicity (figure 2 (b)) and reduce potential soil acidity (figure 2 (c)). Applying 1 or 2 SMP levels of lime increased soil pH to 7.0 or greater in the surface 2.5 cm (figure 2 (a)). The high pH values were expected since the SMP procedure was developed assuming lime would be incorporated and reacting with 15- to 20-cm of topsoil. As expected, lime application increased exchangeable Ca and Mg concentrations, the sum of bases, saturation of CEC with basic cations, and overall CEC in the near-surface in proportion to the rate of lime applied (figures 2 (e), (f), (h), (j), and (l)). Exchangeable K, extractable P, and SOM concentrations were not affected by surface liming (figures 2 (d), (g), and (i)).

In Experiment II, lime incorporated into the top 5 cm migrated an additional 2.5 cm and thus influenced soil chemicals attributes to a depth of 7.5 cm (figure 3; table 3). Changes were similar to those with surface application (Experiment I), including an increase in $CaCl_2$ pH (figure 3 (a)), elimination of aluminum acidity

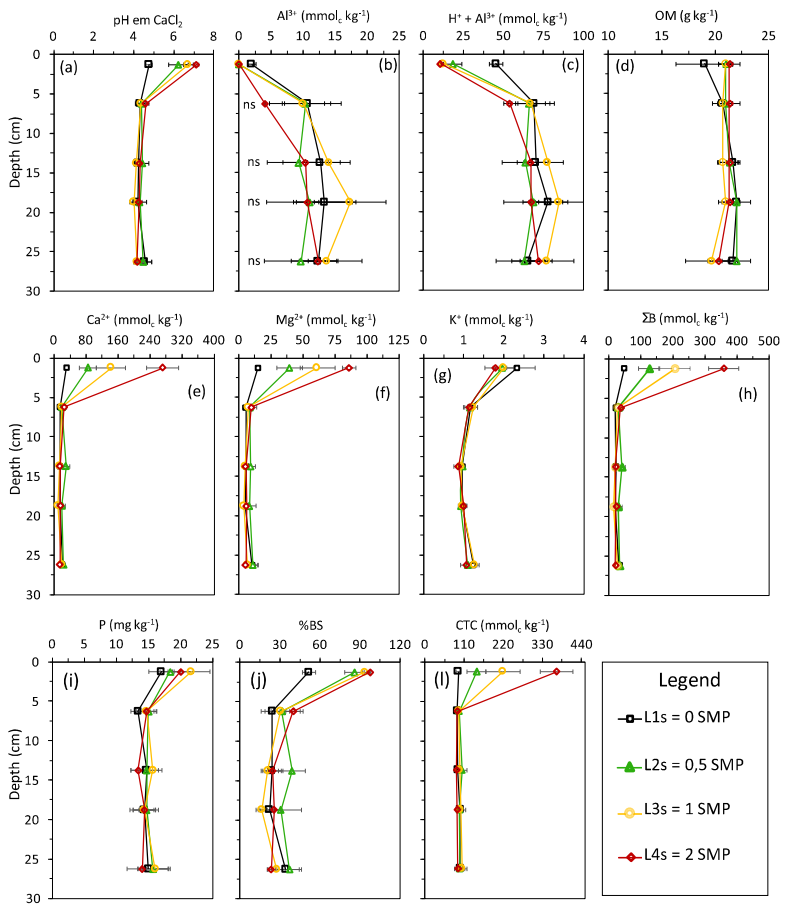

Figure 2. Experiment 1 (soil columns). Chemical attributes of the Rhodic Hapludox (Latossolo) after 50 weeks of incubation with four rates of surface applied lime (L1s, L2s, L3s, L4s) and no straw (S0). OM: organic matter; ΣB (base sum) = K^+ + Ca^{2+} + Mg^{2+}; CEC (cation exchange capacity) = H^+ + Al^{3+} + ΣB; %BS (base saturation) = ΣB/CEC. Horizontal bars indicate the standard deviation of average values.

(figure 3 (b)), and reduction of potential acidity (figure 3 (c)). Increased exchangeable Ca and Mg concentrations, a higher sum of basic cations, greater CEC base saturation and CEC saturation proportional to lime application rates were also noted to a depth of 7.5 cm (figures 3 (e), (f), (h), (j), and (l)). Incorporating lime at rates equivalent to 1 and 2 SMP, however, increased $CaCl_2$ pH to only 6.5 and resulted in a lower average 0 to 7.5 cm depth value than when the same rates were surface applied.

Incorporating straw (Si) into the 0 to 5-cm layer (Experiment III) promoted an increase in SOM content to a depth of 7.5-cm and increased exchangeable K content throughout the entire 20-cm depth (figure 4; table 3). Increases in exchangeable K, the sum of bases, and saturation of CEC with basic cations within the 5- to 7.5-cm depth increment were proportional to straw application rate, with 15.6 Mg ha^{-1} being greatest (figures 4 (f), (h), and (j)). Within the top 2.5-cm straw application increased P content (figure 4 (i)), K and soil acidity indicators (figures 4 (a), (b), and (c)), but did not affect any of the other soil chemical attributes.

In Experiment IV, the 0, 0.5, 1, and 2 SMP application rates were combined with 16 Mg ha^{-1} of straw and incorporated to a depth of 5cm (S4i). This resulted in mitigation of soil acidity, increased $CaCl_2$ pH, decreased

Table 3. ANOVA probability values for chemical attributes of an Oxisol measured at five depth increments in four controlled environment soil column experiments.

