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ORIGINAL PAPER

Correction of soil acidity with the cellulose industry residues in three andisols under wheat cultivation*

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Abstract

Soil acidity is one of the factors affecting agricultural productivity worldwide, and it is corrected with materials from carbonates or hydroxides of Ca and Mg of different origins, including products from the cellulose industry such as ash + dregs (AD) and ash + dregs + sludge (ADS). Field experiments in a split plot design were conducted to evaluate the cellulose industry residues on chemical properties associated with soil acidity in three volcanic soils in Chile, cultivated with wheat in the 2019-2020 season. Treatments included a control without amendment, $CaCO_3$ at an adjusted dose to achieve pH 6.0 (dose 1) and AD and ADS at dose 1 and double dose 1 (dose 2). Results indicated that AD and ADS in the three soils increased pH in the first 30 to 120 day after being applied, and achieved the same overall acidity correction effect at dose 1, with values that increased from pH 5.85 of control to 5.99 and 6.10, for dose 1 of AD and ADL respectively, at Santa Rosa location. In Carillanca location, the increase was from 5.52 of control to 6.27 and 6.24 for AD and ADL respectively, and in Remehue location – the soil reaction rose from pH 5.54 of Control to 5.91 and 5.89 for AD and ADL respectively (p<0.05). Using AD at dose 1 in the three soils had less effect on increased exchangeable Ca, but a greater effect on exchangeable Na and K concentrations. Using ADS at dose 1 showed a quantitatively lower effect on exchangeable Ca and higher exchangeable Mg and Na concentrations in soils. Results indicate that AD and ADS are an alternative to $CaCO_3$.

Keywords: soil acidity, cellulose residues, wheat crop, lime amendment

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INTRODUCTION

Soil acidity could be one of the main production factors in agriculture that affects the availability of some essential nutrients for plants, and increases the concentration of some nutrients that could cause toxicity and reduce productivity (Castro, Crusciol 2013, Fageria, Nascente 2014, Holland et al. 2019). The worldwide area affected by soil acidity is estimated at 30% (4000 million ha) of the total cultivated area (Sumner, Noble 2003, Kalkhoran et al. 2019).

Soil acidity can be divided into three components: (a) active acidity is the activity of H^+ ions in the soil solution expressed on a logarithmic scale, (b) exchangeable acidity is defined by the amount of Al^{3+} adsorbed to soil colloids, and (c) potential acidity ($H^+ + Al^{3+}$), which is the sum of active acidity and exchangeable acidity (Havlin et al. 1999, Ebeling et al. 2011, Moreira et al. 2015). Soil acidification is caused by different factors, including geological material of origin, rainfall, absorption of basic-reacting nutrients by the cultivated plants (physiological acidity), and the use of acid-reacting fertilizers (Havlin et al. 1999, Fageria, Nascente 2014, Kopec et al. 2021). In volcanic soils, it can cause greater plant productivity problems associated with Al and, in some cases, Mn toxicity (Havlin et al. 1999; Neall 2006).

The principal stdosegy to manage and control acidity is liming, which involves the application of calcium carbonate ($CaCO_3$) and calcium × magnesium carbonate ($CaCO_3 \cdot MgCO_3$) – de Vargas et al. (2019). This practice also directly benefits the soil, by increasing the concentration of available bases and nutrients, such as N, P, S, and Mo (Kostrzewska et al. 2022), improving the symbiotic fixation of N_2, and reducing the availability of Al, Fe, and Mn, which are toxic for plants at a high concentration (Fageria, Nascente 2014, Moreira et al. 2015, Kalkhoran et al. 2019). However, the most important effects of liming for surface applications are observed in the top 20 cm of soil (de Vargas et al. 2019, Li et al. 2019). Although incorporating liming materials such as $CaCO_3$ and $CaCO_3 \cdot MgCO_3$ while performing treatments related to stubble have shown greater in-depth movement, an effect on the chemical properties is limited to 40 cm in depth (de Vargas et al. 2019).

Biomass ash from the wood industry (primarily cellulose) is among the materials used to control soil acidity; it is characterized by basic reaction, and provides nutrients such as K, P, Mg, Ca, and micronutrients, while having a low content of heavy metals (Stankowski et al. 2018). These authors conducted an experiment on spring wheat, and pointed out that the application of ash from the wood industry at doses of 2, 4, and 6 Mg ha^{-1} produced a directly proportional increase in soil K, Ca, and Mn concentrations compared with the control without acidity neutralizing materials, but it had no effect on acidity control.

The objective of this study was to evaluate the effect of two lime amendments derived from a combination of ash, dregs and sludge from the cellulose industry on chemical properties in three volcanic soils in Chile.

MATERIALS AND METHODS

The experiment was conducted under field conditions during the 2019-2020 season at three locations, with the same volcanic soil type, but under different climatic conditions: 1) Santa Rosa Experimental Station (36º31′ S; 71º54′ W), INIA-Quilamapu, Chillán, Chile, with Melanoxerand soil and chemical properties of pH 5.6 (1:2.5 soil:water) and exchangeable Ca, Mg, K, Na, and Al values of 4.55, 0.42, 0.50, 0.12, and 0.08 $cmol_+ kg^{-1}$, respectively. The climate is temperate Mediterranean, characterized by a hot dry summer and cold wet winter. Precipitation was concentrated in winter and spring reaching 460 mm, 13.4°C mean temperature, and 980 mm evaporation; 2) INIA-Carillanca Experimental Station, Temuco, Chile (38°41′ S, 72°25′ W), with Hapludands soil and chemical properties of pH 5.2 (1:2.5 soil:water) and exchangeable Ca, Mg, K, Na, and Al values of 4.70, 0.83, 0.81, 0.03, and 0.08 $cmol_+ kg^{-1}$, respectively. The climate at Carillanca is typically temperate with monthly maximum and minimum mean temperatures of 11.1 and 2.5°C, respectively, in the cooler months. In the warmer months, the maximum and minimum mean temp. were 24.5 and 8.4°C, respectively. Precipitation was concentrated in autumn and spring at 925 mm and 716 mm evaporation; and 3) Remehue Experimental Station (40°31′ S, 73°03′ W), INIA-Remehue, Osorno, Chile, with an Andisols soil from the Osorno soil series (Typic Hapludans) and chemical properties of pH 5.4 (1:2.5 soil:water) and exchangeable Ca, Mg, K, Na, and Al values of 2.28, 0.81, 1.39, 0.15, and 0.56 $cmol_+ kg^{-1}$, respectively. The climate is temperate Mediterranean, characterized by hot dry summer and cold wet winter. Annual rainfall at the experimental site in 2019 was 910.4 mm, the mean daily minimum and maximum temp. were 4.3 and 13.1°C in winter and 7.3 and 20.4°C in summer, respectively, and there was 692.3 mm evaporation (Agrometeorologia 2020, USDA 2014).

