

Residual effect of surface-applied lime on soil acidity properties in a long-term experiment under no-till in a Southern Brazilian sandy Ultisol

Danilo S. Rheinheimer^a, Tales Tiecher^{b,*}, Renan Gonzatto^a, Mohsin Zafar^c, Gustavo Brunetto^a

^a Department of Soil Science, Universidade Federal de Santa Maria (UFSM), Santa Maria, Rio Grande do Sul, Brazil

^b Department of Soil Science, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Rio Grande do Sul, Brazil

^c Department of Soil and Environmental Sciences, University of Poonch Rawalakot, Pakistan

ARTICLE INFO

Handling Editor: Junhong Bai

Keywords:

Soil re-acidification
Aluminum saturation
Lime residual effect

ABSTRACT

The changes in soil chemical properties caused by surface lime application depend on the application dose, reaction time, and are limited to the top few centimeters of the soil profile. The present study aimed to monitor and to interpret the impacts of surface lime re-application at different rates and splitting rates on the amelioration of soil acidity and its distribution and migration through soil profile in a sandy Ultisol from Southern Brazil under long-term no-tillage (NT) system. The experiment was installed in an area where the conventional tillage (CT) was practiced till 1988 when the soil was limed (3.1 Mg ha^{-1}) and then the area was maintained under NT. In October 1994, the soil was sampled and lime was reapplied at four rates: 0, 3.6, 5.4, and 6.0 Mg ha^{-1} . The full dose to raise soil pH to 6.0 was applied in 1994 once. The rate of 5.4 Mg ha^{-1} was split in three times, applying $1.8 \text{ Mg lime ha}^{-1}$ in 1994, 1995, and 1999, and the rate of 6.0 Mg ha^{-1} was split in five times, applying $1.2 \text{ Mg lime ha}^{-1}$ in 1994, 1995, 1996, 1999, and 2000. The experimental design was randomized blocks with five replications. In October 2006 and 2012, i.e. after 18 and 24 years of the start of NT or 12 and 18 years after lime re-application (beginning of the experiment), soil samples were taken at each 1 cm depth up to 10 cm layer, each 2.5 cm depth up to 10 to 25 cm layer, and each 5 cm depth from 25 to 60 cm layer. Soil acidity attributes including active acidity (pH- H_2O), aluminum (Al) saturation, exchangeable Al, exchangeable calcium (Ca), exchangeable magnesium (Mg) and base saturation were also evaluated. Results show that the re-acidification of the soil is extremely slow. Even after 24 years without re-application of lime, the re-acidification process resulted in only 20% of the original potential acidity observed in the area under natural grassland. The surface application of lime in a re-acidified soil under NT promoted the formation of an alkalizing front by statistically modifying the soil acidity attributes up to 60 cm. However, it was much less deeper ($< 35 \text{ cm}$) when considering the agronomic interpretation of the soil acidity properties. Nevertheless, for both interpretations, the lime migration and its residual behavior were proportional to the lime application rate and its split application.

1. Introduction

The soils of tropical and subtropical regions have different intensity and age of weathering, but most of them are highly weathered, such as Oxisols and Ultisols. These soils occupy about 16% of the global ice-free land area spread over 72 countries and represent around 50% the world potentially arable land, and Brazil has 571 million hectares of them (67% of national arable land) (IBSRAM, 1985). The mineralogy of these soils is predominantly composed of iron and aluminum oxides and 1:1 type phyllosilicates, i.e., kaolinite, along with non-negligible amount of 2:1 type clay minerals (Bortoluzzi et al., 2015; de Carvalho Filho et al., 2015; Fink et al., 2014, 2016). Moreover, according to Abreu et al. (2003), it is estimated that 75% of the areas with potential for

agricultural activity in Brazil have problems with soil acidity presenting pH between 3.8 and 5.5. In addition, Al is the predominant cation in more than one-third of areas with soil pH below 5.6.

Soil acidity-related problems are well known and the elimination of its deleterious effects is commonly performed through liming. To ameliorate soil acidity in the no-tillage system (NT), surface liming without incorporation is a long-established practice. The short-term beneficial effects of liming to top few centimeters soil profile have been observed (Alleoni et al., 2005; Caires et al., 2006a; Pöttker and Ben, 1998; Rheinheimer et al., 2000b; Tiritan et al., 2016). However, the acidity correction of deeper soil layers is very slow and poorly studied, especially in soils with variable charge (Frageria and Nascence, 2014). The surface-applied lime promotes the formation of alkalizing gradient

* Corresponding author at: Department of Soil Science, Faculty of Agronomy, Bento Gonçalves Avenue 7712, CEP 91540-000 Porto Alegre, State of Rio Grande do Sul, Brazil.
E-mail address: tales.tiecher@ufrgs.br (T. Tiecher).

that moves vertically down into the soil profile. The rate of this alkalizing gradient movement depends on the time, rate, form, and application method of lime as well as on cultivation system, soil characteristics, climate conditions, and the addition of acid fertilizers (Caires et al., 2015; Castro and Crusciol, 2013; Costa and Rosolem, 2007; Costa, 2012; Crusciol et al., 2016; de Oliveira and Pavan, 1996; Fageria and Baligar, 2008; Flower and Crabtree, 2011; Franchini et al., 2004; Gatiboni et al., 2003; Kaminski et al., 2005; Limousin and Tessier, 2007; Martins et al., 2014b).

According to Rheinheimer et al. (2000b), the subsurface layers should be corrected only if the soil pH in the upper layer is higher than 5.5. Nevertheless, the movement of corrective effects of lime under NT system has been studied by several authors in recent years and diverse results have been reported (Alleoni et al., 2005; Bortoluzzi et al., 2014; Briedis et al., 2012; Caires et al., 1998, 1999, 2000, 2002, 2003, 2006c, 2008a, 2015; Kaminski et al., 2005; Martins et al., 2014a, 2014b; Rheinheimer et al., 2000b; Tissi et al., 2004; Weirich Neto et al., 2000). These studies demonstrate that soil correction in the subsurface under NT is favored mainly due to two mechanisms. First, by improving the soil physical and biological characteristics by straw maintenance on the soil surface and no mechanical disturbance which consequently facilitates the lime vertical movement via channels formed due to bio pores formed by dead roots and by soil macro fauna. Secondly, the decomposition of plant residues left on the soil surface contributes to the release of low molecular weight organic acids which can bind to Ca and Mg on the surface and move them to deeper soil layers decreasing the Al activity. However, it is still necessary to better understand the effects of liming at different rates and when splitting lime dose, especially in the long-term.

The Commission of Chemistry and Soil Fertility of the Rio Grande do Sul and Santa Catarina States (CQFS-RS/SC, 2016) in Southern Brazil recommends liming up to 0–20 cm soil layer by plowing and harrowing at the introduction of NT in soils with medium to high acidity potential. This allows neutralizing the Al^{3+} as deeply as possible since NT does not permit soil inversion and mixing in the subsequent years after its deposition. After that, under NT, the lime is applied to the soil surface, and an alkalizing gradient develops from the soil surface. This allows the re-acidification of the deeper soil layers. However, the surface re-application is only suitable if the farmers perform lime up to 20 cm prior to the adoption of the NT. Unfortunately, during the shift from conventional tillage to the no-till system between the 80s and 90s (Casão Junior et al., 2012), most of the farmers simply stopped the soil inversion without a chemical soil evaluation and, particularly, without a deep liming. As a result, presently, a wide-range of the agricultural areas as well pasturelands in Southern Brazil show serious problems of high acidity in subsurface soil layers affecting its production potential (Crusciol et al., 2016; Joris et al., 2016; Tiritan et al., 2016).

Thus, the present study aimed to monitor and to interpret the impacts of surface lime re-application on the amelioration of soil acidity and its distribution and migration through soil profile in a sandy Ultisol under long-term NT system.

2. Material and methods

2.1. Study site description

The study was conducted in the experimental area of the Department of Soil Science, Federal University of Santa Maria, located at 53° 42' 05.6" W, 29° 43' 03.5" S and elevation of 90 m above the sea level (Fig. 1). The soil of the experimental site is an Ultisol, medium texture, wavy relief, and sandstone substrate. The horizons Ap, A, AB, and Bt presented 170, 170, 210, and 290 g kg⁻¹ of clay, 300, 340, 340, and 370 g kg⁻¹ of silt, and 530, 490, 450, and 340 g kg⁻¹ of sand, respectively (Berwanger, 2006). According to Köppen's classification, the climate is humid subtropical climate (Cfa) with average annual rainfall of 1769 mm and average annual temperature of 19.2 °C. The

monthly average temperature and rainfall are presented in Fig. 2.