Depth (cm)	OM	pH_{CaCl2}	P	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	$H^+ + Al^{3+}$	ΣB	CEC	%BS
Experiment 1—surface applied lime											
0–2.5	0.486	< 0.001	0.307	0.440	< 0.001	< 0.001	0.002	< 0.001	< 0.001	< 0.001	< 0.001
5–7.5	0.821	0.666	0.664	0.903	0.458	0.624	0.405	0.602	0.517	0.780	0.542
12.5–15	0.802	0.532	0.544	0.624	0.112	0.333	0.678	0.644	0.095	0.442	0.236
17.5–20	0.784	0.625	0.997	0.878	0.550	0.554	0.644	0.643	0.552	0.711	0.591
25–27.5	0.478	0.507	0.868	0.344	0.301	0.319	0.850	0.764	0.308	0.825	0.452
Experiment 2—lime incorporated within the 0- to 5-cm depth increment											
0–2.5	0.690	0.003	0.293	0.264	< 0.001	< 0.001	0.002	< 0.001	< 0.001	< 0.001	< 0.001
5–7.5	0.821	0.005	0.728	0.198	0.000	0.046	< 0.001	0.000	0.004	0.023	< 0.001
12.5–15	0.659	0.846	0.177	0.172	0.833	0.845	0.755	0.924	0.857	0.943	0.835
17.5–20	0.762	0.887	0.226	0.183	0.867	0.780	0.887	0.891	0.825	0.417	0.910
25–27.5	0.531	0.498	0.166	0.388	0.653	0.563	0.928	0.854	0.630	0.588	0.677
Experiment 3—straw incorporated within the 0- to 5-cm depth increment											
0–2.5	0.035	0.224	0.179	< 0.001	0.947	0.664	0.582	0.110	0.609	0.505	0.275
5–7.5	0.001	0.208	0.465	< 0.001	0.250	0.023	0.371	0.398	0.032	0.617	0.108
12.5–15	0.916	0.782	0.751	< 0.001	0.772	0.689	0.951	0.363	0.766	0.306	0.597
17.5–20	0.337	0.825	0.632	< 0.001	0.780	0.636	0.939	0.731	0.722	0.731	0.698
25–27.5	0.366	0.445	0.199	0.085	0.345	0.388	0.724	0.567	0.405	0.824	0.479
Experiment 4—lime combined with straw incorporated within the 0- to 5-cm depth increment											
0–2.5	0.019	< 0.001	0.507	< 0.001	< 0.001	0.002	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
5–7.5	0.024	< 0.001	0.965	< 0.001	< 0.001	0.006	0.008	0.001	0.002	0.049	0.001
12.5–15	0.736	0.805	0.550	0.727	0.819	0.359	0.663	0.946	0.660	0.995	0.866
17.5–20	0.911	0.948	0.835	0.632	0.534	0.679	0.713	0.908	0.721	0.823	0.903
25–27.5	0.786	0.647	0.961	0.395	0.255	0.787	0.770	0.795	0.636	0.867	0.684

OM: organic matter; ΣB (base sum) = $K^+ + Ca^{2+} + Mg^{2+}$; CEC (cation exchange capacity) = ($H^+ + Al^{3+}$) + ΣB; %BS (base saturation) = ΣB/CEC. The p values lower than 0.05 are bolded.

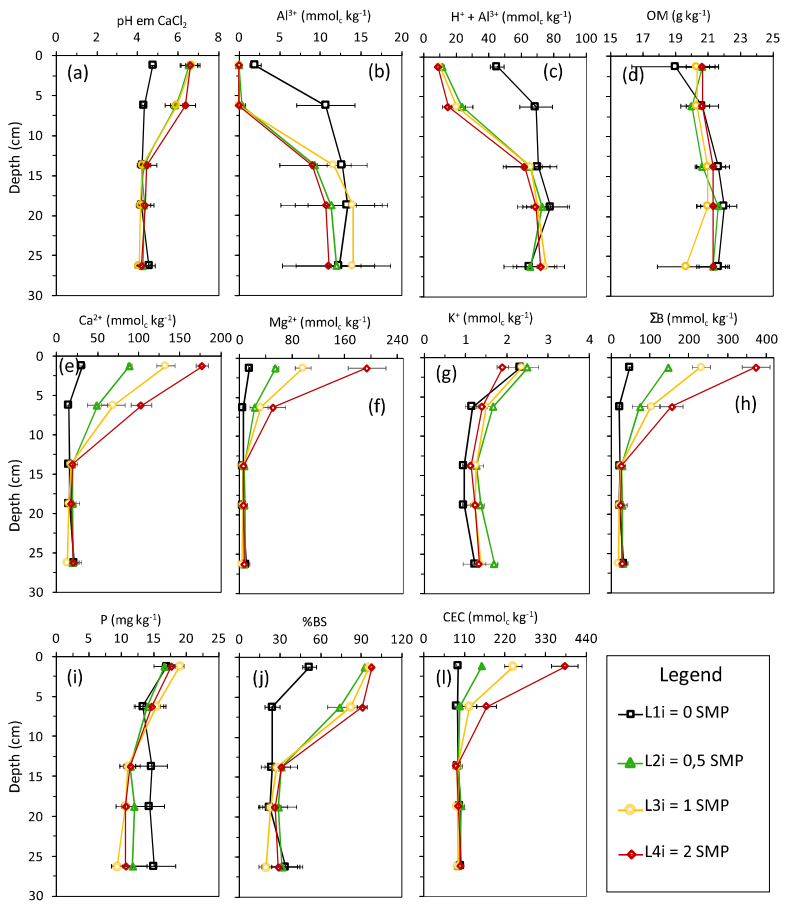

Figure 3. Experiment 2 (soil columns). Chemical attributes of the Rhodic Hapludox (Latossolo) after 50 weeks of incubation with four rates of lime incorporated within the top 5 cm (L1i, L2i, L3i, L4i) and no straw (S0). OM: organic matter; ΣB (base sum) (K+, Ca^{2+}, Mg^{2+}; CEC (cation exchange capacity) (H^+, Al^{3+}); ΣB; %BS (base saturation) (ΣB/CEC. Horizontal bars indicate the standard of average values.

potential soil acidity and reduced exchangeable Al concentrations to a depth of 7.5-cm (figures 5 (a)–(c)). Lime increased cation concentrations, saturation of CEC by bases, and soil CEC (figures 5 (e), (f), (g), (h), and (l)) in this same layer. Incorporation of lime stimulated mineralization of SOM and decreased its content in the top 5 cm at all application rates (figure 5 (d)). Straw incorporation (16 Mg ha^{-1}) also promoted an increase in the concentration of P within the 0 to 7.5-cm soil layer, but lime application rate had no effect on P (figure 5 (i)).