Wheat (*Triticum aestivum* L.) cv. Rocky-INIA was cultivated at the three locations. There were three acidity correction materials, boiler ash + dregs (AD), boiler ash + dregs + sludge (ADS), and commercial calcium carbonate ($CaCO_3$) as a reference (Soprocal). The AD and ADS materials were obtained from the CMPC Pulp Company, a factory plant located in Santa Fe, Biobío Region, Chile. The characterization of the acidity correction materials is shown in Table 1. The $CaCO_3$ reference dose was determined under laboratory conditions (determination of soil buffering power) to obtain water pH 6.0 (Sadzawka et al. 2006), which was defined as dose 1. In addition, the acidity correction materials AD and ADS were used at the same dose as the $CaCO_3$ reference and at twice dose 1 (dose 2), although the neutralizing power of these two materials was lower than $CaCO_3$ (Table 1). The evaluated treatments at each location were the following: (1) Control without any application of soil acidity correction materials, (2) AD dose 1 to reach water pH 6.0 in each soil, (3) AD dose 2, equivalent to twice dose 1 used in each

Table 1

Chemical characterization of soil acidity neutralizing materials

Technical information	Boiler ash + dregs (AD)	Boiler ash + dregs + lime sludge (ADS)	$CaCO_3$ (Soprocal)
Water pH	12.01	12.10	12.40
Moisture (%)	5.53	5.83	< 0.50
Neutralizing power (%)	60.0	61.0	90.0
CaO (%)	30.22	31.95	51.4
MgO (%)	3.43	3.11	0.95
Na (%)	3.8	3.19	nd
K_2O (%)	1.35	1.32	nd
P_2O_5 (%)	0.83	0.92	nd
S (%)	0.72	0.71	nd
Fe (%)	1.79	1.76	nd
Mn (%)	0.53	0.48	nd
B (mg kg^{-1})	41.0	40.3	nd
Cu (mg kg^{-1})	76.2	68.1	nd
Zn (mg kg^{-1})	239.4	223.6	nd

nd – not determined

soil, (4) ADS dose 1 to reach pH 6.0 in each soil, (5) ADS dose 2, equivalent to twice dose 1 used in each soil, and (6) commercial $CaCO_3$ at the dose necessary to reach water pH 6.0 in each soil (dose 1). The doses of the acidity correction materials for each soil and treatment are shown in Table 2. Each treatment had three replicates. All the treatments were applied between 5 and 30 May 2019, 30 d before sowing the wheat crop, and starting in the areas with earlier rainfall. The size of each experimental unit was 25 m^2 (5 m wide × 5 m long), and the experimental area at each study site was 450 m^2.

The crop was sown on 5, 15, and 30 June 2019 at the Remehue, Carillanca, and Santa Rosa locations, respectively, and agronomic management was typical for this crop under irrigated valley conditions. To determine the evolution of the soil chemical properties in terms of the acidity or basicity indicators, soils were sampled from the 0-20 cm depth on 0, 15, 30, 60, 120, 180, 240, and 360 d after applying the acidity correction materials. The soil chemical properties that were determined included pH, Ca, Mg, K, Na, exchangeable Al, effective cationic exchange capacity (CECe), and Al saturation. Composite samples were collected manually from the 0-20 cm soil depth to analyze the soil's chemical properties. All samples were air-dried and sieved (2 mm mesh). Soil pH was determined in 1:2.5 soil:water extracts. Soil extractable P was 0.5 M $NaHCO_3$ (Olsen P) according to the molybdate-ascorbic acid method. Exchangeable Ca, Mg, K, and Na were determined

Table 2

Doses of acidity neutralizing materials used in each soil and treatment

Acidity neutralizing material treatments	Dose of acidity neutralizing material (Mg ha^{-1})		
	Santa Rosa	Carillanca	Remehue
AD dose 1	3.11	8.51	6.82
AD dose 2	6.22	17.02	13.64
ADS dose 1	3.11	8.51	6.82
ADS dose 2	6.22	17.02	13.64
$CaCO_3$	3.11	8.51	6.82

AD – boiler ash + dregs, ADS – boiler ash + dregs + lime sludge, dose 1 – $CaCO_3$ reference dose, dose 2 – 2 × dose 1

by 1 M NH_4OAc extraction followed by flame spectroscopy: absorption (Ca and Mg) and emission (K and Na). Soil exchangeable Al concentration was found by 1 M KCl extraction according to absorption spectroscopy. The CECe was determined as the sum of Ca, Mg, K, Na, and Al. The Al saturation (%) was determined as the ratio between exchangeable Al and CECe multiplied by 100. The total nutrient content analyses for the material that controls soil acidity were performed according to Erich, Ohno (1992) and ASTM (2019).

At each location, the experimental design was a split plot with three replicates; the main plot was the sample time and the split plot was the treatment where the material for soil acidity control was applied. Results were analyzed by ANOVA and the Tukey's test (p=0.05) in the SAS PROC MIXED Model procedure (SAS 1989).

RESULTS AND DISCUSSION

The analysis of significance indicated an effect of the evaluation time for all the determined chemical properties in the three volcanic soils, except exchangeable Ca, Al, and Al saturation at the Remehue location (Table 3). The applied treatments showed significant effects on all the evaluated chemical properties and soils (Table 3). Few interactions were found between evaluation time and the treatment of the acidity correction materials (Table 3). Soil interactions occurred with exchangeable Ca and Na, exchangeable Al and Al saturation, and exchangeable Na at the Santa Rosa, Carillanca, and Remehue locations, respectively (Table 3). In this type of experiments, interactions are typically reported between evaluation time and the treatment effect (Hirzel et al. 2016, 2018). Values for soil chemical properties at the Santa Rosa location were generally similar to those indicated by Undurraga et al. (2009) and Hirzel et al. (2020) for the same study area.

Wheat yield results were reported by Hirzel et al. (2020); all soils

Table 3

Analysis of significance for the evolution of the soil chemical properties at the three locations under study

Santa Rosa			
Chemical parameter	time	Treatment	Interaction
pH	**	**	ns
Exchangeable Ca	*	**	*
Exchangeable Mg	**	**	ns
Exchangeable K	**	**	ns
Exchangeable Na	**	**	**
Exchangeable Al	**	**	ns
Al saturation	**	**	ns
Carillanca			
Chemical parameter	time	treatment	interaction
pH	**	**	ns
Exchangeable Ca	**	**	ns
Exchangeable Mg	**	**	ns
Exchangeable K	**	**	ns
Exchangeable Na	**	**	ns
Exchangeable Al	**	**	**
Al saturation	**	**	**
Remehue			
Chemical parameter	time	treatment	interaction
pH	**	**	ns
Exchangeable Ca	ns	**	ns
Exchangeable Mg	**	**	ns
Exchangeable K	**	**	ns
Exchangeable Na	**	**	**
Exchangeable Al	ns	**	ns
Al saturation	ns	**	ns

* significant (p<0.05), ** highly significant (p<0.01), ns – non-significant (p>0.05)

showed a positive effect of acidity correction treatments compared with the control. There were no yield differences when using AD and ADS at both doses compared with $CaCO_3$, and the values of grain yield in the treatments with amendments fluctuated between 9.9 to 10.4 Mg ha^{-1} in Santa Rosa; 5.4 to 6.5 Mg ha^{-1} in Carillanca; and 9.5 to 10.3 Mg ha^{-1} in Remehue (data not shown).

