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Tillage system and lime application in a tropical region: Soil chemical fertility and corn yield in succession to degraded pastures

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ABSTRACT

The chemical degradation of soils, due to acidity, and erosion processes, resulting from a traditional tillage system method, are one of the main factors responsible for decreasing the productive capacity of tropical pastures. Thus, establishing the crop-livestock integration system (CLIS) by applying lime on surface without disrupting the soil is interest. The objectives of this study were to evaluate the chemical changes in a soil following surface application or incorporation of lime and to determine the effects of liming on plant nutrition, corn (*Zea mays* L.) grain yields, and various yield components in cultivated areas of degraded *Brachiaria decumbens* Stapf pasture. A randomized block experimental design with a split-plot arrangement consisting of two management systems (tillage and no-tillage system) and three lime rates (0.0; 2.7 and 5.4 Mg ha^{-1}) was used. The highest reactivity of calcium carbonate was observed after six months of liming, since during the sampling time the level of exchangeable Ca^{2+} and Mg^{2+} decreased to 0.05 m depth, and increased Al^{3+} and soil acidity to 0.3 m. The incorporation of lime did not increase the movement or reaction of the bases in the degraded soil profile. Therefore, surface liming under perennial forage crop residues (*B. decumbens* Stapf. pasture) provided the best alternative to increase the soil pH index at a depth of up to 0.3 m. Macronutrients uptake by plant, yield components, and corn grain yield were not affected by the application method. However, the use of limestone showed viability to maximize up to 20% in corn productivity, regardless of lime rate. The results suggest that it is possible to ameliorate soil acidity and chemical properties of degraded grassland only by surface application of limestone; however, the strategy is considered effective just for soils with no physical restriction to root development.

1. Introduction

Increasing worldwide consumption of meat, grains, fibers, and bioenergy has made it necessary to expand the productive capacity of agricultural lands, including those considered to have low fertility. Tropical soils are considered as major agricultural borders (Borlaug and Dowswell, 1998), since have favorable environmental factors for agricultural activity. Recently, the consolidation of CLIS in tropical regions, including the integration of annual crop production (corn, soybeans, rice, cotton and sorghum) with meat and milk production (Carvalho et al., 2011; Loss et al., 2011; Mateus et al., 2011; Borghi et al., 2013; Crusciol et al., 2014), has confirmed the potentials of these productive soils.

It is estimated that the Brazilian cerrado region, which has native vegetation similar to that of African savannahs, could produce 250 million tons of grain and 12 million tons of meat annually (Lee et al., 2012). However, despite this high potential, approximately 50 million hectares of pasture in this region have been subjected to some level of degradation (Borghi et al., 2013). The naturally acidic conditions of tropical soils, which have been intensified by the use of nitrogenous fertilizers containing ammonia (Caires et al., 2015), have limited the agricultural potentials of these soils in many regions of the world. In most cases, the low chemical fertility of these degraded soils result from aluminum and manganese toxicity and low

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availability of exchangeable bases, such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) (Oliveira and Pavan, 1996; Caires et al., 2005; Calegari et al., 2013).

Liming is one of the most common and effective practices for reducing or neutralizing the negative effects resulting from acidity. In addition, liming is important for increasing the availability of Ca and Mg in soils (Caires et al., 1998; Soratto and Crusciol, 2008; Joris et al., 2013). Due to its low solubility, lime is usually incorporated into the soil by conventional methods (plowing and harrowing). However, these proceedings drastically changes the soil physical properties, including the soil structure and porosity (Pöttker and Ben, 1998), which are often good where perennial forage species are cultivated. (Salton et al., 2008; Cavalieri et al., 2009, 2010).