3.2. Field experiment

Interactions between cropping system and liming were not significant for any of the soil chemical indicators (table 4). As a single factor, cropping system did significantly affect SOM, Ca, Mg and ΣB in the 17.5- to 20-cm soil layer, and CEC, in the 5- to 7.5-cm and 17.5- to 20-cm soil layers, respectively (table 4). Liming significantly affected 11 soil chemical indicators to a depth of 2.5 cm, nine indicators (excluding P and K) within the 5- to 7.5-cm depth, and eight indicators (excluding P, K, and CEC) within the 12.5- to 15-cm and 17.5- to 20-cm increments. Within the 0 to 10-cm layer the magnitude of change was proportional to lime rate. Applying the equivalent of 1 SMP increased pH in water and KCl to approximately 6.0 and 5.5, respectively, and decreased

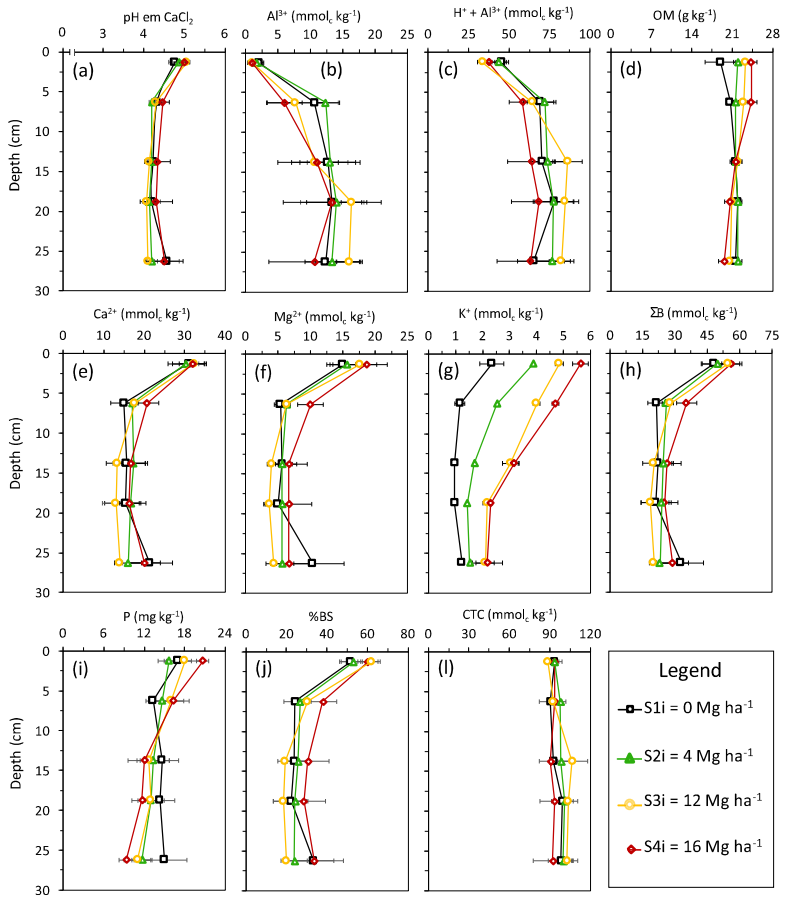

Figure 4. Experiment 3 (soil columns). Chemical attributes of the Rhodic Hapludox (Latossolo) after 50 weeks of incubation with four rates of straw incorporated within the top 5 cm (S1i, S2i, S3i, S4i) and no lime (L0). OM: organic matter; ΣB (base sum) (K+, Ca2+, Mg2+; CEC (cation exchange capacity) (H+ + Al3+); %BS (base saturation) (ΣB/CEC). Horizontal bars indicate the standard of average values.

exchangeable Al to 0 $mmol_c\ kg^{-1}$ within both cropping systems. Similarly, applying the 4 SMP rate increased pH in water and KCl to approximately 7.0 and 6.0, respectively, and decreased exchangeable Al to 0 $mmol_c\ kg^{-1}$ (figures 6 (a), (b), (c)). Increases in exchangeable Ca and Mg concentrations, sum of soil bases, and saturation of CEC by basic cations within the top 10 cm were also proportional to lime application rate (figures 6 (e), (f), (i), (j)). At the 4 SMP rate, there was also a small increase in pH immediately below where lime was incorporated, as well as measurable increases in exchangeable Ca, Mg, and CEC saturation by bases; and a slight decrease in exchangeable Al. At the 1 SMP rate there was a slight decrease in Al content, but no detectable changes in the other indicators. Applying lime at 4 SMP also decreased P content in the surface soil layer in soybean monoculture plots (figure 6 (h)) and reduced SOM content in the 0 to 5-cm depth increment under the 5-crop rotation (figure 6). Liming had no significant effect on soil chemical indicators within the 25- to 27.5-cm increment, confirming that under field conditions migration into the soil profile occurred very slowly, even with application rates as high as 4 SMP (33.2 Mg ha^{-1}). For both cropping systems, lime incorporation affected soil chemical attributes to a depth of only 10 cm. It had no effect at the 20 cm sampling depth (figure 6; table 4).