The area was planted with corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) until 1988 under conventional tillage with one plowing and two disc harrowing preceding summer crops and one disc harrowing before the establishment of winter cover crops (*Avena strigosa* Schreb.). The sowing was carried out on the leveled wide basis terraces. A composite soil sample containing five subsamples from 0 to 20 cm depth was analyzed for physicochemical soil properties. The particle size distribution was 140, 250, 610 g kg⁻¹ of clay, silt, and sand, respectively. The organic matter content was 11 g kg⁻¹, pH-H₂O 4.8, exchangeable Al 1.70 cmol_c kg⁻¹, Ca + Mg 2.90 cmol_c kg⁻¹, available P (Mehlich-1) 3.2 mg kg⁻¹ and exchangeable K 35 mg dm⁻³.

2.2. Experimental details and cropping history

In November 1988, dolomite limestone was applied at the rate of 3.1 Mg ha⁻¹ with 60% equivalent carbonate to raise the soil pH to 6.0 followed by plowing and harrowing. Since then, the experiment was shifted and maintained under the no-tillage system and was cultivated with corn and oat (*Avena strigosa* Schreb.) + common vetch (*Vicia sativa* L.) until 1993–94. Broad base terraces were built to control water runoff at the beginning of NT. In September 1994, soil samples were collected from the 0–20 cm for evaluation of acidity attributes. The chemical results were: pH-H₂O 5.0, SMP index 5.8, exchangeable Al 0.40 cmol_c kg⁻¹, Ca + Mg 3.0 cmol_c kg⁻¹, available P (Mehlich-1) 10 mg kg⁻¹ and exchangeable K 75 mg kg⁻¹.

In October 1994, the experiment was installed, and treatments were set based on estimated acidity to raise pH to 6.0 as recommended by CQFS-RS/SC (2016) for the NT. The surface limestone applications rates consisted of (i) control (without liming), (ii) 3.6 Mg lime ha⁻¹ (full dose applied in 1994 once), (iii) 5.4 Mg lime ha⁻¹ (1.8 Mg lime ha⁻¹ was applied three times: 1994, 1995, and 1999), and (iv) 6.0 Mg lime ha⁻¹ (1.2 Mg lime ha⁻¹ was applied five times: 1994, 1995, 1996, 1999, and 2000). The experiment was laid down under randomized block design with four treatments, five replications and the size of the plot (10 × 15 m) distributed along a slope gradient of 7%.

Corn was cultivated in 1994–95, 1997–98, 1999–2000 and 2000–01; oat in winter of 1995, 1996, 1998 and 2000 to 2005; soybean in 1995–96, 1996–97, 200–02, 2002–03, 2003–04 and 2004–05; oat + vetch in winter of 1997; hemp (*Crotalaria juncea* L.) in 1998–99; wheat (*Triticum aestivum* L.) in winter of 1999, 2007 and 2013; soybean + castor (*Ricinus communis* L.) in 2007–08; and millet (*Pennisetum glaucum* L.) in 2008–09. During the spring/summer period of 2005–06, 2009–10, 2010–11, and 2011–12 and winter of 2006 and 2008–2012 the area was left as fallow. The results of crop yields from 1994–95 to 1996–97 have been discussed by Rheinheimer et al. (2000a), and of crops from 2000 to 2001 by Gatiboni et al. (2003).

2.3. Soil sampling and analysis

In October 2006 and 2012, at 12 and 18 years lime application, we opened a trench per plot with dimensions of 1 m deep × 1 m wide × 1 m long to collect soil samples. The soil samples were collected at each 1 cm depth from 0 to 10 cm depth; at each 2.5 cm from 10 to 25 cm depth; and at each 5 cm depth from 25 to 60 cm layer. Each sample was composed of two subsamples taken from two sides of the trench. Soil samples were also collected from an adjacent native area (Campos Biome). The soil samples were dried at ± 55 °C to avoid organic matter losses (Tedesco et al., 1995) and then ground and sieved with a 2-mm mesh. The chemical characteristics determined include soil pH in water (1:1 v/v); exchangeable Ca, Mg, and Al extracted by 1.0 mol L⁻¹ KCl (soil:extractant ratio 1:25) (Tedesco et al., 1995). Exchangeable Al in the KCl extract was determined by titration with 0.0125 mol L⁻¹ NaOH solution; Ca and Mg were determined by atomic absorption spectrophotometry. The potential acidity (H + Al) was calculated using the Eq. (1) proposed by Kaminski et al. (2001) and



Fig. 1. Map of the study site at Santa Maria, Rio Grande do Sul State, Brazil.

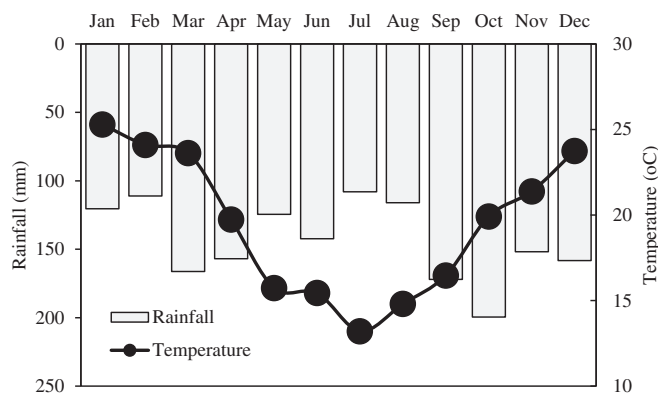


Fig. 2. Monthly average temperature and rainfall in Santa Maria, Rio Grande do Sul, Southern Brazil.

adopted by CQFS-RS/SC (2016) (Eq. (1)):

$$H + Al = e^{10.665 - 1.1483 \cdot \text{pH SMP} / 10} \quad (1)$$

where the $H + Al$ is estimated by the pH balance of the soil with 1.78 mol L^{-1} SMP solution (triethanolamine, paranitrofenol, K_2CrO_4 , $\text{Ca}(\text{CH}_3\text{COO})_2$ and $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$) buffered at pH 7.5 (Shoemaker et al., 1961). Effective cation exchange capacity (CEC_{ef}) was calculated as the sum of $\text{Al}^{3+} + \text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^+$. Cation exchange capacity at pH 7.0 ($\text{CEC}_{\text{pH } 7.0}$) was calculated as the sum of $\text{H}^+ + \text{Al}^{3+} + \text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^+$. Aluminum saturation (m) was calculated as follow: $m (\%) = \text{Al} / (\text{CTC}_{\text{ef}}) \times 100$. Base saturation (V) was calculated as follow: $V (\%) = (\text{Ca} + \text{Mg} + \text{K}) / (\text{CTC}_{\text{pH } 7.0}) \times 100$.

2.4. Statistical analysis

For the analysis of variance of the soil acidity parameters, the following model was used:

$$Y_{ijkl} = \mu + B_i + L_j + \text{error } a(i,j) + D_k + \text{error } b(i,k) + LD_{jk} + \text{error } c(i,j,k) + T_l + \text{error } d(i,l) + LT_{jl} + \text{error } e(i,j,l) + DT_{kl} + \text{error } f(i,k,l) + LDT_{jkl} + \text{error } g(i,j,k,l)$$

where, μ = overall experimental average; B = blocks ($i = 1, 2, 3, 4, 5$); L = lime doses ($j = 1, 2, 3, 4, 5$); D = depth ($k = 1, 2, \dots, 22$); T = time ($l = 1, 2$) and error = experimental error. The lime rates were considered the main plot and depth and time were considered as sub-plots. When treatment effect was significant at 5% probability of error by F test, the differences between means of lime rates, depth, and time were compared by Tukey's honestly significant difference (HSD) at $p < 0.05$.