In most grain-producing areas that use no-tillage systems, soil acidity correction has only been performed via surface liming (Conyers et al., 2003; Soratto and Crusciol, 2008; Briedis et al., 2012) because preserving the soil structure is extremely important for obtaining good root development and for reducing degradation processes, such as erosion. Despite the benefits of surface application, several studies have demonstrated that the speed of the limestone reaction is slower in the subsurface when the lime is not incorporated (Pöttker and Ben, 1998; Caires at al., 2008). Soratto and Crusciol (2008) presents contradictory results because they confirm that liming affects the subsurface layers after a relatively short period. However, these results are still discordant, and the viability of surface liming for recovering degraded pastures remains unknown.

The need for limestone in agricultural systems with minimal mobilization is smaller than that in conventional systems, with greater soil mobilization (Pöttker and Ben, 1998; Caires et al., 2000). This difference is attributed to the complexation of exchangeable Al by soil organic matter, which is an intense process within conservation systems and involves the accumulation of large amounts of organic matter (van Hees et al., 2000). Knowledge of changes in soil chemical attributes and their effects on grain yield are necessary for establishing and adjusting lime requirements in CLIS. However, in areas with no physical limitations, such as compaction or erosion, and where low pasture productivity exclusively results from reduced soil chemical fertility, it is likely that reducing soil acidity by adding lime to the surface can provide results that are comparable with those obtained when using conventional methods.

The objectives of this study were to evaluate the chemical changes in the soil that were affected by the surface application or incorporation of lime and to determine the effects of these methods on plant nutrition, yield components, and corn grain yield in a degraded *Brachiaria decumbens* Stapf pasture.

2. Materials and methods

2.1. Site description

This experiment was performed in Botucatu City (in the State of São Paulo in southeastern Brazil; 48° 23′ W, 22° 51′ S, 765 m above sea level) during two growing seasons. According to the Koppen classification system, the climate of the study area is Cwa, which is tropical with dry winters and hot and rainy summers (Lombardi and Drugowich, 1994). The rainfall and the mean maximum and minimum temperatures recorded during the experimental period are shown in Table 1 (Unicamp, 2012).

The soil is a sandy clay loam, kaolinitic, thermic Typic Haplorthox with 600, 208 and 192 $g\,kg^{-1}$ of clay, silt and sand, respectively. In our study, the soil was managed using conventional tillage (one disk plow with a working depth of 200 mm and two leveling harrows with a working depth of 100 mm) for five or more years before the trial began. The area was cultivated following its use as a *Brachiaria decumbens* Stapf. pasture without soil mobility.

Before starting the experiment, the soil chemical characteristics were determined at depths of 0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.30 m (Table 2). These initial values were only used for comparison with the following results and were not considered in the statistical analysis. The soil pH was determined in 0.01 mol L^{-1} $CaCl_2$ (1:2.5 soil/solution ratio). Exchangeable Al was extracted using neutral 1 mol L^{-1} KCl with a 1:10 soil/solution ratio and determined by titration in 0.025 mol L^{-1} NaOH (Yuan, 1959). The soil organic matter content was evaluated using the Walkley–Black method (Walkley and Black, 1934). Exchangeable basic cations (Ca^{2+}, Mg^{2+}, and K^+) and available P were extracted using an ionic resin (van Raij et al., 1986). Exchangeable Ca^{2+}, Mg^{2+} and K^+ were determined using a Shimadzu AA-6300 atomic absorption/Flame-Emission spectrophotometer. Phosphorus was determined colorimetrically (Murphy and Riley, 1962), using a FEMTO 600S spectrophotometer. Base saturation values were calculated using

Table 2
Chemical characteristics of the soil before the experiment.

Depth m	pH ($CaCl_2$)	SOM $g\,dm^{-3}$	P (resin) $mg\,dm^{-3}$	Al^{3+}	H + Al	Ca^{2+}	Mg^{2+}	K^+	BS %
				$mmol_c dm^{-3}$					
0.00–0.05	3.9	31	13	27	62	7.7	5.8	0.8	19
0.05–0.10	3.8	30	8	30	67	5.5	5.0	1.0	15
0.10–0.20	3.7	27	10	33	90	4.7	4.1	0.5	9
0.20–0.30	3.6	25	4	36	85	2.1	2.0	0.2	5
0.00–0.20	3.8	30	10	30	70	6.2	5.1	0.8	15

Table 1
Rainfall, maximum and minimum temperatures at Botucatu, São Paulo State, Brazil, during the study period and long-term average.