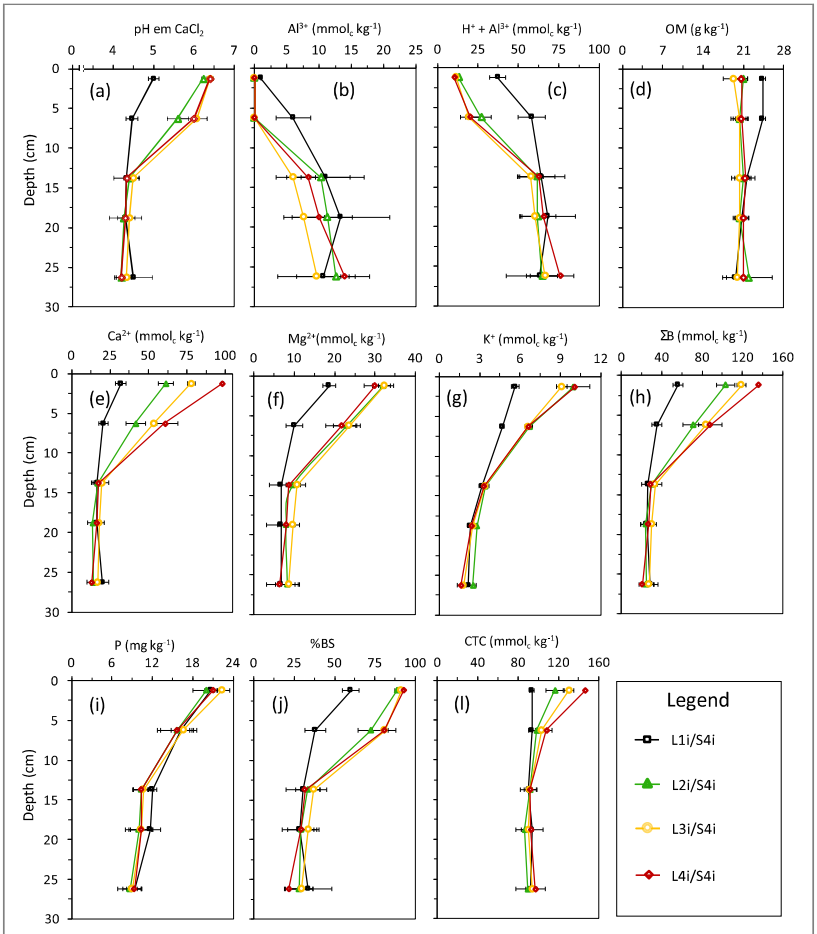

Figure 5. Experiment 4 (soil columns). Chemical attributes of the Rhodic Eutrodox (Latossolo) after 50 weeks of incubation with 16 Mg ha^{-1} (S4i) plus lime at four different rates (L1i, L2i, L3i, L4i), both incorporated. OM: organic matter; ΣB (base sum) [illegible] Ca^{2+} [illegible] Mg^{2+}; CEC (cation exchange capacity) [illegible] H^+ [illegible] Al^{3+}) [illegible] B; %BS (base saturation) [illegible] B/CEC. Horizontal bars indicate the standard deviation of average values.

4. Discussion

Four 50-week controlled environments and a 130-week field study with two different cropping systems confirmed lime movement in the soil profile was minimal and the positive effects were limited to approximately 2.5-cm below where the lime was added or incorporated. This response was consistent for all application rates (figures 2, 3, 5 and 6). These results agree with several previous studies under similar conditions (Pöttker and Ben 1998, Rheinheimer et al 2000, Ernani et al 2004, Bortolanza and Klein 2016). However, there are studies where surface application of lime to NT sites has been shown to mitigate soil acidity and increase exchangeable Ca and Mg content to a depth of 20 cm or more (Oliveira and Pavan 1996, Caires et al 2005, Caires et al 2008, Joris et al 2013, Caires et al 2015, Costa et al 2016).

Many of the contrasting results regarding lime movement to 20 cm or more are associated with long-term trials, coarse-textured soils, under high annual precipitation and high lime rates (table 5, Oliveira and Pavan 1996, Tang et al 2003, Caires et al 2005, Caires et al 2008, Joris et al 2013 and Caires et al 2015,

Table 4. ANOVA probability values for chemical attributes of a highly weathered soil under no-till measured at five depth increments, 130-weeks after lime incorporation.

Factor	OM	pH_{H2O}	pH_{KCl}	P	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	Σ B	CEC	%BS
					Depth 0 to 2.5-cm						
CS	0.062	0.940	0.602	0.238	0.396	0.797	0.192	0.313	0.398	0.276	0.860
LR	0.041	< 0.001	< 0.001	0.007	0.019	< 0.001	< 0.001	0.002	< 0.001	0.005	< 0.001
CS × LR	0.213	0.303	0.439	0.588	0.061	0.309	0.980	0.257	0.421	0.489	0.096
					Depth 5- to 7.5-cm						
CS	0.136	0.119	0.284	0.695	0.956	0.229	0.579	1.000	0.491	0.001	0.381
LR	0.009	< 0.001	< 0.001	0.406	0.335	< 0.001	< 0.001	< 0.001	< 0.001	0.012	< 0.001
CS × LR	0.312	0.383	0.137	0.794	0.507	0.251	0.609	0.899	0.273	0.060	0.087
					Depth 12.5- to 15-cm						
CS	0.401	0.069	0.243	0.758	0.247	0.205	0.067	0.639	0.192	0.057	0.627
LR	0.303	< 0.001	< 0.001	0.573	0.820	0.004	< 0.001	< 0.001	0.002	0.103	< 0.001
CS × LR	0.741	0.054	0.236	0.865	0.969	0.297	0.291	0.433	0.313	0.284	0.220
					Depth 17.5- to 20-cm						
CS	0.039	0.100	0.179	0.437	0.107	0.011	0.031	0.256	0.010	0.001	0.697
LR	0.495	0.002	0.002	0.525	0.082	< 0.001	0.008	< 0.001	< 0.001	0.656	0.008
CS × LR	0.239	0.718	0.650	0.712	0.838	0.465	0.559	0.699	0.598	0.242	0.4782
					Depth 25- to 27.5-cm						
CS	0.059	0.087	0.439	0.367	0.188	0.263	0.035	0.403	0.607	0.010	0.206
LR	0.211	0.242	0.573	0.504	0.722	0.371	0.446	0.729	0.626	0.852	0.547
CS × LR	0.259	0.857	0.956	0.631	0.892	0.986	0.573	0.996	0.999	0.607	0.978