3. Results and discussion

3.1. The soil re-acidification

In order to evaluate the soil re-acidification dynamics, we discuss here some interesting data obtained in the control treatment. The soil in the adjacent natural grassland area (Campos Biome) showed a high active acidity (soil pH- H_2O) (Fig. 3a) and Al saturation (Fig. 3b). Up to 10 cm depth, the Al saturation reached 75% and stabilized at 80% till 60 cm (Fig. 3b). When the area was managed under the CT, the routine application of lime and fertilizers was carried out, and soil loss was high due to erosion. The last time lime addition to raise the pH up to 6.0 at 0–20 cm was carried out before shifting to the NT back in 1988. Even after 18 and 24 years of this lime application, the soil pH is still higher

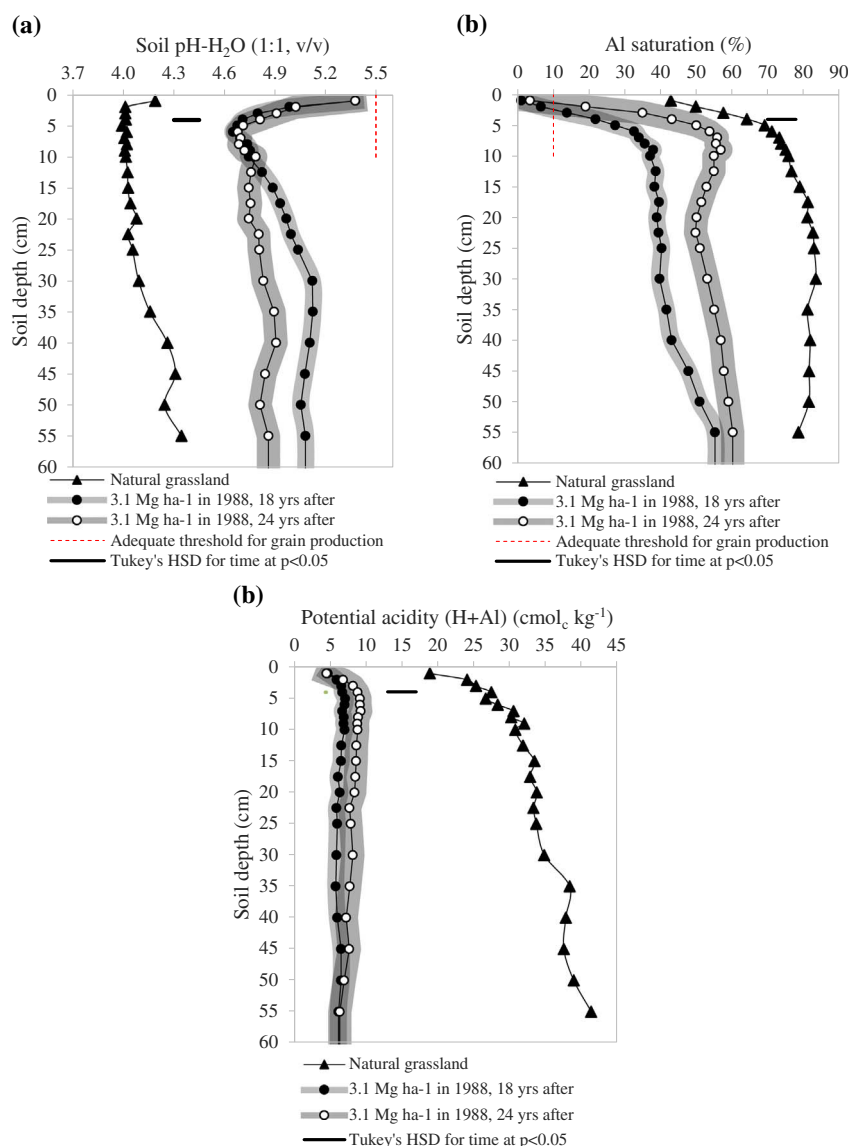


Fig. 3. Changes in active acidity (pH-H₂O) (a), Al saturation (b), and potential acidity (H + Al) (c) at different depths and time in a no-tilled sandy Ultisol from Southern Brazil. Line widths indicate the average 95% confidence interval for each treatment. Natural grassland is used for comparison and was not included in the statistical analysis.

than the observed in the natural grassland area up to 70 cm (Fig. 3a). Moreover, compared to the adjacent natural grassland, the potential acidity (H + Al) was approximately 5 and 4 times lower in the 0–60 cm soil layer in the soil that received lime in 1998 (Fig. 3c). In addition, potential acidity (H + Al) was not different ($p > 0.05$) in the 0–60 cm soil layer for sampling periods after 18 and 24 years after the last lime application (Fig. 3c). This demonstrates the long-term residual effect of liming, similar to results reported by the Azevedo et al. (1996) and Tiritan et al. (2016) in Oxisol under long-term lime application experiments. This behavior indicates that the soil did not return to its natural acidity state even after 24 years after the addition of limestone, demonstrating that under these conditions, the reacidification process is extremely slow. It also corroborates with Barrow (1999), who affirm that the disorders caused by liming and the magnitude of the acidification process will rarely return the acidity levels to its initial soil condition without the addition of corrective agent.

3.2. The lime residual effects

Lime surface reapplication in NT (3.6 Mg ha⁻¹ to raise soil pH to 6.0) in 1994 has changed the soil chemical properties throughout profile after 12 and 18 years (Figs. 4 to 10). After 12 years of lime reapplication, the soil pH (Fig. 4a), exchangeable Ca (Fig. 7a) and Mg

(Fig. 8a), and base saturation (Fig. 10a) was higher ($p < 0.05$) in the 3.6 Mg ha⁻¹ lime rate than in the control treatment up to 7, 25, 20, and 20 cm deep, respectively. On the other hand, potential acidity (H + Al) (Fig. 5a), exchangeable Al (Fig. 6a), and Al saturation (Fig. 9a) was lower than in the control treatment up to 17 cm deep. These effects were more pronounced after 18 years of lime reapplication, when the soil pH (Fig. 4b), exchangeable Ca (Fig. 7b) and Mg (Fig. 8b), and base saturation (Fig. 10b) was higher ($p < 0.05$) in the 3.6 Mg ha⁻¹ lime rate than in the control treatment up to 60, 40, 30, and 60 cm deep, respectively. Contrary, potential acidity (H + Al) (Fig. 5b), exchangeable Al (Fig. 6b), and Al saturation (Fig. 9b) was lower than in the control treatment up to 45, 60, and 60 cm deep. The effective cation exchange capacity (CEC_{ef}) of the soil was little affected by application of the 3.6 Mg ha⁻¹ of lime to raise soil pH to 6.0, suggesting that there was a simple in the exchange of Al by Ca and Mg added by limestone (Fig. 11).

Low Al toxicity in top few centimeters of soil profile allows the primary plant roots to grow in the less toxic environment. This compensates the toxic effect of Al on crop yields as roots can reach the soil with high exchangeable Al and continue to grow (Alleoni et al., 2010; Brown et al., 2009; Caires et al., 2008b; Kidd and Proctor, 2001; Nogueirol et al., 2014). In contrast, in cases where the roots are in contact with high Al contents at early growth stage and after grow to

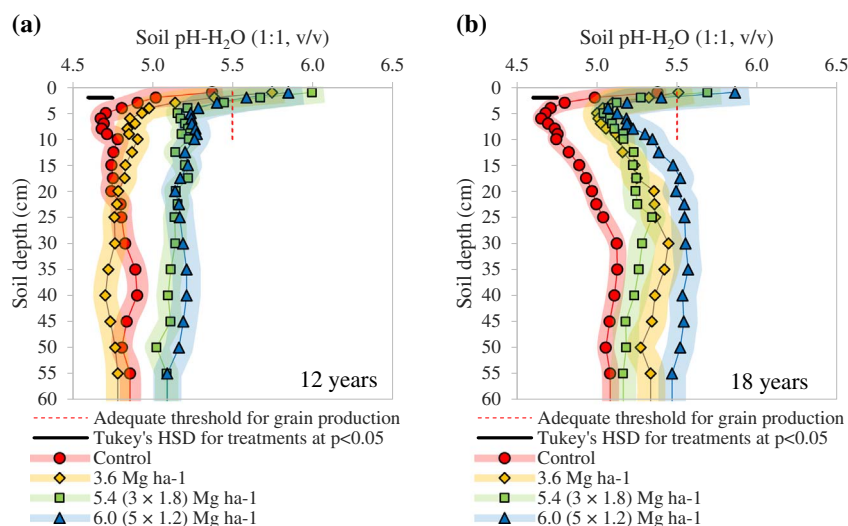


Fig. 4. Changes in soil pH-H₂O at different profile depths as affected by lime treatments 12 (a) and 18 (b) years after the beginning of the experiment in a no-tilled sandy Ultisol from Southern Brazil. Line widths indicate the average 95% confidence interval for each treatment.

the soil portion even without the presence of a toxic element, they do not recover and show lower growth and expansion and hence affect the crop production. In cropping systems like the NT, the surface lime re-application combined with high carbon content decreases the toxicity of Al (Brown et al., 2009). Organic acids and other compounds plant exudate and that are generated by the decomposition of the roots can form organometallic complexes with Al (Alleoni et al., 2010). The Al toxicity which is free in the soil solution is substantially reduced thus favoring an environment without restricting root growth (Brown et al., 2009).