Climate characteristics	Month								
	Sep	Oct	Nov	Dec.	Jan.	Feb.	Mar.	Apr.	May
First season									
Monthly rain, mm	90.4	133.9	146.3	290.3	400.1	203.5	111.0	70.3	44.8
Mean max. temp., °C	25.3	27.1	27.8	28.0	27.9	28.3	28.4	25.8	22.8
Mean min. temp., °C	13.7	14.9	15.3	18.9	20.0	19.8	19.3	16.1	13.4
Second season									
Monthly rain, mm	–	–	–	183.8	220.7	227.9	162.4	12.1	10.3
Mean max. temp., °C	–	–	–	28.9	27.8	27.4	27.0	27.1	24.4
Mean min. temp., °C	–	–	–	18.7	19.1	19.0	18.6	17.0	14.1
Long-term (50-yr) avg.									
Monthly rain, mm	71.3	126.5	133.3	184.6	224.0	203.2	140.9	66.5	75.8
Mean max. temp., °C	26.2	26.7	27.2	27.2	28.1	28.0	28.0	27.0	24.0
Mean min. temp., °C	12.4	14.2	15.1	16.4	17.1	17.4	19.0	17.0	15.0

the exchangeable bases and total acidity results at pH 7.0 (H + Al) (van Raij et al., 2001).

2.2. Experimental design and treatments

A randomized block experimental design was used with a split plot scheme and four replications. The treatments consisted of the following two management systems: (1) conventional tillage—lime was incorporated in one pass using a disk plow and two passes using a leveling harrow and (2) no-tillage—lime was applied on the soil surface without incorporation. In addition, the following three dolomitic limestone rates were used: (1) 0.0 Mg ha^{-1} (no liming), (2) 2.7 Mg ha^{-1}, and (3) 5.4 Mg ha^{-1}. Greater liming rates were calculated to achieve a base saturation of 70% (van Raij et al., 1997). The dolomitic limestone composition consisted of 30% Ca and 7.2% Mg, with an effective calcium carbonate equivalence (ECCE) of 82%. The main plots were 150 m^2 (5 × 30 m), with sub plots of 50 m^2 (5 × 10 m). Each sub plot consisted of five 10-m long corn rows that were spaced at 0.9 m. Data samples were collected in three central rows, which were 1 m from the end of each plant row. Two external rows surrounded the central rows.

2.3. Liming application

Lime was manually applied uniformly on the soil surface at the beginning of the rainy season (September) during the first year of the experiment. The next day, incorporation was conducted in the plots with conventional tillage. Incorporation was performed using a Massey Ferguson 299 with 6 cylinders and 130 hp. The following implements were used: a) BALDAN$^{(r)}$ AFL Mounted Disc Plough with 4 discs (30″ diameter), a working width of 1200 mm, and a working depth of 200 mm and b) a BALDAN$^{(r)}$ NVCR remote Control

Table 3
ANOVA significance for soil chemical attributes.