CS: cropping system; LR: lime rate; OM: organic matter; Σ B (base sum) = K^+ + Ca^{2+} + Mg^{2+}; CEC (cation exchange capacity) = (H^+ + Al^{3+}) + Σ B; %BS (base saturation) = Σ B/CEC. The p values lower than 0.05 are bolded.

Costa et al 2016, and Santos et al 2018). In those studies, lime particles can migrate to deeper soil layers because compared to clay soils, coarse-textured soils have higher macroporosity and increased water flow, especially where annual precipitation is high. For example, Caires et al (2005), Joris et al (2013) and Caires et al 2015 who showed surface-applied lime mitigated soil acidity at a depth of 20 cm conducted their long-term trials on a sandy clay loam (47% sand) which received high annual precipitation (1550-mm). Those conditions combined with high lime rates (6 Mg ha^{-1}) and cropping systems with high residue resulted in increased soil pH below the point of placement (table 5). Other studies conducted in coarse-textured soils also reported surface-applied lime mitigation of soil acidity to depths of 50-, 55- and 60-cm, but only after 15 (Tang et al 2003), 18 (Santos et al 2018), or 10 years (Caires et al 2008), respectively (table 5). Short-term liming effects, however, tend to be limited to where the material was applied or incorporated even in soils with high sand content and high annual precipitation (1560-mm (table 5; figures 2, 3, 4, 7).

In general, liming effects are limited to the specific areas where the material is applied or incorporated for several reasons, including low solubility (Shainberg et al 1989) and soil texture. Pöttker and Ben (1998), Alleoni et al (2005), and Bortolanza and Klein (2016) demonstrated that after 3, 2.5 and 11 years the main effects of surface-applied lime to weathered soils under NT were limited to depths of 5, 10 and 5 cm, respectively (table 5). The trials described by those authors, as well as our field trial which was conducted under high annual precipitation (1500-mm) and with high lime rates (7.2 Mg/ha), were conducted on soils with high clay content (37%), and therefore increased resistance to lime movement (Conyers et al 2003).

A slow response to surface-applied lime was also measured in several other studies (table 5). Godsey et al (2007) reported that after 3 to 5 years, lime movement was limited to 7.5-cm or less at three NT sites on soils with clay content ranging from 240 to 320 g kg^{-1} and annual rainfall ranging from 800- to 1000-mm. Similarly, Barth et al (2018) found that lime effects for two NT studies conducted on silt loam soils with annual rainfall ranging from 350 to 580 mm were limited to 6 cm when evaluated 1.5-years after initiation. Conyers et al (2003) reported a pH increase at 10 cm for soil having 290 g kg^{-1} clay and receiving an annual rainfall of 570 mm, but only 8-years after surface liming. Combining results from the studies cited above with those from our studies suggest that surface-applied or shallow incorporated lime tends to move slowly into soil profiles such as ours and is therefore inefficient for quickly decreasing subsoil acidity under NT (figure 7).

Since lime moves very slowly into the soil profile, continued surface applications can cause chemical stratification (Bortolanza and Klein 2016, Martínez et al 2016, Barth et al 2018). Surface liming increases soil pH to levels above the optimum for crop growth (Fageria 2009) in the uppermost surface layer (figures 2, 3, and 6), decreasing absorption of cation micronutrients such as Cu, Zn and Mn (Caires and Fonseca 2000, Tahervand and Jalali 2017). In addition, it is inefficient at decreasing subsurface acidity (figures 2, 3, and 6), resulting in potential limitations to deep root development under NT (Veronese et al 2012, Seguel et al 2015).