The evolution of pH was different in the three evaluated soils (Figures 1*a*, *b*, *c*). The pH at the Santa Rosa location increased during the first 30 d, and this value was maintained until day 360, with only slight

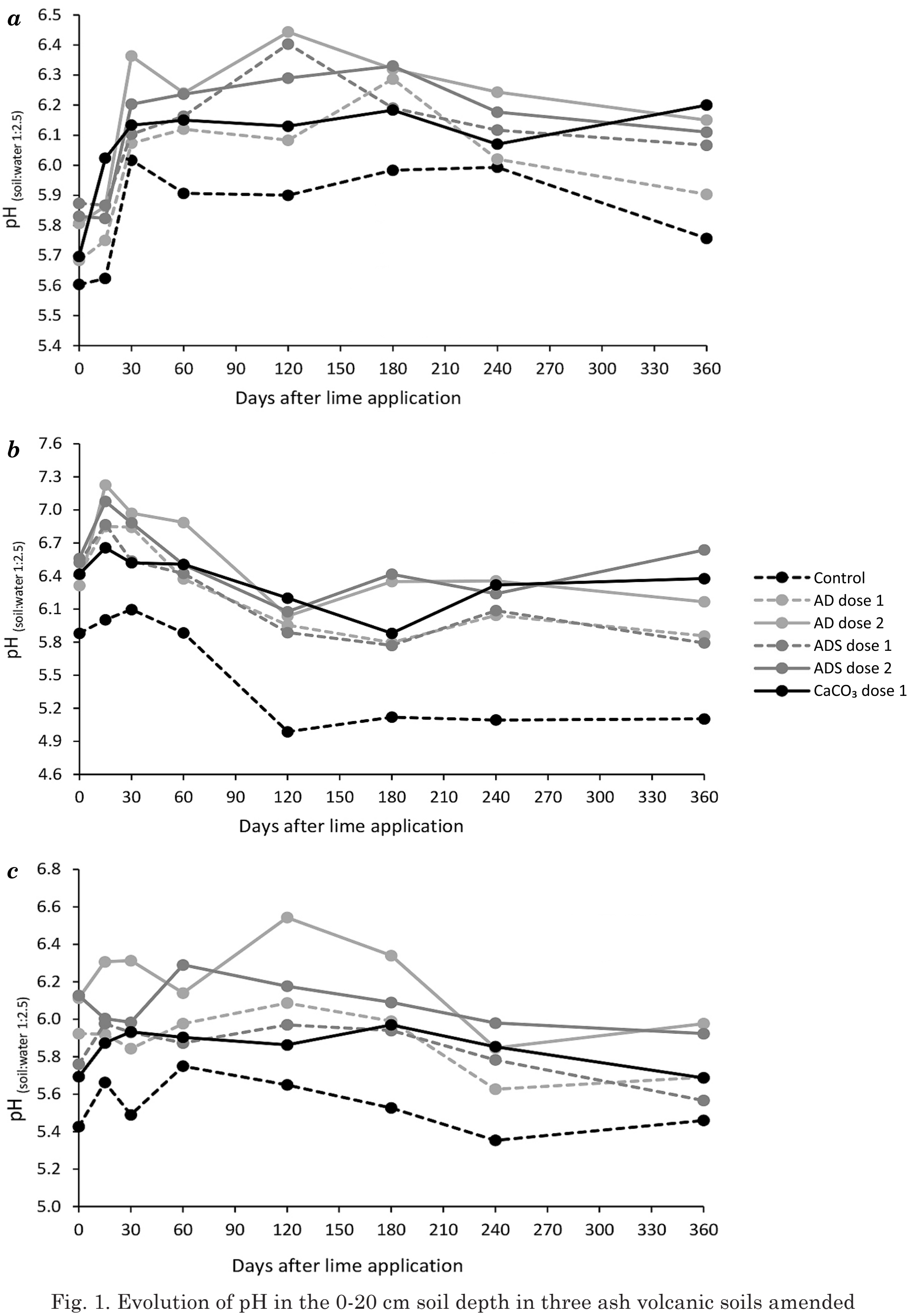

Fig. 1. Evolution of pH in the 0-20 cm soil depth in three ash volcanic soils amended with different soil acidity correction materials; Locations: *a)* – Santa Rosa, *b)* – Carillanca, and *c)* – Remehue; AD – boiler ash + dregs, ADS – boiler ash + dregs + lime sludge, dose 1 – $CaCO_3$ reference dose, dose 2 – 2 × dose 1

variations (Figure 1*a*). Some increases were observed on day 120 with AD dose 2 and ADS dose 1, while a marked decrease in pH occurred from day 180 with AD dose 1 or an increase between days 240 and 360 with $CaCO_3$ (Figure 1*a*). However, the highest pH mean values for the entire experiment and overall behavior of the pH evolution in this soil were obtained with AD dose 2 (p<0.05) – Table 4. All the treatments that received soil acidity

Table 4

Soil chemical properties as the mean of evaluation time in the three ash volcanic soils

Santa Rosa						
Chemical parameter	Control	AD dose 1	AD dose 2	ADL dose 1	ADL dose 2	$CaCO_3$ dose 1
pH	5.85 *d*	5.99 *c*	6.18 *a*	6.10 *ab*	6.13 *ab*	6.07 *bc*
Exchangeable Ca	4.02 *c*	4.65 *bc*	5.81 *a*	5.36 *ab*	5.48 *a*	6.09 *a*
Exchangeable Mg	0.34 *b*	0.41 *a*	0.45 *a*	0.42 *a*	0.44 *a*	0.43 *a*
Exchangeable K	0.47 *a*	0.48 *a*	0.48 *a*	0.42 *b*	0.44 *ab*	0.42 *b*
Exchangeable Na	0.08 *d*	0.23 *c*	0.44 *a*	0.28 *bc*	0.30 *b*	0.10 *d*
Exchangeable Al	0.08 *a*	0.06 *b*	0.03 *c*	0.05 *bc*	0.04 *c*	0.04 *c*
Al saturation	1.75 *a*	1.03 *b*	0.50 *c*	0.75 *bc*	0.67 *c*	0.67 *c*
Carillanca						
Chemical parameter	Control	AD dose 1	AD dose 2	ADL dose 1	ADL dose 2	$CaCO_3$ dose 1
pH	5.52 *b*	6.27 *a*	6.54 *a*	6.24 *a*	6.55 *a*	6.36 *a*
Exchangeable Ca	3.61 *c*	11.21 *bc*	16.18 *a*	11.79 *ab*	14.87 *ab*	17.04 *a*
Exchangeable Mg	0.61 *d*	1.19 *ab*	1.31 *a*	0.99 *bc*	1.10 *ab*	0.79 *cd*
Exchangeable K	0.60 *bc*	0.86 *a*	0.86 *a*	0.70 *abc*	0.79 *ab*	0.52 *c*
Exchangeable Na	0.04 *c*	1.32 *a*	2.09 *a*	0.98 *ab*	1.54 *a*	0.06 *b*
Exchangeable Al	0.08 *a*	0.02 *b*	0.01 *b*	0.02 *b*	0.01 *b*	0.02 *b*
Al saturation	1.73 *a*	0.19 *b*	0.11 *b*	0.19 *b*	0.09 *b*	0.10 *b*
Remehue						
Chemical parameter	Control	AD dose 1	AD dose 2	ADL dose 1	ADL dose 2	$CaCO_3$ dose 1
pH	5.54 *c*	5.91 *b*	6.23 *a*	5.89 *b*	6.09 *b*	5.87 *b*
Exchangeable Ca	2.62 *c*	5.40 *b*	8.99 *a*	5.44 *b*	8.66 *a*	8.44 *a*
Exchangeable Mg	0.84 *cd*	1.01 *b*	1.18 *a*	0.97 *b*	0.94 *bc*	0.80 *c*
Exchangeable K	1.30 *b*	1.26 *bc*	1.41 *ab*	1.49 *a*	1.11 *cd*	0.98 *d*
Exchangeable Na	0.12 *d*	0.53 *c*	1.15 *a*	0.42 *c*	0.73 *b*	0.09 *d*
Exchangeable Al	0.46 *a*	0.15 *bc*	0.08 *c*	0.19 *b*	0.08 *c*	0.11 *bc*
Al saturation	9.04 *a*	1.94 *bc*	0.98 *cd*	2.49 *b*	0.80 *d*	1.23 *cd*

AD – boiler ash + dregs, ADS – boiler ash + dregs + lime sludge, dose 1 – $CaCO_3$ reference dose, dose 2 – 2 × dose 1.