3.3. Splitting lime dose effects

The results have shown significant changes in soil acidity attributes in deeper soil layers when the split application of the recommended lime doses was practiced instead of a single full application (Figs. 4 to 10). In the treatment where full lime dose 3.6 Mg ha⁻¹ was applied, the subsurface soil layers (4–60 cm) on average showed pH 5.2 (Fig. 4b), exchangeable Al 0.8 (Fig. 6b), exchangeable Ca < 1.2 (Fig. 7b) and exchangeable Mg < 0.8 cmol_c kg⁻¹ (Fig. 8b). Aluminum saturation and base saturation were 32% (Fig. 9b) and < 25% (Fig. 10b), respectively. However, the treatment receiving 5.4 Mg lime ha⁻¹ (split

into 3 doses of 1.8 Mg lime ha⁻¹ and application after each 2 years), the average pH was 5.3 (Fig. 4b), exchangeable Al 0.5 (Fig. 6b), exchangeable Ca < 1.9 (Fig. 7b) and exchangeable Mg < 1.0 cmol_c kg⁻¹ (Fig. 8b). Aluminum saturation ranged from 14 to 20% in the 4–10 cm soil layer and between 20 and 40% in deeper soil layers (Fig. 9b). The base saturation was close to 32% below 4 cm depth in all soil layers (Fig. 10b). Similarly, the treatment receiving lime at 6.0 Mg ha⁻¹ (5 split application of 1.2 Mg lime ha⁻¹) the difference in the base saturation below the surface layer varied between 36 and 43% (Fig. 10b) while Al saturation ranged from 10 to 12% (Fig. 9b). The pH, exchangeable Ca and Mg were higher, and the Al contents were lower than the other treatments.

Our results demonstrate that the deeper lime effect is not only proportional to the rate of lime application. One of the main reasons is probably because the splitting lime application may have prevented its runoff loss. Another important point is that splitting lime application also decreased its losses because lime is less reactive in the soil surface when applied in higher doses due to the higher soil pH of the surface layer, thus reducing its solubility and allowing its migration only in particulate form throughout the soil profile. Here, the migration of lime particles via bio pores reinforces the importance of soil physical quality and its temporal availability on the soil surface. The surface application

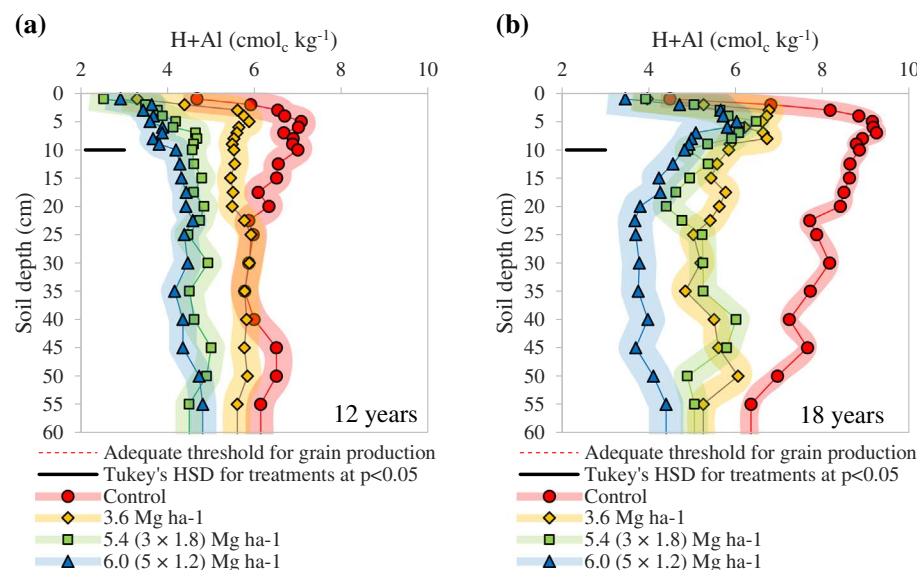


Fig. 5. Changes in potential acidity (H + Al) at different profile depths as affected by lime treatments 12 (a) and 18 (b) years after the beginning of the experiment in a no-tilled sandy Ultisol from Southern Brazil. Line widths indicate the average 95% confidence interval for each treatment.

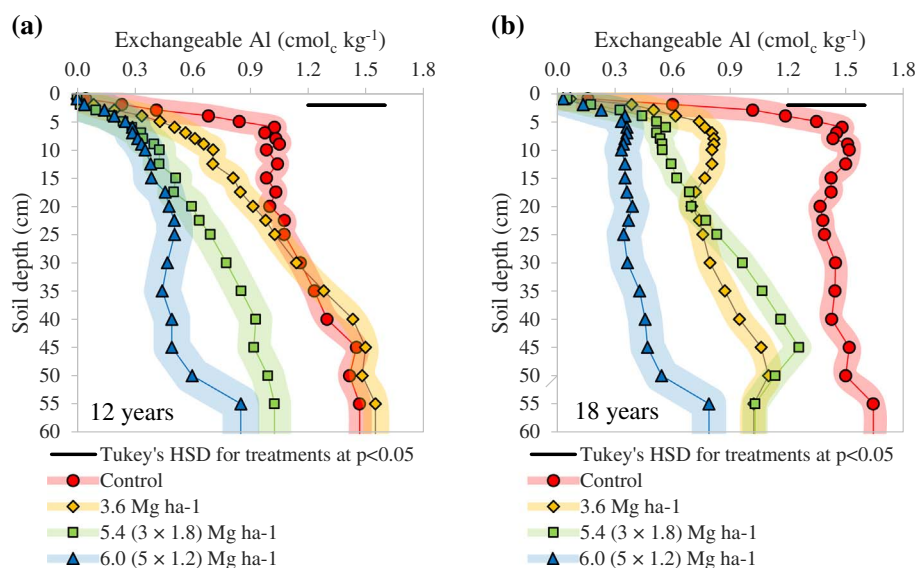


Fig. 6. Changes in exchangeable Al at different profile depths as affected by lime treatments 12 (a) and 18 (b) years after the beginning of the experiment in a no-tilled sandy Ultisol from Southern Brazil. Line widths indicate the average 95% confidence interval for each treatment.

creates a neutralization gradient from the soil surface, but the acidity correction of deeper layers in the soil profile will only occur when the acidity of the top layer is neutralized. The rate of forward movement of the neutralization gradient mainly depends on the migration of fine particles of limestone in association with the water-soluble organic binder with hydroxyl (R—OH) and carboxyl (COOH—R) functional groups present on the soil surface under NT (Amaral et al., 2004a, 2004b; Franchini et al., 2001; Veronese et al., 2012).

3.4. Statistical and agronomic interpretation of liming effect

The interpretation of soil acidity data can be made in two different ways (Tiecher et al., 2017). The most commonly used is the comparison by statistical methods. However, this approach does not take into account the agronomic relevance of the effects. Sometimes even small changes such as pH change of 0.1 units or $\pm 5\%$ variance in the Al or base saturation can be significant however it has little or no relevance for agriculture management implications and crop production. Another way is to consider critical limits for crop response, which is normally pre-established for each region. In the State of Rio Grande do Sul, Southern Brazil, there is the official recommendation the Committee on

Soil Chemistry and Fertility (CQFS-RS/SC, 2016) that defines the critical limits for plant grow and yields based on several years of agricultural experimentation (Table 1). Therefore, in this section, in addition to the traditional statistical interpretation, we used the agronomic thresholds present in Table 1 to interpret the results of liming effects.

Many authors have studied the effectiveness of surface liming on soil chemical properties related to acidity by using statistical comparisons (Alleoni et al., 2005; Amaral et al., 2004b; Bortoluzzi et al., 2014; Briedis et al., 2012; Caires et al., 1998, 1999, 2000, 2002, 2003, 2006a, 2006b, 2006c, 2008a, 2015; Calezari et al., 2013; Castro and Crusciol, 2013; Crusciol et al., 2016; Kaminski et al., 2005; Martins et al., 2014a; Pöttker and Ben, 1998; Rheinheimer et al., 2000b; Soratto and Crusciol, 2008; Tiritan et al., 2016; Tissi et al., 2004; Weirich Neto et al., 2000; Zambrosi et al., 2007). The effects show that it is possible to make comparison by considering significant changes in the chemical properties of the soil surface layer when compared to the native soil when a single recommended lime dose was applied to increase soil pH to 6.0. The magnitude of the effect varies in depth according to the soil characteristics such as texture and structure, application rate, time, and chemical characteristics under consideration. Regarding subsurface layers, in some cases significant effect was observed in pH rise, high