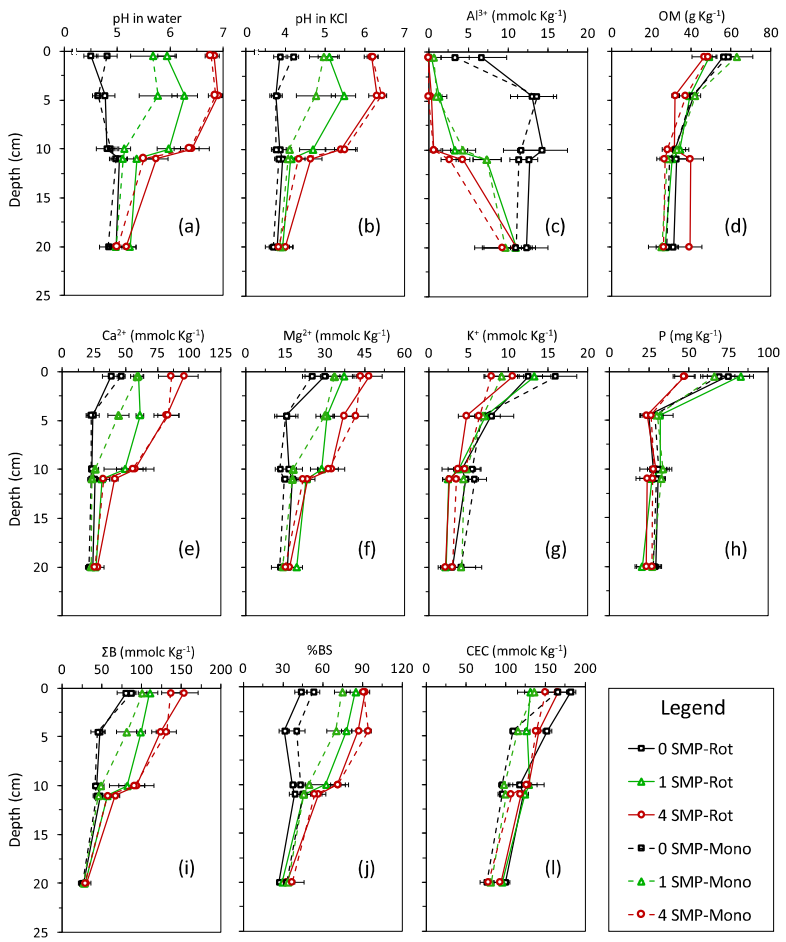

Figure 6. Field trial. Soil chemical attributes after applying three rates of lime to a Rhodic Hapludox with a 10-year history of no agronomic crops and then growing no-till monoculture soybean or growing a no-till crop rotation for 130 weeks. OM: organic matter; ΣB (base sum) [K^+ + Ca^{2+} + Mg^{2+}]; CEC (cation exchange capacity) [H^+ + Al^{3+}] + ΣB; %SB (base saturation) [ΣB/CEC]. Horizontal bars indicate the standard deviation of average values.

Excess lime can also affect soil biology (Paradelo et al 2015, Barth et al 2018). Under controlled conditions, lime application reduced SOM content in the 0 to 5-cm depth, hence increasing the availability of K in the topsoil (figure 5). Under field conditions, when applied at the high rate (four times above the conventional recommendation) lime decreased the amount of SOM within the 0 to 2.5- and 5- to 7.5-cm depths (table 4, figure 6 (d)). Paradelo et al (2015) performed an extensive review considering studies conducted in several countries under different conditions of weather, vegetation, soil type, soil management, duration of experiments, and rate and forms of lime application. They concluded that lime effects on soil carbon remain ambiguous, with some reporting that liming increased soil organic carbon by increasing soil biomass, but others stressing that liming can reduce soil organic carbon by increasing pH and accelerating SOM mineralization. Caires et al (2015) report that SOM content in the topsoil layer under NT is not altered by the surface lime practices, which contrasted with our findings. Those authors studied lower lime rates (4 to 12 Mg ha^{-1}) for a longer time (8-years), in comparison to our studies.

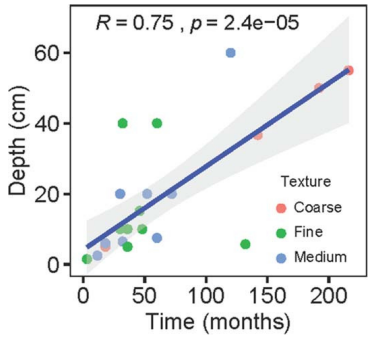

Figure 7. Depth of significant effect of surface-applied lime on soil pH as a function of experiment length under no-till systems in different soil textures.

Table 5. Significant effect of surface-applied lime on soil pH in no-till systems, reported by studies under different soil texture, annual precipitation, application rates, and study length.

Study	Texture Group	Texture Class	Sand	Clay	Prec.	Rate[a]	Time[b]	Depth[c]	Soil pH
			%	%	mm	Mg/ha	Month	cm	
Tang et al (2003)	Coarse	Sand	NA	NA	362	2.5	192	50	6.0 ($CaCl_2$)
Santos et al (2018)		Sandy loam	55	19	1769	17	216	55	4.9 (water)
Rheinheimer et al (2000)		Sandy loam	61	14	1688	3.6	18	5	4.8 ($CaCl_2$)
	Mean Coarse		58	16.5	1273	7.7	142	37	
Caires et al (2005)	Medium	Sandy clay loam	47	29	1495	6	30	20	6.0 ($CaCl_2$)
Caires et al (2008)		Sandy clay loam	47	29	1495	9	120	60	4.9 (water)
Joris et al (2013)		Sandy clay loam	47	29	1495	12	52	20	4.8 ($CaCl_2$)
Cairis et al (2015)		Sandy clay loam	47	29	1495	12	72	20	6.0 ($CaCl_2$)
Greenhouse studies		Sandy clay loam	59	32	1747	15.6	11.5	2.5	4.9 (water)
Godsey et al (2007)		Silt loam	NA	24	872	4.5	60	7.5	4.8 ($CaCl_2$)
Godsey et al (2007)		Silt loam	NA	24	872	4.5	60	7.5	6.0 ($CaCl_2$)
Barth et al (2018)		Silt loam	NA	NA	580		18	6	4.9 (water)
Barth et al (2018)		Silt loam	NA	NA	400		18	6	4.8 ($CaCl_2$)
	Mean Medium		49	24	617	4.5	32	6.5	
Conyers et al (2003)	Fine	Clay loam	10	29	570	1.5	48	10	—
Godsey et al (2007)		Silty clay loam	NA	32	1390	8.4	36	5	6.2 (KCl)
Potker and Ben (1998)		Sandy clay	NA	38	1746	10.7	36	10	6.2 (water)
Oliveira and Pavan (1996)		Clay	NA	62	1495	5.5	32	40	4.6 ($CaCl_2$)
Potker and Ben (1998)		Clay	NA	58	1318	7.2	36	10	5.8 (water)
Ernani et al (2004)		Clay	NA	NA	NA	14	3	1.5	6.7 (water)
Alleoni et al (2005)		Clay	21	73	1527	7.8	30	10	5.8 ($CaCl_2$)
Bortolanza and Klein (2016)		Clay	16.5	59	1724	16	132	10	5.1 (water)
Costa et al (2016)		Clay	NA	NA	1324	4	60	40	4.0 ($CaCl_2$)
	Mean Fine		16	50	1387	8	46	15	

[a] Lime rate surface-applied.
[b] Period between lime addition and soil sampling.
[c] Maximum depth where significant effects of lime on soil pH were observed; NA, not available. The studies that reported lime effect below 10-cm are bolded.