Different letters in the same row indicate statistical differences according to the Tukey's test (p<0.05).

neutralizing materials reached a higher pH than the control (Table 4, Figure 1*a*). At the Carillanca location, pH increased in the first 15 d in most treatments (except the control), decreased until day 120, and later showed a slight increase in some treatments (Figure 1*b*). All the treatments with soil acidity neutralizing materials reached the same pH mean value for the evaluation period (p>0.05), which was higher than the control (p<0.05) – Table 4. At the Remehue location, there was an erratic effect of increased or decreased pH in the treatments until day 120, a drop in pH until day 240, and thereafter further erratic effects until the end of the evaluation period (Figure 1*c*). The highest pH mean for the evaluation period was obtained with AD dose 2 (p<0.05), and pH in all the treatments was higher than in the control (p<0.05) – Table 4. Long-term studies usually indicate a gradual increase in pH over time as the result of applying acidity correction materials (Castro, Crusciol 2013, Caires et al. 2015), especially when using high lime doses (> 2 Mg ha^{-1}) and because lime solubility depends on rainfall and irrigation (Fageria, Nascente 2014). When this effect has been measured in different soil strata (0-5, 5-10, 10-20 cm), this increase is higher at the soil surface layer (Castro, Crusciol 2013, Caires et al. 2015, de Vargas et al. 2019). The erratic effects for pH during some of the evaluation period in some of the soils evaluated in this experiment can be explained by differences in rainfall in each study area, given that there is a distance of 600 km between the extreme locations of the study area (Santa Rosa and Remehue).

The evolution of exchangeable Ca was also different in the three evaluated soils (Figures 2*a*, *b*, *c*). The most erratic effects occurred at the Santa Rosa location (Figure 2*a*), which were also detected in the significant interaction between treatments and evaluation time (Table 3). The most stable effects occurred at the Carillanca location (Figure 2*b*). Interaction effects between evaluation time and treatments for this type of experiment has been mentioned by some authors (Hirzel et al. 2016, Hirzel et al. 2018). The highest exchangeable Ca mean for the entire evaluation period for the soil at the Santa Rosa location occurred in treatments AD dose 2, ADS dose 2, and $CaCO_3$ (p<0.05); all treatments surpassed the control, except AD dose 1 (p>0.05) – Table 4. In the soil at the Carillanca location, the highest exchangeable Ca was obtained with AD dose 2 and $CaCO_3$ (p<0.05), and all the treatments surpassed the control (p<0.05) – Table 4. All the treatments in the soil at the Remehue location and the mean of the evaluation period surpassed the control (p<0.05); the highest exchangeable Ca was obtained with AD dose 2, ADS dose 2, and $CaCO_3$ (p<0.05) – Table 4. The highest concentration of Ca in $CaCO_3$, which was used as a reference in the present study (Table 1), for AD and ADS at the same dose was confirmed in the soil exchangeable Ca concentration for the treatments of acidity correction materials at the Remehue location, while only partially at the other locations. This can be explained by the buffering capacity of each soil and the low initial soil exchangeable Ca concentration at the Remehue location compared with the other two locations (Havlin Beatonand 1999, Neall 2006). Various

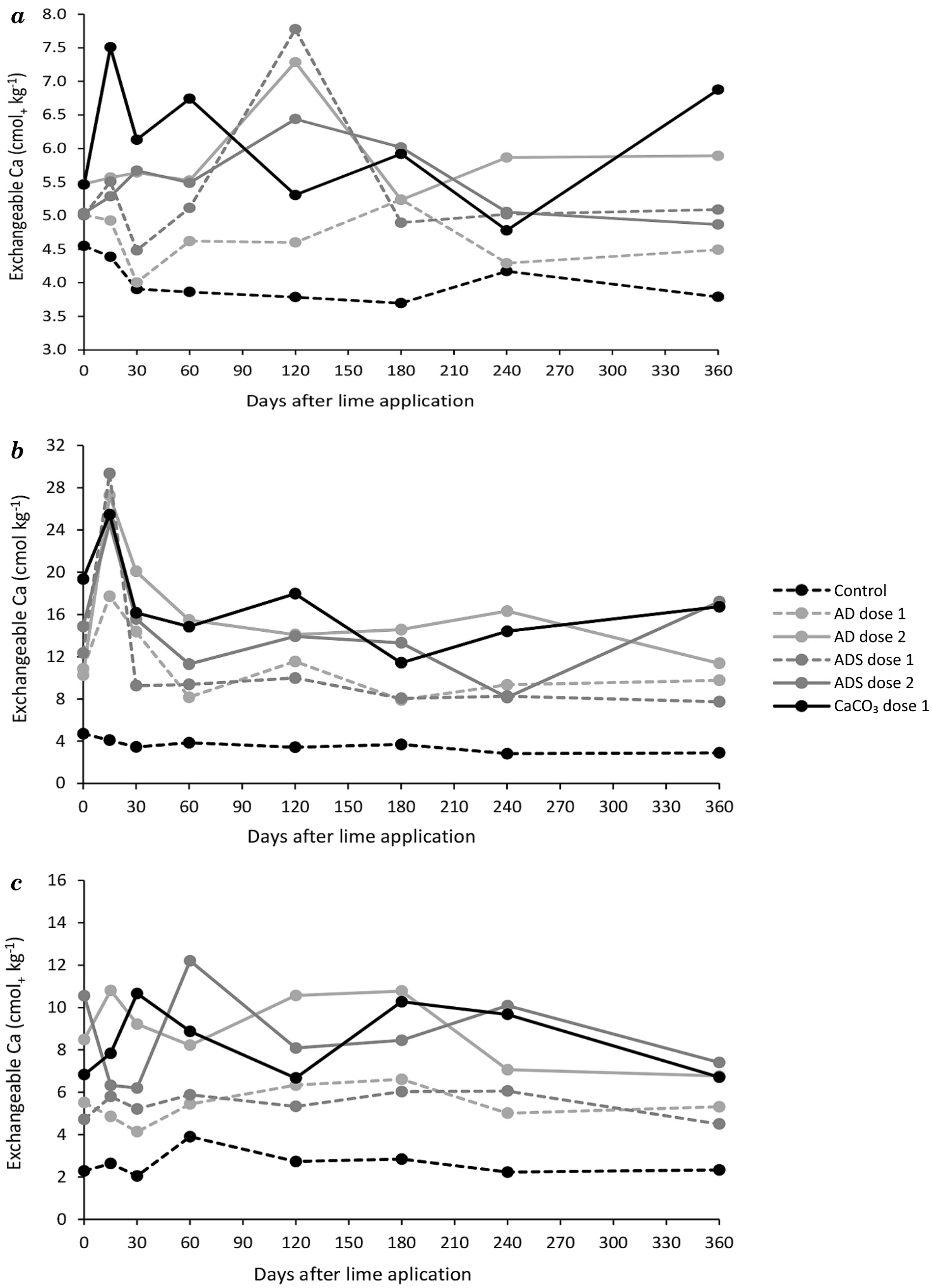

Fig. 2. Exchangeable calcium (Ca) evolution in the 0-20 cm soil depth in three ash volcanic soils amended with different soil acidity correction materials; Locations: *a)* – Santa Rosa, *b)* – Carillanca, and *c)* – Remehue; AD – boiler ash + dregs, ADS – boiler ash + dregs + lime sludge, dose 1 – $CaCO_3$ reference dose, dose 2 – 2 × dose 1

authors have indicated the positive effect of increased exchangeable Ca when using lime (Castro, Crusciol 2013, de Vargas et al. 2019), which is associated with the Ca content in these products (Table 1).