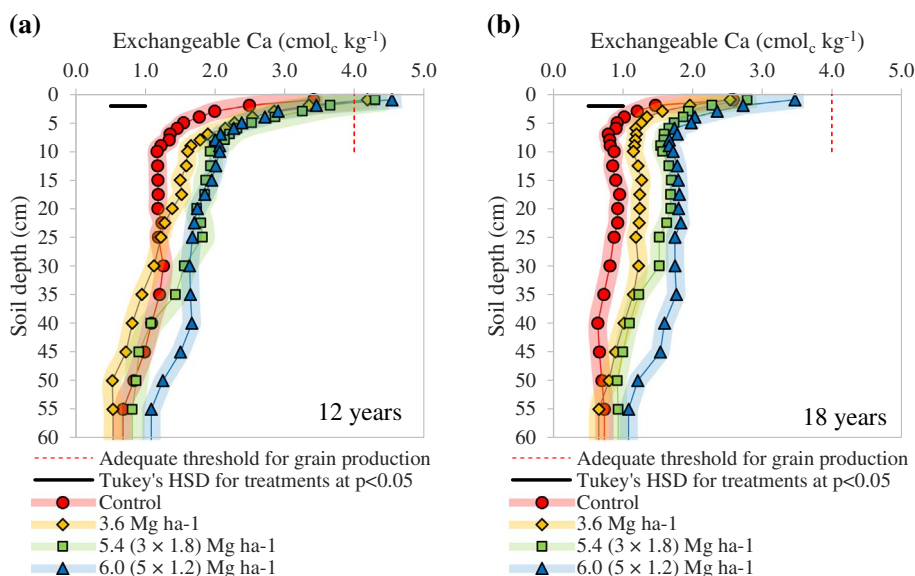


Fig. 7. Changes in exchangeable Ca at different profile depths as affected by lime treatments 12 (a) and 18 (b) years after the beginning of the experiment in a no-tilled sandy Ultisol from Southern Brazil. Line widths indicate the average 95% confidence interval for each treatment.

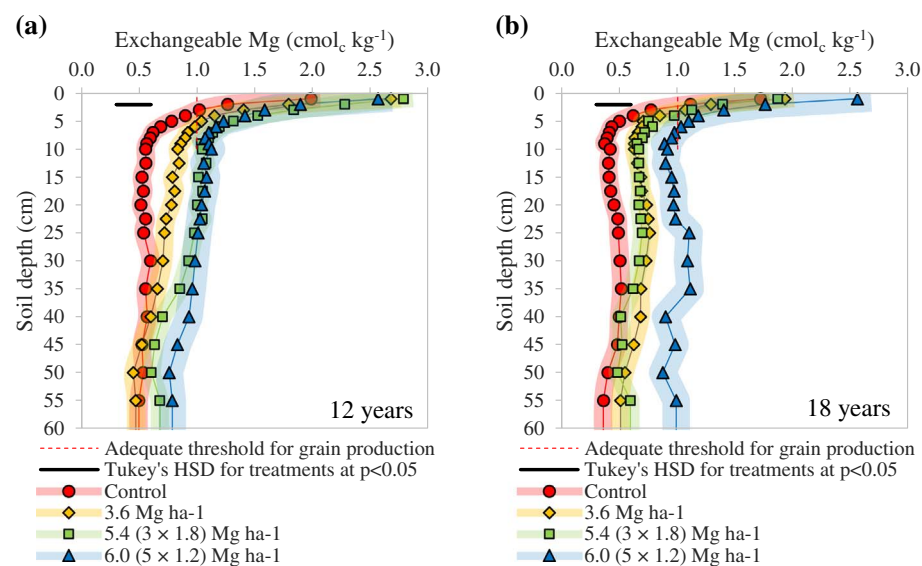


Fig. 8. Changes in exchangeable Mg at different profile depths as affected by lime treatments 12 (a) and 18 (b) years after the beginning of the experiment in a no-tilled sandy Ultisol from Southern Brazil. Line widths indicate the average 95% confidence interval for each treatment.

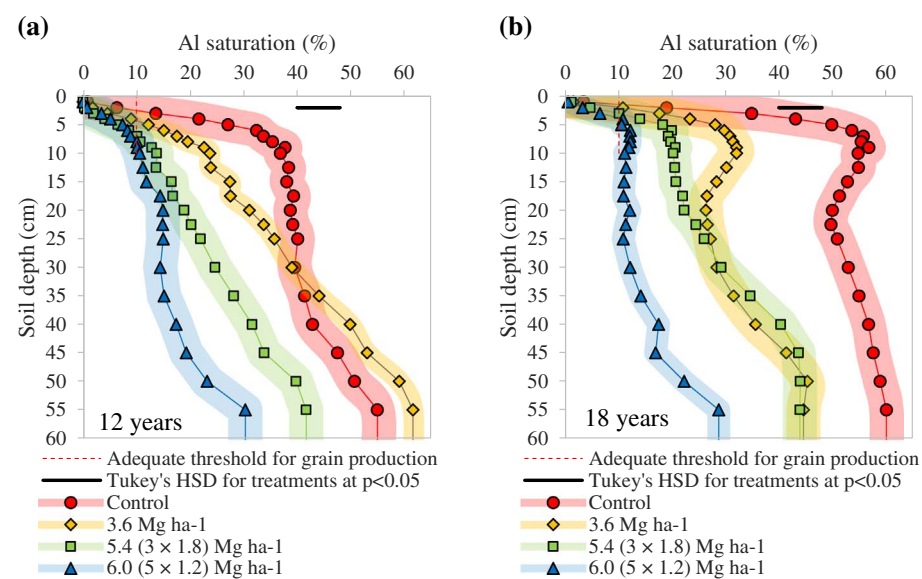


Fig. 9. Changes in Al saturation at different profile depths as affected by lime treatments 12 (a) and 18 (b) years after the beginning of the experiment in a no-tilled sandy Ultisol from Southern Brazil. Line widths indicate the average 95% confidence interval for each treatment.

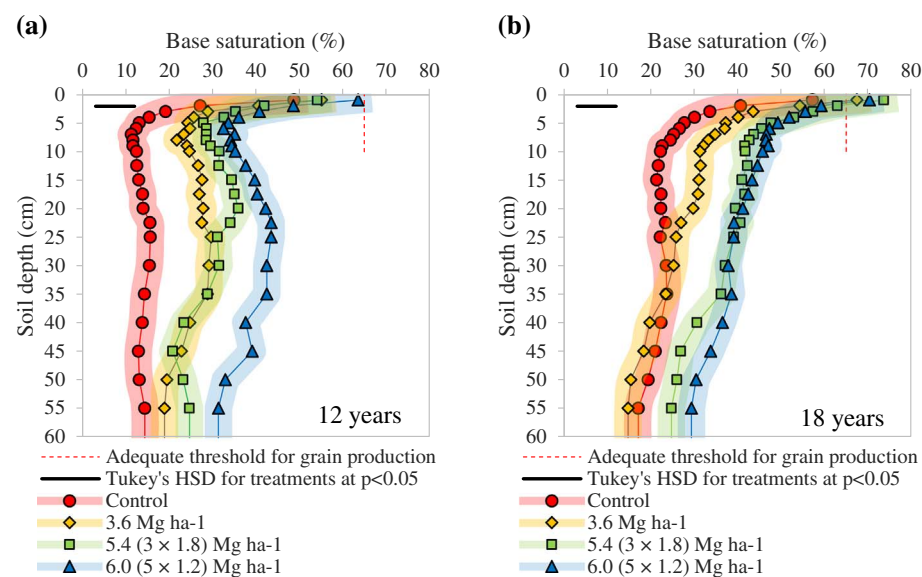


Fig. 10. Changes in base saturation at different profile depths as affected by lime treatments 12 (a) and 18 (b) years after the beginning of the experiment in a no-tilled sandy Ultisol from Southern Brazil. Line widths indicate the average 95% confidence interval for each treatment.

