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Lime movement through highly weathered soil profiles

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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) 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 occurs 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 liming 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 Distrofico (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 (28º14′18″ S, 52º20′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
10-ml of sodium hydroxide (0.1 mol l\(^{-1}\)); (3) dispersing mechanically with a Wagner type shaker TE-160/24 rotated 360° 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 (28°11’20"S, 52°19’62"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\(_2\)O\(_3\), 190 g kg\(^{-1}\) Al\(_2\)O\(_3\), 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 > 1 suggest a predominance of kaolinite, Ki values < 1 suggest the dominance of oxides, and Ki values > 2 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.

| 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 dm\(^{-3}\) | 1.5      | 1.3      |
| Exchangeable Ca        | mmol dm\(^{-3}\) | 17       | 20       |
| Exchangeable Mg        | mmol dm\(^{-3}\) | 10       | 12       |
| Exchangeable Al        | mmol dm\(^{-3}\) | 12       | 27       |
| Potential acidity      | mmol dm\(^{-3}\) | 96      | 135      |
| Sum of bases           | mmol dm\(^{-3}\) | 28      | 34      |
| Cation exchangeable capacity | mmol dm\(^{-3}\) | 124 | 169 |
| Base saturation        | %             | 28        | 20        |
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

| Exp. | Applied | Lable | Lime Rate$^*$ | Straw Rate |
|------|---------|-------|---------------|------------|
| 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         |

$^*$ Lime rate equivalent to 0; 0.5, 1 and 2 times the SMP.
\[ \Sigma B = K + Ca + Mg \], the cation exchange capacity (CEC = H + Al + \Sigma B), and the base saturation of CEC (%BS = \Sigma B/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 \(\sim 2.5\) 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
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), (g), (h), and (j)). Incorporating lime at rates equivalent to 1 and 2 SMP, however, increased CaCl2 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 (figures 4(a), (b), (c), and (i)). 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 5 cm (S4i). This resulted in mitigation of soil acidity, increased CaCl2 pH, decreased

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.
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<sub>CaCl<sub>2</sub></sub> | P   | K<sup>+</sup> | Ca<sup>2+</sup> | Mg<sup>2+</sup> | Al<sup>3+</sup> | H<sup>+</sup> + Al<sup>3+</sup> | 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 | 0.199 | <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 | <0.001 | 0.002 | <0.001 | <0.001 | <0.001 | <0.001 |
| 5–7.5      | 0.024 | <0.001 | 0.965 | <0.001 | <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 | 0.253 | 0.787 | 0.770 | 0.795 | 0.636 | 0.867 | 0.684 |

OM: organic matter; ΣB (base sum) = K<sup>+</sup> + Ca<sup>2+</sup> + Mg<sup>2+</sup>; CEC (cation exchange capacity) = (H<sup>+</sup> + Al<sup>3+</sup>) + ΣB; %BS (base saturation) = ΣB/CEC. The p values lower than 0.05 are bolded.
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
exchangeable Al to 0 mmol 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 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), (g), (i)). 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 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\(^+\) + 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.
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.

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**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) = K⁺ + Ca²⁺ + Mg²⁺; CEC (cation exchange capacity) = (H⁺ + Al³⁺) + ΣB; %BS (base saturation) = ΣB/CEC. Horizontal bars indicate the standard deviation of average values.
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 | pHH2O | pHKCl | P | K⁺ | Ca⁺⁺ | Mg⁺⁺ | Al⁺⁺ | ΣB | CEC | %BS |
|--------|----|-------|-------|---|----|------|------|------|----|-----|-----|
| 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 0 to 2.5-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 | 0.12 | <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 5- to 7.5-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 | <0.001 | 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 12.5- to 15-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 17.5- to 20-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 |
| Depth 25- to 27.5-cm |

CS: cropping system; LR: lime rate; OM: organic matter; ΣB (base sum) = K⁺ + Ca⁺⁺ + Mg⁺⁺; CEC (cation exchange capacity) = (H⁺ + Al⁺⁺) / ΣB; %BS (base saturation) = ΣB / 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 (1500-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 ≥1500-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 (>57%), 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).
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 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; $\Sigma B$ (base sum) = $K^+ + Ca^{2+} + Mg^{2+}$; CEC (cation exchange capacity) = ($H^+ + Al^{3+}) + \Sigma B$; %SB (base saturation) = $\Sigma B$/CEC. Horizontal bars indicate the standard deviation of average values.
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  |
|------------------------|---------------|-------------------|------|------|-------|--------|--------|---------|----------|
| Tang et al (2003)      | Coarse        | Sand              | NA   | NA   | 362   | 2.5    | 192    | 50      | 6.0 (CaCl₂) |
| 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 (CaCl₂) |
| Mean Coarse            |               |                   | 58   | 16.5 | 1273  | 7.7    | 142    | 37      |          |
| Caires et al (2008)    | Medium        | Sandy clay loam   | 47   | 29   | 1495  | 6      | 30     | 20      | 6.0 (CaCl₂) |
| Caires et al (2008)    | Medium        | Sandy clay loam   | 47   | 29   | 1495  | 9      | 120    | 60      | 4.9 (water) |
| Joris et al (2013)     | Medium        | Sandy clay loam   | 47   | 29   | 1495  | 12     | 52     | 20      | 4.8 (CaCl₂) |
| Cairis et al (2015)    | Medium        | Sandy clay loam   | 47   | 29   | 1495  | 12     | 72     | 20      | 6.0 (CaCl₂) |
| Greenhouse studies     |              | Sandy clay loam   | 59   | 32   | 1747  | 15.6   | 11.5   | 2.5     | 4.9 (water) |
| Godsey et al (2007)    | Mean Medium   | Silt loam         | NA   | 24   | 872   | 4.5    | 60     | 7.5     | 4.8 (CaCl₂) |
| Godsey et al (2007)    | Mean Medium   | Silt loam         | NA   | 24   | 872   | 4.5    | 60     | 7.5     | 6.0 (CaCl₂) |
| Barth et al (2018)     | Mean Medium   | Silt loam         | NA   | 58   | 580   | 18     | 6      | 4.9     | (water)   |
| Barth et al (2018)     | Mean Medium   | Silt loam         | NA   | 400  | 400   | 18     | 6      | 4.8     | (CaCl₂)   |
| Conyers et al (2003)   | Fine          | Clay loam         | 10   | 29   | 570   | 1.5    | 48     | 10      | —        |
| Godsey et al (2007)    | Fine          | Silty clay loam   | NA   | 32   | 1390  | 8.4    | 36     | 5       | 6.2 (KCl) |
| Potker and Ben (1998)  | Fine          | 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 (CaCl₂) |
| 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 (CaCl₂) |
| Bortolanza and Klein (2016)| Clay | NA                | NA   | 1324 | 4     | 60     | 40      | 4.0 (CaCl₂) |
| Costa et al (2016)     | Mean Fine     | Clay              | 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 seedling 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-applied 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.

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