Exchangeable Mg increased in the first 15 d, subsequently dropped, and varied slightly during the rest of the evaluation period at the Santa Rosa (Figure 3*a*) and Carillanca (Figure 3*b*) locations. Exchangeable Mg values at the Remehue location were more stable during the entire evaluation period, except on days 180 and 240 for some treatments (Figure 3*c*). The mean of all the treatments of the evaluation period (Table 4) for the soil at the Remehue location surpassed the control (p<0.05), and there was no difference between them (p>0.05). In the soil at the Carillanca location, all treatments with AD and ADS at both doses surpassed the control (p<0.05). In the soil at the Remehue location, only the AD treatments at both doses and ADS dose 1 surpassed the control (p<0.05). The exchangeable Mg concentration at the Carillanca and Remehue locations was similar to the control (p>0.05) – Table 4. The contribution of Mg in AD and ADS compared with $CaCO_3$ was observed only in the soil at the Remehue location and partially at the other locations; this was likely associated with the high dose of AD and ADS used at the Remehue location compared with the Santa Rosa location. However, a similar effect was expected at the Carillanca location, where the AD and ADS dose was also high. Some studies have demonstrated a higher concentration of soil exchangeable Mg when using liming materials that contribute Mg compared with using $CaCO_3$ (Castro, Crusciol 2013, de Vargas et al. 2019).

Overall, exchangeable K in all the soils decreased from day 15 after the start of the experiment (Figures 4*a*, *b*, *c*), and this was noted more at the Santa Rosa (Figure 4*a*) and Carillanca (Figure 4*b*) locations. The mean effect of the evaluation period was different in the three soils (Table 4). In the soil at the Santa Rosa location, the highest exchangeable K concentration was obtained in the control and AD at both doses (p<0.05). In the soil at the Carillanca location, the highest exchangeable K concentration was obtained with AD at both doses (p<0.05). In the soil at the Remehue location, the highest value was obtained with ADS dose 1. The use of $CaCO_3$ in the three soils generated lower exchangeable K, although it was consistently lower only at the Remehue location than with AD and ADS at the same dose (Table 4). This lower value of exchangeable K obtained with $CaCO_3$ at the same dose as AD and ADS is associated with the K contribution with these two acidity correction materials (Table 1), which could be quantitatively important at the Carillanca and Remehue locations (Table 2). Moreover, the volcanic soils showed significant K desorption (Havlin et al. 1999, Neall 2006), which, in addition to the fertilization used in the crop, could mask significant effects of the contribution of this element with AD and ADS. Castro, Crusciol (2013) and Moreira et al. (2015) found no differences in the exchangeable K concentration when using soil acidity correction materials

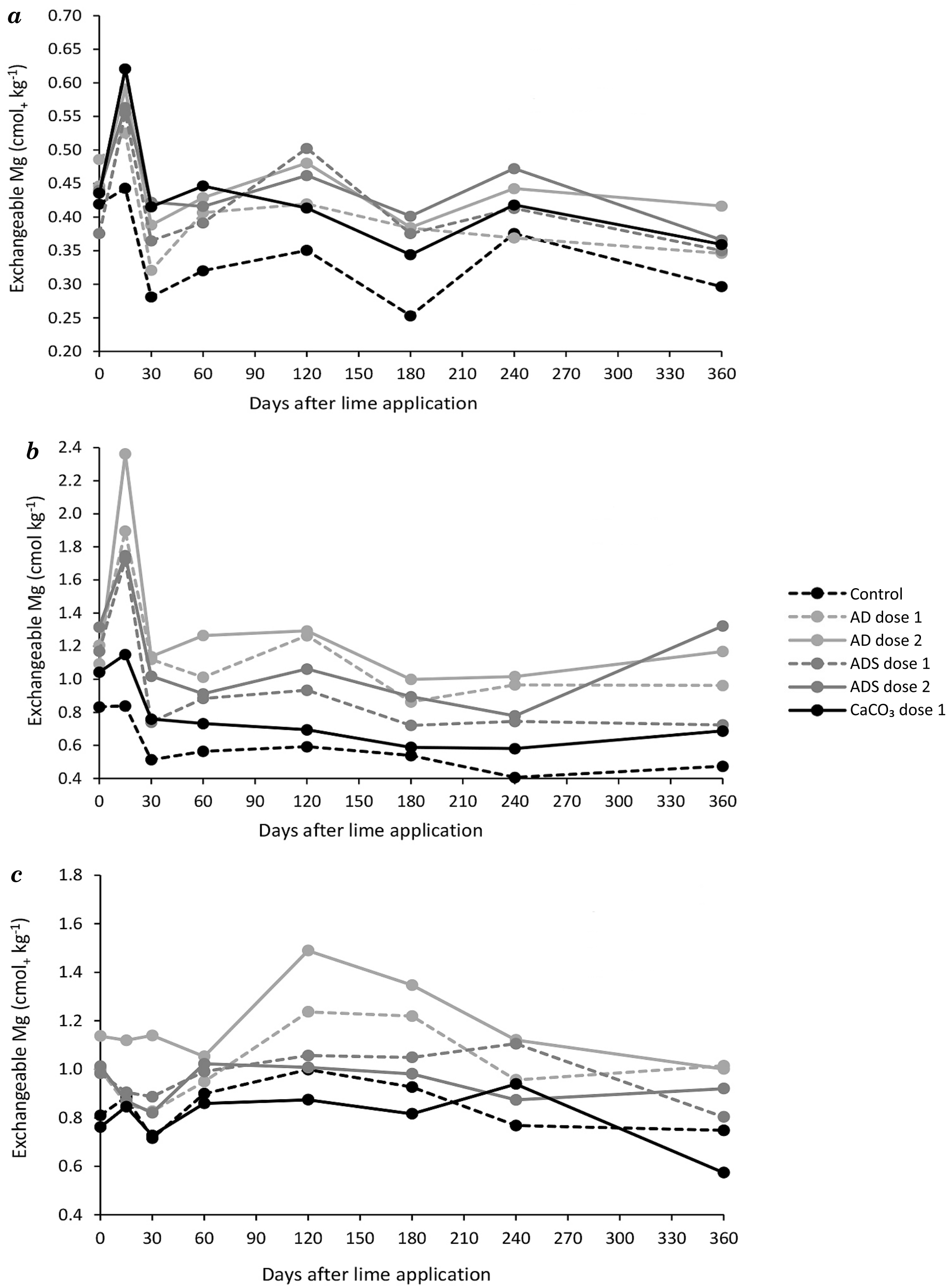

Fig. 3. Exchangeable magnesium (Mg) evolution in the 0-20 cm soil depth in three ash volcanic soils amended with different materials for soil acidity correction; Locations: *a)* – Santa Rosa, *b)* – Carillanca, and *c)* – Remehue; AD – boiler ash + dregs, ADS – boiler ash + dregs + lime sludge, dose 1 – $CaCO_3$ reference dose, dose 2 – 2 × dose 1