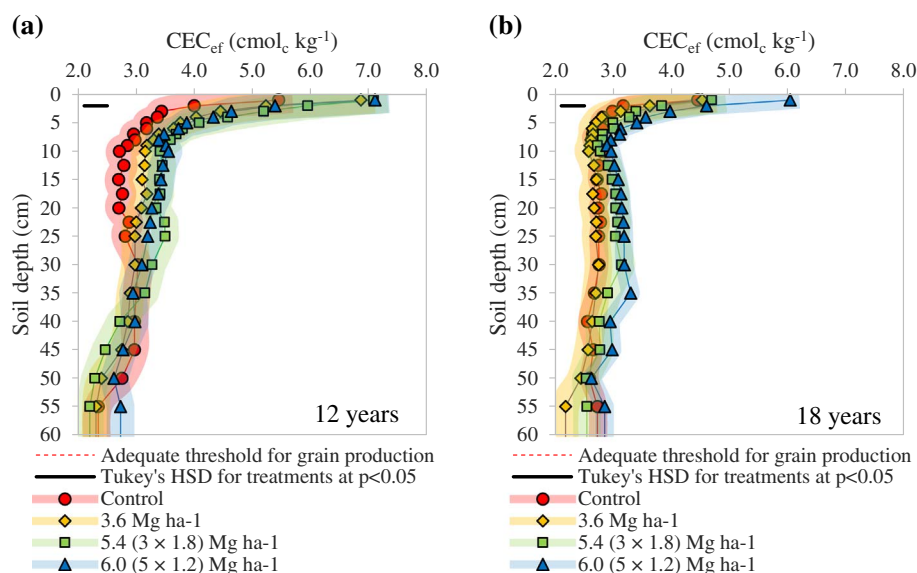


Fig. 11. Changes in effective cation exchange capacity (CEC_{ef}) at different profile depths as affected by lime treatments 12 (a) and 18 (b) years after the beginning of the experiment in a no-tilled sandy Ultisol from Southern Brazil. Line widths indicate the average 95% confidence interval for each treatment.

Table 1
Interpretation of soil acidity properties according to the Committee on Soil Chemistry and Fertility (CQFS-RS/SC, 2016).

Agronomic interpretation	Soil pH	Base saturation (%)	Al saturation (%)	Exchangeable Ca (cmol _c kg ⁻¹)	Exchangeable Mg (cmol _c kg ⁻¹)
Very low	< 5.0	< 45	< 1	–	–
Low	5.1–5.4	45–64	1–10	< 2.0	< 0.5
Medium	5.5–5.9	65–80	10.1–20	2.1–4.0	0.6–1.0
High	> 6.0	> 80	> 20	> 4.0	> 1.0
Very high	–	–	–	–	–

Table 2
Variation induced by surface lime application on soil profile depth (cm) inferred by conventional statistical analysis ($p < 0.05$) and by the agronomic interpretation based on CQFS-RS/SC (2016) (Table 1).

Soil parameter	After 12 years (cm)			After 18 years (cm)		
Lime rate (Mg ha ⁻¹)	3.6 ^a	5.4 ^b	6.0 ^c	3.6	5.4	6.0
Statistical interpretation						
Al saturation (%)	17	60	60	60	60	60
pH-H ₂ O	7	60	60	60	30	60
Exchangeable Al (cmol _c kg ⁻¹)	17	60	60	60	60	60
Exchangeable Ca (cmol _c kg ⁻¹)	25	60	60	40	40	60
Exchangeable Mg (cmol _c kg ⁻¹)	20	35	60	30	60	60
Base saturation (%)	20	60	60	60	45	60
Interpretation based on CQFS-RS/SC (2016)						
Al saturation (%)	4	6	12	2	2	35
pH-H ₂ O	1	2	2	1	1	1
Exchangeable Mg (cmol _c kg ⁻¹)	5	10	25	3	4	35
Exchangeable Ca (cmol _c kg ⁻¹)	6	8	6	2	2	6
Base saturation (%)	1	1	1	0	0	0

^a Lime reapplication at the time of experiment installation in 1994.

^b Lime reapplication at 1.8 Mg ha⁻¹ at the time of experiment installation; 1.8 Mg ha⁻¹ after 24 months and 1.8 Mg ha⁻¹ after 48 months.

^c Lime reapplication at 1.2 Mg ha⁻¹ at time of experiment installation; 1.2 Mg ha⁻¹ after 12 months, 1.2 Mg ha⁻¹ after 24 months, 1.2 Mg ha⁻¹ after 36 months, and 1.2 Mg ha⁻¹ after 48 months.

base saturation and reduction in Al saturation to a depth of 60 cm at application rates ranging from 2 to 5.5 Mg ha⁻¹ in medium and clayey soils in 12 split application after 72 months (de Oliveira and Pavan, 1996; da Silva et al., 2007; Soratto and Crusciol, 2008).

In the present study, after 12 years of surface lime re-application the

treatment showed significant effects up to 7–60 cm depth, depending on the rate of lime application and attribute considered (Table 2). The treatment which received lime at 3.6 Mg ha⁻¹ as a single dose has significant change in soil pH, Al saturation and base saturation up to 7, 17, and 20 cm depth, respectively. In the treatments where lime dose was split (1.8 Mg ha⁻¹ three times and 1.2 Mg ha⁻¹ five times, totaling 5.4 Mg ha⁻¹ and 6.0 Mg ha⁻¹, respectively), significant effects were observed up to 60 cm depth for most of the analyzed attributes. Similarly, after 18 years of treatment application, the effects on Al saturation were statistically significant up to 60 cm depth in all treatments (Table 2).

When using the agronomic threshold proposed by the Committee on Soil Chemistry and Fertility (CQFS-RS/SC, 2016) to interpret the results, we observed that the depth in which liming have effects on soil acidity properties was much lower (Table 2). At both sampling periods (12 and 18 years after the beginning of the experiment), in both 3.6 Mg ha⁻¹ and 5.4 Mg ha⁻¹ treatments, the Al saturation remained below 10% only in top 6 cm soil layer (Table 2). The pH and base saturation values were insufficient to maintain a chemically favorable environment for root development below 4 cm deep. The treatment where the reapplication of 6.0 Mg ha⁻¹ in 5 split doses was carried out only maintained Al saturation correction up to 12 and 35 cm depth at 12 and 18 years after the installation of experiment, respectively (Table 2). From these results, it appears that the significant effect of liming is only for statistical comparison between treatments and native grassland and there is an overestimation of depth changes from the agronomic point of view.

Finally, the results clearly indicate the migrating effects of liming and its advance from the top few centimeters to the deeper layers by increasing the pH and decreasing the Al saturation depend on the rate and splitting of the lime application. However, in the 4 to 12 cm layer, the pH decreased from surface to subsurface layer in the order of 0.2 pH

units from 12 to 18 years, and this behavior can be attributed to the soil acidification process that is induced by rain, fertilization, plants and soil genetic features.

4. Conclusions

In this study, we have monitored and interpreted the impacts of surface lime re-application at different rates and splitting rates on the amelioration of soil acidity and its distribution and migration through soil profile in a sandy Ultisol from Southern Brazil after 18 and 24 years of the start of NT system and 12 and 18 years after lime re-application (beginning of the experiment). Results show that the re-acidification of the soil is extremely slow. Even after 24 years without re-application of lime, the re-acidification process resulted in only 20% of the original potential acidity observed in the area under natural grassland. After 18 years of surface lime re-application liming promoted alkalization gradient formation in the soil profile by statistically modifying the soil acidity attributes up to 60 cm depth, but it was much less deeper (< 35 cm) when considering the agronomic interpretation of the soil acidity properties. Nevertheless, for both interpretations, the migration of neutralizing agents and its residual effect was greater when the liming dose was split and provided increased amelioration of soil pH, base saturation and aluminum saturation in deeper soil layers.