The slow movement of lime through the soil profile suggests that new liming techniques need to be developed to achieve deeper and faster lime response, mainly under NT conditions (Flower and Crabtree 2011, Kirkegaard et al 2014). Santos et al (2018) showed that lime incorporation before the adoption of NT is more efficient and faster in mitigating Al toxicity to the roots as compared to the surface liming. Other examples include applying lime using a chisel plow adapted to insert the material to greater depths (Richards et al 1995) and using seeders equipped with fixed shanks and openers for deeper placement (Nunes et al 2015). Flower and Crabtree (2011) have shown that even relatively small increases in soil disturbance at seeding can improve the liming effect in both topsoil and subsoil within NT fields. According to those authors, differences in soil disturbance, caused by various seed openers, affected lime response. They concluded that the use of openers accelerated the liming effect and made the practice even more effective at the 10- to 20-cm depth. These and other adapted technologies may provide simple low-cost alternatives for improving chemical conditions in subsurface layers within NT fields and decrease the concentration of lime in near-surface topsoil.

5. Conclusion

These greenhouse and field studies demonstrated that lime movement through the soil profile occurred very slowly. Liming impacts were limited to just a few centimeters below where the lime was applied or incorporated, independent of the rate applied (up to 33.2 Mg ha^{-1}). Surface liming increased soil pH and exchangeable Ca and Mg concentrations in the uppermost layer, but it was inefficient for mitigating subsoil acidity, hence promoting chemical stratification within the soil profile. Analyzing data from the literature, we found that lime movement through the soil profile can vary depending on several inherent and management factors. In general, significant effects of lime surface-apllied on soil pH within deeper soil layers were associated with long-term trials and coarse-textured soils. Additional investigations across a wider geographic area, greater range of weather and climatic conditions, methods and rates of lime application need to be conducted to improve lime recommendation for high weathered soil managed using no-till practices.

Acknowledgments

Thanks to the São Paulo Research Foundation [FAPESP, Brazil (Process number 2015/12934-3)] for the scholarships and funding. We express thanks also to the Brazilian Agricultural Research (EMBRAPA) for support.

ORCID iDs

Márcio R Nunes https://orcid.org/0000-0002-3674-279X

References

Alleoni L R F, Cambri M A and Caires E F 2005 Chemical attributes of a Cerrado Oxisol under no-tillage as affected by lime application methods and doses *Rev. Bras. Cienc. Solo* 29 923–34

Barth V P, Reardon C L, Coffey T, Klein A M, McFarland C, Huggins D R and Sullivan T S 2018 Stratification of soil chemical and microbial properties under no-till after liming *Applied Soil Ecology* 130 169–77

Blevins R L, Murdock L W and Thomas G W 1978 Effect of lime application on no-tillage and conventionally tilled corn *Agron. J.* 70 322–6

Bortolanza D R and Klein V A 2016 Soil chemical and physical properties on an Inceptisol after liming (surface and incorporated) associated with gypsum application. *Rev. Bras. Ci. Solo* 40 e0150377

Caires E F and Fonseca A F 2000 Soybean nutrient uptake as a function of liming surface application, under a no-tillage system *Bragantia* 59 213–20

Caires E F, Haliski A, Bini A R and Scharr D A 2015 Surface liming and nitrogen fertilization for crop grain production under no-till management in Brazil *Eur. J. Agron.* 66 41–53

Caires E F, Garbuio F J, Churka S, Barth G and Corrêa J C L 2008 Effects of soil acidity amelioration by surface liming on no-till corn, soybean, and wheat root growth and yield *Eur. J. Agron.* 28 57–64

Caires E F, Alleoni L R F, Cambri M A and Barth G 2005 Surface application of lime for crop grain production under a no-till system *Agron. J.* 97 791–8

Conyers M K, Heenan D P, McGhie W J and Poile G P 2003 Amelioration of acidity with time by limestone under contrasting tillage *Soil Till. Res.* 72 85–94

Correia J R, Reatto A and Spera S T 2004 Solos e suas relações com o uso e o manejo ed D M G Sousa and E Lobato *Cerrado: correção do solo e adubação.* (Planaltina: Embrapa Cerrados; Brasília, DF: Embrapa Informação Tecnológica, cap) 1, pp 29–61

Costa C H M, Crusciol C A C, Ferrari Neto J and Castro G S A 2016 Residual effects of superficial liming on tropical soil under no-tillage system *Pesq. Agropec. Bras.* 51 1633–42

Dairon R, Dutertre A, Tournebize J, Marks-Perreau J and Carluer N 2017 Long-term impact of reduced tillage on water and pesticide flow in a drained context *Environ. Sci. Pollut. Res.* 24 6866–77