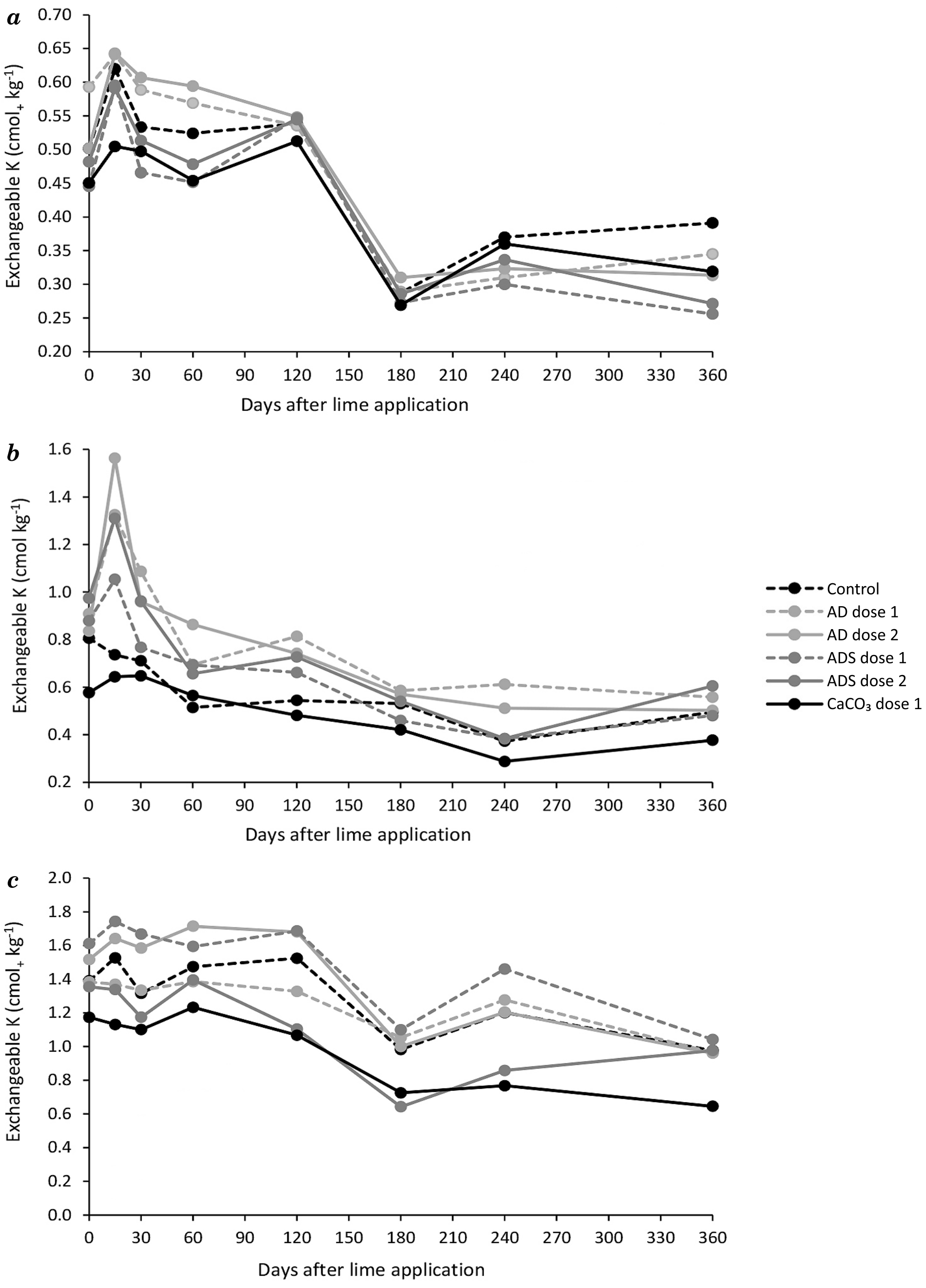

Fig. 4. Exchangeable potassium (K) evolution in the 0-20 cm soil depth in three ash volcanic soils amended with different soil acidity correction materials; Locations: *a)* – Santa Rosa, *b)* – Carillanca, and *c)* – Remehue; AD – boiler ash + dregs, ADS – boiler ash + dregs + lime sludge, dose 1 – $CaCO_3$ reference dose, dose 2 – 2 × dose 1

that did not contribute K. Moore, Ouimet (2014) showed erratic effects of different lime doses on soil exchangeable K.

The evolution of exchangeable Na showed an increase until day 15 in the soils at the Santa Rosa and Carillanca locations and in some treatments in the soil of the Remehue location, and later dropped for the rest of the evaluation period (Figures 5*a*, *b*, *c*). The soil at the Santa Rosa location showed erratic effects between days 30 and 180 of the evaluation, while effects were slightly erratic in the soil at the Remehue location between days 120 and 240 of the evaluation, which were detected in the interaction of the analysis of significance (Table 3). The mean of all the treatments with AD and ADS in the evaluation period and in the three soils surpassed the control (p<0.05); there was a directly proportional effect of the dose being used in the soils at the Santa Rosa and Remehue locations (Table 4), and the control had the same exchangeable Na value as $CaCO_3$ (p>0.05). The contribution of Na when using AD and ADS compared with $CaCO_3$ at the same dose was only consistently demonstrated at the Santa Rosa and Remehue locations (Table 4); this is likely associated with the buffering capacity of the soil at the Carillanca location. This buffering capacity was also expected in the other two soils, as it has been described for this characteristic in volcanic soils (Havlin et al. 1999, Neall 2006). Other studies with acidity neutralizing materials on exchangeable Na concentration and studies about the incubation of volcanic soils with $CaCO_3$ and $CaCO_3 \cdot MgCO_3$ at different doses showed no effects on exchangeable Na (Hirzel et al. 2016). Likewise, the absence of the effect of lime application at different doses on soil exchangeable Na in field experiments has been reported by Moore, Ouimet (2014).

Overall, there were few changes in exchangeable Al in the three soils during the evaluation period (Figures 6*a*, *b*, *c*), except for the control, where the exchangeable Al concentration gradually increased over time, and it was more noticeable in the soil at the Carillanca location (Figure 6*b*). The mean of all the treatments in the evaluation period and in the three soils exhibited a lower Al concentration than in the control (p<0.05) – Table 4. For the three soils in general, using AD and ADS at both doses resulted in an exchangeable Al concentration similar to the one achieved by using $CaCO_3$ (p>0.05) – Table 4. There was an inversely proportional relationship between the AD and ADS dose and exchangeable Al (Table 4). Effects on the exchangeable Al concentration when applying different soil acidity correction materials have been reported by several authors (Caires et al. 2015, Moreira et al. 2015, Hirzel et al. 2016). The inversely proportional effect between soil exchangeable Al and soil pH has been described by Hirzel et al. (2016).