References

- Abreu Jr., C.H., Muraoka, T., Lavorante, A.F., 2003. Relationship between acidity and chemical properties of Brazilian soils. *Sci. Agric.* 60, 337–343. <http://dx.doi.org/10.1590/S0103-90162003000200019>.
- Alleoni, L.R.F., Cambri, M.A., Caires, E.F., 2005. Atributos químicos de um Latossolo de cerrado sob plantio direto, de acordo com doses e formas de aplicação de calcário. *Rev. Bras. Ciênc. Solo* 29, 923–934. <http://dx.doi.org/10.1590/S0100-06832005000600010>.
- Alleoni, L.R.F., Cambri, M.A., Caires, E.F., Garbuio, F.J., 2010. Acidity and aluminum speciation as affected by surface liming in tropical no-till soils. *Soil Sci. Soc. Am. J.* 74, 1010. <http://dx.doi.org/10.2136/sssaj2009.0254>.
- Amaral, A.S., Anghinoni, I., Deschamps, F.C., 2004a. Resíduos de plantas de cobertura e mobilidade dos produtos da dissolução do calcário aplicado na superfície do solo. *Rev. Bras. Ciênc. Solo* 28, 115–123. <http://dx.doi.org/10.1590/S0100-06832004000100012>.
- Amaral, A.S., Anghinoni, I., Hinrichs, R., Bertol, I., 2004b. Movimentação de partículas de calcário no perfil de um Cambissolo em plantio direto. *Rev. Bras. Ciênc. Solo* 28, 359–367. <http://dx.doi.org/10.1590/S0100-06832004000200014>.
- Azevedo, A.C., Kämpf, N., Bohnen, H., 1996. Alterações na dinâmica evolutiva de Latossolo Bruno pela calagem. *Rev. Bras. Ciênc. Solo* 20, 191–198.
- Barrow, N.J., 1999. The four laws of soil chemistry: the Leeper lecture 1998. *Aust. J. Soil Res.* 37, 787.
- Berwanger, A.L., 2006. Alterações e transferências de fósforo do solo para o meio aquático com o uso de dejetos líquido de suínos. Master Dissertation In: Soil Science. Federal University of Santa Maria, Brazil.
- Bortoluzzi, E.C., Parize, G.L., Korchagin, J., da Silva, V.R., Rheinheimer, D. dos S., Kaminski, J., 2014. Soybean root growth and crop yield in response to liming at the beginning of a no-tillage system. *Rev. Bras. Ciênc. Solo* 38, 262–271. <http://dx.doi.org/10.1590/S0100-06832014000100026>.
- Bortoluzzi, E.C., Pérez, C.A.S., Ardisson, J.D., Tiecher, T., Caner, L., 2015. Occurrence of iron and aluminum sesquioxides and their implications for the P sorption in subtropical soils. *Appl. Clay Sci.* 104, 196–204. <http://dx.doi.org/10.1016/j.clay.2014.11.032>.
- Briedis, C., Sá, J.C.D.M., Caires, E.F., Navarro, J.D.F., Inagaki, T.M., Boer, A., Neto, C.Q., Ferreira, A.D.O., Canalli, L.B., Santos, J.B. Dos, 2012. Soil organic matter pools and carbon-protection mechanisms in aggregate classes influenced by surface liming in a no-till system. *Geoderma* 170, 80–88. <http://dx.doi.org/10.1016/j.geoderma.2011.10.011>.
- Brown, A.G., Carey, C., Erkens, G., Fuchs, M., Hoffmann, T., Macaire, J.-J., Moldenhauer, K.-M., Walling, D.E., 2009. From sedimentary records to sediment budgets: multiple approaches to catchment sediment flux. *Geomorphology* 108, 35–47. <http://dx.doi.org/10.1016/j.geomorph.2008.01.021>.
- Caires, E.F., Chueiri, W.A., Madruga, E.F., Figueiredo, A., 1998. Alterações de características químicas do solo e resposta da soja ao calcário e gesso aplicados na superfície em sistema de cultivo sem preparo do solo. *Rev. Bras. Ciênc. Solo* 22, 27–34. <http://dx.doi.org/10.1590/S0100-06831998000100004>.
- Caires, E.F., Fonseca, A.F., Mendes, J., Chueiri, W.A., Madruga, E.F., 1999. Produção de milho, trigo e soja em função das alterações das características químicas do solo pela aplicação de calcário e gesso na superfície, em sistema de plantio direto. *Rev. Bras. Ciênc. Solo* 23, 315–327. <http://dx.doi.org/10.1590/S0100-06831999000200016>.
- Caires, E.F., Banzatto, D.A., Fonseca, A.F., 2000. Calagem na superfície em sistema plantio direto. *Rev. Bras. Ciênc. Solo* 24, 161–169. <http://dx.doi.org/10.1590/S0100-06832000000100018>.
- Caires, E.F., Feldhaus, I.C., Barth, G., Garbuio, F.J., 2002. Lime and gypsum application on the wheat crop. *Sci. Agric.* 59, 357–364. <http://dx.doi.org/10.1590/S0103-90162002000200023>.
- Caires, E.F., Blum, J., Barth, G., Garbuio, F.J., Kusman, M.T., 2003. Alterações químicas do solo e resposta da soja ao calcário e gesso aplicados na implantação do sistema plantio direto. *Rev. Bras. Ciênc. Solo* 27, 275–286. <http://dx.doi.org/10.1590/S0100-06832003000200008>.
- Caires, E.F., Barth, G., Garbuio, F.J., 2006a. Lime application in the establishment of a no-till system for grain crop production in Southern Brazil. *Soil Tillage Res.* 89, 3–12. <http://dx.doi.org/10.1016/j.still.2005.06.006>.
- Caires, E.F., Corrêa, J.C.L., Churka, S., Barth, G., Garbuio, F.J., 2006b. Surface application of lime ameliorates subsoil acidity and improves root growth and yield of wheat in an acid soil under no-till system. *Sci. Agric.* 63, 502–509. <http://dx.doi.org/10.1590/S0103-90162006000500013>.
- Caires, E.F., Garbuio, F.J., Alleoni, L.R.F., Cambri, M.A., 2006c. Calagem superficial e cobertura de aveia preta antecedendo os cultivos de milho e soja em sistema plantio direto. *Rev. Bras. Ciênc. Solo* 30, 87–98. <http://dx.doi.org/10.1590/S0100-06832006000100010>.
- Caires, E.F., Barth, G., Garbuio, F.J., Churka, S., 2008a. Soil acidity, liming and soybean performance under no-till. *Sci. Agric.* 65, 532–540. <http://dx.doi.org/10.1590/S0103-90162008000500013>.
- Caires, E.F., Garbuio, F.J., Churka, S., Barth, G., Corrêa, J.C.L., 2008b. 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. <http://dx.doi.org/10.1016/j.eja.2007.05.002>.
- Caires, E.F., Haliski, A., Bini, A.R., 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. <http://dx.doi.org/10.1016/j.eja.2015.02.008>.
- Calegari, A., Tiecher, T., Hargrove, W.L., Ralisch, R., Tessier, D., de Tourdonnet, S., Guimarães, M.D.F., dos Santos, D.R., 2013. Long-term effect of different soil management systems and winter crops on soil acidity and vertical distribution of nutrients in a Brazilian Oxisol. *Soil Tillage Res.* 133, 32–39. <http://dx.doi.org/10.1016/j.still.2013.05.009>.
- de Carvalho Filho, A., Inda, A.V., Fink, J.R., Curi, N., 2015. Iron oxides in soils of different lithological origins in Ferriferous Quadrilateral (Minas Gerais, Brazil). *Appl. Clay Sci.* 118, 1–7. <http://dx.doi.org/10.1016/j.clay.2015.08.037>.
- Casão Junior, R., Araújo, A.G., Llanillo, R., 2012. No-till Agriculture in Southern Brazil: Factors That Facilitated the Evolution of the System and the Development of the Mechanization of Conservation Farming. The Food and Agriculture Organization of the United Nations and Instituto Agronômico do Paraná.
- Castro, G.S.A., Crusciol, C.A.C., 2013. Effects of superficial liming and silicate application on soil fertility and crop yield under rotation. *Geoderma* 195–196, 234–242. <http://dx.doi.org/10.1016/j.geoderma.2012.12.006>.
- Costa, M.C.G., 2012. Soil and crop responses to lime and fertilizers in a fire-free land use system for smallholdings in the northern Brazilian Amazon. *Soil Tillage Res.* 121, 27–37. <http://dx.doi.org/10.1016/j.still.2012.01.017>.
- Costa, A., Rosolem, C.A., 2007. Liming in the transition to no-till under a wheat–soybean rotation. *Soil Tillage Res.* 97, 207–217. <http://dx.doi.org/10.1016/j.still.2007.09.014>.
- CQFS-RS/SC, 2016. Manual de Calagem e Adubação para os Estados do Rio Grande do Sul e Santa Catarina. (Liming and Fertilizing Manual for Rio Grande do Sul and Santa Catarina States). Núcleo Regional Sul da Sociedade Brasileira de Ciência do Solo, Frederico Westphalen.
- Crusciol, C.A.C., Artigiani, A.C.C.A., Arf, O., Carmeise Filho, A.C.A., Soratto, R.P., Nascente, A.S., Alvarez, R.C.F., 2016. Soil fertility, plant nutrition, and grain yield of upland rice affected by surface application of lime, silicate, and phosphogypsum in a tropical no-till system. *Catena* 137, 87–99. <http://dx.doi.org/10.1016/j.catena.2015.09.009>.
- Fageria, N.K., Baligar, V.C., 2008. Ameliorating soil acidity of tropical oxisols by liming for sustainable crop production. *Adv. Agron.* 99, 345–399. [http://dx.doi.org/10.1016/S0065-2113\(08\)00407-0](http://dx.doi.org/10.1016/S0065-2113(08)00407-0).
- Fink, J.R., Inda, A.V., Bayer, C., Torrent, J., Barrón, V., 2014. Mineralogy and phosphorus adsorption in soils of south and central-west Brazil under conventional and no-tillage systems. *Acta Sci. Agron.* 36, 379. <http://dx.doi.org/10.4025/actasciagron.v36i3.17937>.
- Fink, J.R., Inda, A.V., Bavaresco, J., Barrón, V., Torrent, J., Bayer, C., 2016. Adsorption and desorption of phosphorus in subtropical soils as affected by management system and mineralogy. *Soil Tillage Res.* 155, 62–68. <http://dx.doi.org/10.1016/j.still.2015.07.017>.
- Flower, K.C., 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 Crop Res.* 121, 75–87. <http://dx.doi.org/10.1016/j.fcr.2010.11.014>.
- Frageria, N.K., Nascente, A.S., 2014. Management of soil acidity of South American soils for sustainable crop production. *Adv. Agron.* 128, 221–275. <http://dx.doi.org/10.1016/B978-0-12-802139-2.00006-8>.
- Franchini, J.C., Meda, A.R., Cassiolato, M.E., Miyazawa, M., Pavan, M.A., 2001. Potencial de extratos de resíduos vegetais na mobilização do calcário no solo por método biológico. *Sci. Agric.* 58, 357–360. <http://dx.doi.org/10.1590/S0103-90162001000200020>.
- Franchini, J.C., Pavan, M.A., Miyazawa, M., 2004. Redistribution of phosphorus in soil through cover crop roots. *Braz. Arch. Biol. Technol.* 47, 381–386. <http://dx.doi.org/10.1590/S1516-89132004000300007>.
- Gatiboni, L.C., Kaminski, J., Rheinheimer, D.S., Brunetto, G., 2003. Superphosphate and rock phosphates as phosphorus sources for grass-clover pasture on a limed acid soil in southern Brazil. *Commun. Soil Sci. Plant Anal.* 34, 2503–2514. <http://dx.doi.org/10.1081/CSS-120024782>.