Derpsch R, Franzluebbers A J, Duiker S W, Reicosky D C, Koeller K, Friedrich T, Sturny W G, Sá J C M and Weiss K 2014 Why do we need to standardize no-tillage research? Soil Tillage Res. 137 16–22
Donagema G K, Campos D V B, Calderano S B, Teixeira W G and Viana J H M 2011 Manual of Soil Method Analysis 2nd edn (Rio de Janeiro: Embrapa Solos)
Ernani P R, Ribeiro M F S and Bayer C 2004 Chemical modifications caused by liming below the limed layer in a predominantly variable charge acid soil Commun. Soil Sci. Plant Anal. 35 889–901
Fageria N K 2009 The use of Nutrients in crop Plants. (United States of America: CRC Press Taylor & Francis Group)
FAO-Food and Agriculture Organization of the United Nations 2016 Agriculture and Consumer Protection Department: Conservation Agriculture
Farina M P W, Channon P and Thibaud G R 2000 A comparison of strategies for ameliorating subsoil acidity: I. Long-term growth effects Soil Sci. Soc. Am. J. 64 646–51
Flower K C and Crabtree W L 2011 Soil pH change after surface application of lime related to the levels of soil disturbance caused by no-tillage seeding machinery Field Crops Res. 121 75–87
Gee G W and Or D 2002 Particle-size analysis ed J H Dane and G C Topp Methods of Soil Analysis. (Madison, Wisconsin, USA: Soil Science Society of America) pp 255–93
Godsey C B, Pierzynski G M, Mengel D B and Lamond R E 2007 Management of soil acidity in no-till production systems through surface application of lime Agron. J. 99 764–72
Joris H A W, Caires E F, Bini A R, Scharr D A and Haliski A 2013 Effects of soil acidity and water stress on corn and soybean performance under a no-till system Plant Soil 365 409–24
Kassam A, Friedrich T, Derpsch R and Kienzle J 2015 Overview of the worldwide spread of conservation agriculture Field Actions Science Reports 8 12
Kirkegaard J A, Conyers M K, Hunt J R, Kirkby C A, Watt M and Rebetzke G J 2014 Sense and nonsense in conservation agriculture: principles, pragmatismo and productivity in Australian mixed farming systems Agric. Ecosyst. Environ. 187 133–45
Martínez I, Chervet A, Weisskopf P, Sturny W G, Etana A, Stettler M, Forkmann J and Keller T 2016 Two decades of no-till in the Oberacker long-term field experiment: I. Crop yield, soil organic carbon and nutrient distribution in the soil Soil Till. Res. 163 141–51
Miyazawa M, Pavan M A and Franchini J C 2002 Evaluation of plant residues on the mobility of surface applied lime Braz. Arch. Biol. Technol 45 251–6
Nunes M R 2014 Mitigação da compactação do solo em plantio direto Masters Thesis Universidade Federal de Pelotas p 125
Nunes M R, Denardin J E, Faganello A, Pauletto E A and Pinto L F S 2014 Efeito de semeadora com haste sulcadora para ação profunda em solo manejado com plantio direto Rev. Bras. Ci. Solo. 38 328–638
Nunes M R, Denardin J E, Pauletto E A, Faganello A and Pinto L F S 2015 Mitigation of clayey soil compaction managed under no-tillage Soil Till. Res. 148 119–26
Nunes M R, Silva A P, Denardin J E, Giarola N F B, Vaz C M P, van Es H M and Silva A R 2017a Soil chemical management drives structural degradation of Oxisols under a no-till cropping system Soil Res. 55 819–83
Nunes M R, Vaz C M P, Denardin J E, van Es H M, Libardi P L and Silva A P 2017b Physicochemical and structural properties of an Oxisol under the addition of straw and lime Soil Sci. Soc. Am. J. 81 1328–39
Oliveira E L and Pavan M A 1996 Control of acidity in no-tillage system soybean production Soil Tillage Res. 38 47–57
Pöttker D and Ben J R 1998 Calagem para uma rotação de culturas no sistema plantio direto Rev. Bras. Ciênc. Solo 22 675–84
R Core Team 2014 R: a language and environment for statistical computing R Foundation for Statistical Computing (Austria: Vienna)
Rheinheimer D S, Santos E J S, Kaminski J and Xavier F M 2000 Surface application of lime on no-tillage Ci. Rural 30 263–8
Richards J E, Misener G C, Milburn P and McMillian L P 1995 Incorporation of limestone into naturally compacted subsoil during deep-ripping Soil Till. Res. 36 21–32
Santos D R, Tiecher T, Gonzatto R, Santanna M A, Brunetto G and Silva L S 2018 Long-term effect of surface and incorporated liming in the conversion of natural grassland to no-till system for grain production in a highly acidic sandy-loam Ultisol from South Brazilian Campos Soil Tillage Res. 180 222–31
Santos H G, Jacomine P K T, Anjos L H C, Oliveira V A, Lumbreras J F, Coelho M R, Almeida J A, Cunha T J F and Oliveira J B 2013 Sistema brasileiro de classificação de solos Rev. eampl. 3rd edn (Brasília: Embrapa) p 353
Seguel A, Barea J M, Cornejo P and Borie F 2015 Role of arbuscular mycorrhizal symbiosis in phosphorus-uptake efficiency and aluminum tolerance in barley growing in acid soils Crop. Pasture Sci.. 66 696
Shainberg I, Sumner M E, Miller W P, Farina M W P, Pavan M A and Fey M V 1989 Use of gypsum on soils: a review Adv. Soil Sci. 9 1–111
Shoemaker H E, McLean E O and Pratt P F 1961 Buffer methods for determining lime requirement of soil with appreciable amounts of extractable aluminium Soil Sci. Soc. Am. Proceedings 25 274–7
Soares M R, Alleoni L R F, Vidal-Torrado P and Cooper M 2006 Mineralogy and ion exchange properties of the particle size fractions of some Brazilian soils in tropical humid areas Geoderma 125 355–67
Tahervand S and Jalali M 2017 Sorption and desorption of potentially toxic metals (Cd, Cu, Ni and Zn) by soil amended with bentonite, calcite and zeolite as a function of pH J. Geochem. Explor. 181 148–59
Tang C, Rengel Z, Diatloff E and Gazey C 2003 Responses of wheat and barley to liming on a sandy soil with subsoil acidity Field Crops Res. 80 235–44
Tedesco M J, Gianello C, Bissani C A, Bohnen H and Volkweiss S J 1995 Análise de solo, plantas e outros materiais. 2.ed Porto Alegre, Universidade Federal do Rio Grande do Sul. 174p. (Boletim Técnico de Solos, 5)
Veronese M, Francisco E A B, Zancanaro L and Rosolem C A 2012 Plantas de cobertura e calagem na implantação do sistema plantio direto Pesq. Agropec. Bras. 47 1158–65