The Al saturation in the three soils (Figures 7*a*, *b*, *c*) was similar to the evolution described for exchangeable Al (Figures 6*a*, *b*, *c*). The mean of all the treatments in the evaluation period and in the three soils had lower Al saturation than the control (p<0.05) – Table 4, and the use of AD and

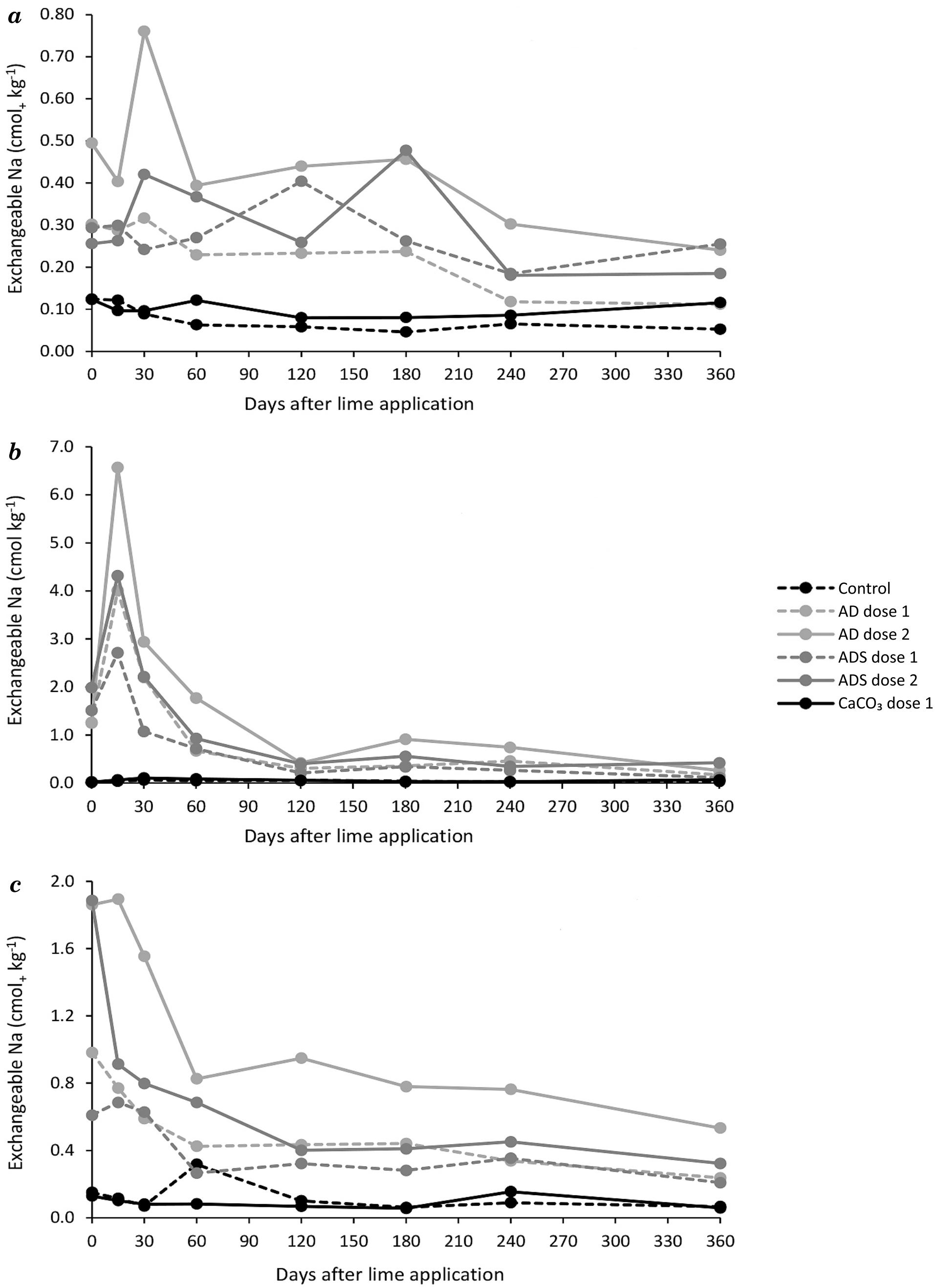

Fig. 5. Exchangeable sodium (Na) evolution in the 0-20 cm soil depth in three ash volcanic soils amended with different soil acidity correction materials; Locations: *a)* – Santa Rosa, *b)* – Carillanca, and *c)* – Remehue; AD – boiler ash + dregs, ADS – boiler ash + dregs + lime sludge, dose 1 – $CaCO_3$ reference dose, dose 2 – 2 × dose 1