- IBSRAM, 1985. Acid Tropical Soils Management Network. International Board of Soil Research and Management, Bangkok, Tailândia.
- Joris, H.A.W., Caires, E.F., Schar, D.A., Bini, Â.R., Haliski, A., 2016. Liming in the conversion from degraded pastureland to a no-till cropping system in Southern Brazil. *Soil Tillage Res.* 162–177.
- Kaminski, J., Rheinheimer, D., Bartz, H., 2001. Proposta de nova equação para determinação do valor de H + Al pelo uso do índice SMP em solos do RS e SC. In: *Anais Da Reunião Anual Da ROLAS*, (Frederico Westphalen (RS)).
- Kaminski, J., dos Santos, D.R., Gatiboni, L.C., Brunetto, G., da Silva, L.S., 2005. Eficiência da calagem superficial e incorporada precedendo o sistema plantio direto em um argissolo sob pastagem natural. *Rev. Bras. Ciênc. Solo* 29, 573–580. <http://dx.doi.org/10.1590/S0100-06832005000400010>.
- Kidd, P.S., Proctor, J., 2001. Why plants grow poorly on very acid soils: are ecologists missing the obvious? *J. Exp. Bot.* 52, 791–799. <http://dx.doi.org/10.1093/jexbot/52.357.791>.
- Limousin, G., Tessier, D., 2007. Effects of no-tillage on chemical gradients and topsoil acidification. *Soil Tillage Res.* 92, 167–174. <http://dx.doi.org/10.1016/j.still.2006.02.003>.
- Martins, A.P., de Andrade Costa, S.E.V.G., Anghinoni, I., Kunrath, T.R., Balerini, F., Cecagno, D., Carvalho, P.C.D.F., 2014a. Soil acidification and basic cation use efficiency in an integrated no-till crop–livestock system under different grazing intensities. *Agric. Ecosyst. Environ.* 195, 18–28. <http://dx.doi.org/10.1016/j.agee.2014.05.012>.
- Martins, A.P., Anghinoni, I., Costa, S.E.V.G.d.A., Carlos, F.S., Nichel, G.D.H., Silva, R.A.P., Carvalho, P.C.D.F., 2014b. Amelioration of soil acidity and soybean yield after surface lime reapplication to a long-term no-till integrated crop–livestock system under varying grazing intensities. *Soil Tillage Res.* 144, 141–149. <http://dx.doi.org/10.1016/j.still.2014.07.019>.
- Nogueiro, R.C., Cerri, C.E.P., Da Silva, W.T.L., Alleoni, L.R.F., 2014. Effect of no-tillage and amendments on carbon lability in tropical soils. *Soil Tillage Res.* 143, 67–76. <http://dx.doi.org/10.1016/j.still.2014.05.014>.
- de Oliveira, E.L., Pavan, M.A., 1996. Control of soil acidity in no-tillage system for soybean production. *Soil Tillage Res.* 38, 47–57. [http://dx.doi.org/10.1016/0167-1987\(96\)01021-5](http://dx.doi.org/10.1016/0167-1987(96)01021-5).
- Pöttker, D., Ben, J.R., 1998. Calagem para uma rotação de culturas no sistema plantio direto. *Rev. Bras. Ciênc. Solo* 22, 675–684. <http://dx.doi.org/10.1590/S0100-06831998000400013>.
- Rheinheimer, D.S., Santos, E.J. da S., Kaminski, J., Xavier, F.M., 2000a. Aplicação superficial de calcário no sistema plantio direto consolidado em solo arenoso. *Cienc. Rural* 30, 263–268. <http://dx.doi.org/10.1590/S0103-84782000000200011>.
- Rheinheimer, D.S., Santos, E.J.S., Kaminski, J., Bortoluzzi, E.C., Gatiboni, L.C., 2000b. Alterações de atributos do solo pela calagem superficial e incorporada a partir de pastagem natural. *Rev. Bras. Ciênc. Solo* 24, 797–805. <http://dx.doi.org/10.1590/S0100-06832000000400012>.
- Shoemaker, H.E., McLean, E.O., Pratt, P.F., 1961. Buffer methods for determining lime requirement of soils with appreciable amounts of extractable aluminum. *Soil Sci. Soc. Am. J.* 25, 274. <http://dx.doi.org/10.2136/sssaj1961.03615995002500040014x>.
- da Silva, M.A.C., Natale, W., Prado, R. de M., Corrêa, M.C.M., Stuchi, E.S., Andrioli, I., 2007. Aplicação superficial de calcário em pomar de laranja pêssego em produção. *Rev. Bras. Frutic.* 29, 606–612. <http://dx.doi.org/10.1590/S0100-29452007000300036>.
- Soratto, R.P., Crusciol, C.A.C., 2008. Atributos químicos do solo decorrentes da aplicação em superfície de calcário e gesso em sistema plantio direto recém-implantado. *Rev. Bras. Ciênc. Solo* 32, 675–688. <http://dx.doi.org/10.1590/S0100-06832008000200022>.
- Tedesco, M.J., Gianello, C., Bissani, C., Bohnen, H., Volkweiss, S.J., 1995. *Análises de Solo, Planta e Outros Materiais*. Universidade Federal de Porto Alegre, Porto Alegre, RS.
- Tiecher, T., Calegari, A., Caner, L., Rheinheimer, D.D.S., 2017. Soil fertility and nutrient budget after 23-years of different soil tillage systems and winter cover crops in a subtropical Oxisol. *Geoderma* 308. <http://dx.doi.org/10.1016/j.geoderma.2017.08.028>.
- Tiritan, C.S., Büll, L.T., Crusciol, C.A.C., Carmes Filho, A.C.A., Fernandes, D.M., Nascente, A.S., 2016. Tillage system and lime application in a tropical region: Soil chemical fertility and corn yield in succession to degraded pastures. *Soil Tillage Res.* 155, 437–447. <http://dx.doi.org/10.1016/j.still.2015.06.012>.
- Tissi, J.A., Caires, E.F., Pauletti, V., 2004. Efeitos da calagem em semeadura direta de milho. *Bragantia* 63, 405–413. <http://dx.doi.org/10.1590/S0006-87052004000300010>.
- Veronese, M., Francisco, E.A.B., Zancanaro, L., Rosolem, C.A., 2012. Plantas de cobertura e calagem na implantação do sistema plantio direto. *Pesq. Agrop. Brasileira* 47, 1158–1165. <http://dx.doi.org/10.1590/S0100-204X2012000800017>.
- Weirich Neto, P.H., Caires, E.F., Justino, A., Dias, J., 2000. Correção da acidez do solo em função de modos de incorporação de calcário. *Cienc. Rural* 30, 257–261. <http://dx.doi.org/10.1590/S0103-84782000000200010>.
- Zambrosi, F.C.B., Alleoni, L.R.F., Caires, E.F., 2007. Teores de alumínio trocável e não trocável após calagem e gessagem em Latossolo sob plantio direto. *Bragantia* 66, 487–495. <http://dx.doi.org/10.1590/S0006-87052007000300016>.