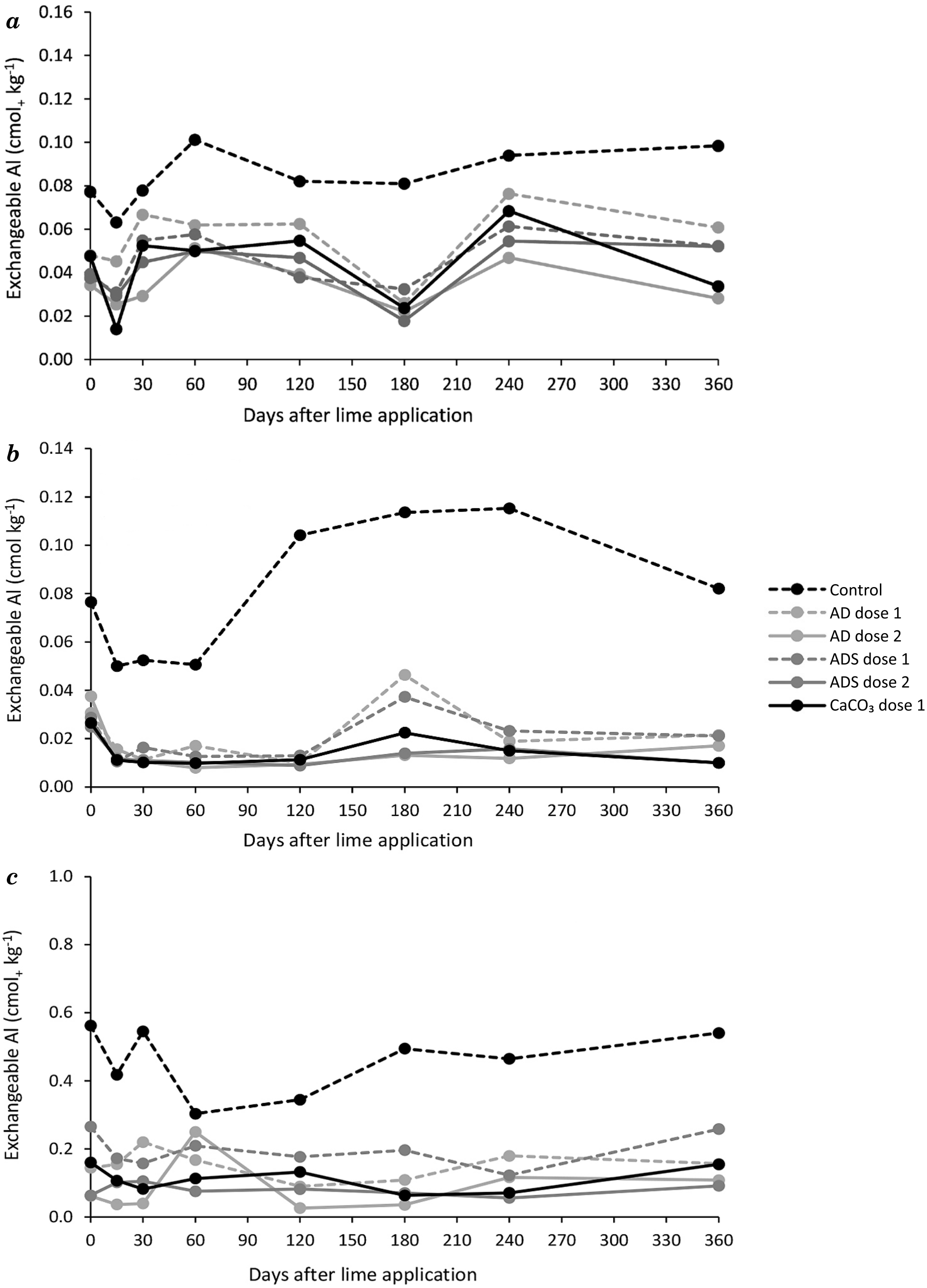

Fig. 6. Exchangeable aluminum (Al) evolution in the 0-20 cm soil depth in three ash volcanic soils amended with different soil acidity correction materials; Locations: *a)* – Santa Rosa, *b)* – Carillanca, and *c)* – Remehue; AD – boiler ash + dregs, ADS – boiler ash + dregs + lime sludge, dose 1 – $CaCO_3$ reference dose, dose 2 – 2 × dose 1

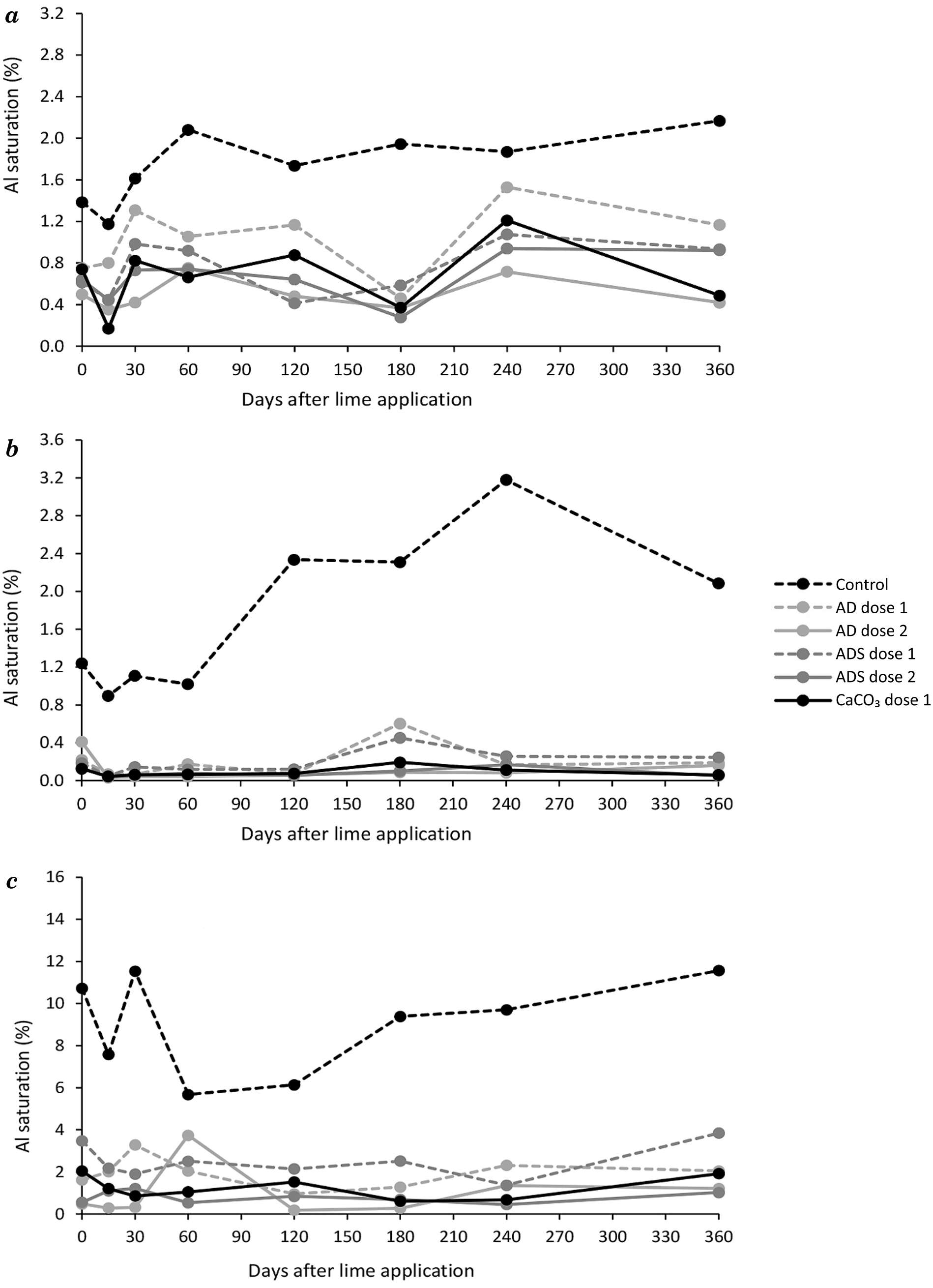

Fig. 7. Aluminum (Al) saturation evolution in the first 0.2 m soil depth in three ash volcanic soils amended with different soil acidity correction materials; Locations: *a)* – Santa Rosa, *b)* – Carillanca, and *c)* – Remehue; AD – boiler ash + dregs, ADS – boiler ash + dregs + lime sludge, dose 1 – $CaCO_3$ reference dose, dose 2 – 2 × dose 1

ADS at both doses in the three soils showed Al saturation similar to the $CaCO_3$ treatment ($p>0.05$) – Table 4. Just as for exchangeable Al in the soils at the Santa Rosa and Remehue locations, there was an inversely proportional relationship between the AD and ADS dose being used and Al saturation (Table 4). Moore, Ouimet (2014) has mentioned a directly proportional increase between the saturation of the soil bases (inverse effect to Al saturation) and the applied lime dose; these results concur with those obtained in our study.

CONCLUSIONS

The results of the present study indicated that using boiler ash + dregs (AD) and boiler ash + dregs + sludge (ADS) in three Andisols soils increased pH in the first 30 to 120 d after their application. Overall, at the same dose as $CaCO_3$, they achieved the same acidity correction effect (pH), exchangeable Al, and Al saturation, although there was no consistent effect on the chemical properties of acidity indicators. The evolution of the chemical properties of acidity indicators in the three soils had an erratic behavior during the evaluation period, which is typical for this type of experiments. Using AD at the same dose as $CaCO_3$ in the three soils had less effect on the increase in the exchangeable Ca concentration, but a greater effect on the exchangeable Na and K concentrations. Using ADS at the same dose as $CaCO_3$ had erratic effects on the increase in the exchangeable Ca concentration in the three soils; however, these were quantitatively lower. The exchangeable Mg and Na concentrations in most of the soils were higher when ADS was used at the same dose as $CaCO_3$. Finally, the results of the chemical property acidity indicators of soils at the three locations under study indicate that the use of AD and ADS constitutes a commercial alternative as soil acidity correction amendments.

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