Depth (m)	Blocks	System (S)	Rates (R)	Time sampling (TS)	S × R	S × TS	R × TS	S × R × TS
pH								
0-0.05	0.4783	0.8439	<0.0001	<0.0001	0.7623	0.4493	0.5734	0.7482
0.05-0.10	0.6392	0.8832	0.0007	<0.0001	0.7238	0.6673	0.7739	0.8287
0.10-0.20	0.7492	0.9804	0.0012	<0.0001	0.4899	0.4373	0.6225	0.6399
0.20-0.30	0.5298	0.9268	<0.0001	0.0071	0.5381	0.5389	0.5298	0.7464
H + Al								
0-0.05	0.7392	0.9777	<0.0001	<0.0001	0.5391	0.5483	0.5638	0.6299
0.05-0.10	0.2648	0.9853	0.0022	<0.0001	0.3529	0.4542	0.7333	0.7109
0.10-0.20	0.4683	0.9942	<0.0001	0.0302	0.6539	0.6571	0.6313	0.8321
0.20-0.30	0.6184	0.9978	0.0149	0.0156	0.5211	0.7299	0.5831	0.6778
Exchangeable Al^{3+}								
0-0.05	0.3849	0.9752	<0.0001	<0.0001	0.6830	0.3382	0.5511	0.8833
0.05-0.10	0.2395	0.9872	<0.0001	<0.0001	0.7382	0.4366	0.4121	0.8492
0.10-0.20	0.5639	0.9722	<0.0001	<0.0001	0.5930	0.7441	0.5391	0.6976
0.20-0.30	0.4693	0.9699	0.0022	<0.0001	0.6349	0.6111	0.5830	0.7087
Soil organic matter								
0-0.05	0.5483	0.9735	0.3781	0.4384	0.7322	0.8383	0.7868	0.7999
0.05-0.10	0.4729	0.9682	0.5011	0.2579	0.7644	0.7492	0.6745	0.8842
0.10-0.20	0.5582	0.9750	0.3897	0.5771	0.5328	0.7960	0.7253	0.7483
0.20-0.30	0.4439	0.7436	0.2971	0.6382	0.4499	0.6988	0.6288	0.9672
Phosphorus								
0-0.05	0.5438	0.9362	0.0079	0.2461	0.4682	0.5594	0.5789	0.9055
0.05-0.10	0.4724	0.9514	0.0033	0.5188	0.6381	0.4493	0.6940	0.8656
0.10-0.20	0.5922	0.8853	0.4670	0.2393	0.5932	0.6583	0.7422	0.7581
0.20-0.30	0.5290	0.9804	0.6825	0.3366	0.7392	0.8481	0.8131	0.8939
Exchangeable Ca^{2+}								
0-0.05	0.3438	0.9924	<0.0001	<0.0001	0.4382	0.4829	0.5392	0.6473
0.05-0.10	0.5325	0.9851	<0.0001	0.7468	0.3842	0.5730	0.6171	0.7488
0.10-0.20	0.4280	0.9196	0.0244	0.6142	0.5291	0.6788	0.6444	0.6961
0.20-0.30	0.4655	0.9823	0.0099	0.8677	0.6466	0.7573	0.5780	0.7107
Exchangeable Mg^{2+}								
0-0.05	0.7432	0.9684	<0.0001	<0.0001	0.4482	0.5392	0.5390	0.6675
0.05-0.10	0.6489	0.9842	<0.0001	<0.0001	0.5729	0.8493	0.5777	0.8767
0.10-0.20	0.7745	0.9467	<0.0001	<0.0001	0.6201	0.6382	0.6506	0.7694
0.20-0.30	0.6533	0.9623	<0.0001	<0.0001	0.6822	0.5494	0.7218	0.5868
Exchangeable K^{+}								
0-0.05	0.5438	0.9743	<0.0001	<0.0001	0.5392	0.5784	0.6737	0.8953
0.05-0.10	0.8302	0.9438	<0.0001	<0.0001	0.6539	0.8464	0.5648	0.7769
0.10-0.20	0.4729	0.9576	0.0182	0.0189	0.7593	0.6667	0.6471	0.6201
0.20-0.30	0.3799	0.9051	0.0264	0.0101	0.6585	0.8541	0.5544	0.7858
Base saturation								
0–0.05	0.3689	0.9911	<0.0001	<0.0001	0.4730	0.6121	0.4532	0.5778
0.05–0.10	0.2276	0.9935	<0.0001	<0.0001	0.4211	0.4212	0.5949	0.7656
0.10–0.20	0.4729	0.9928	0.0045	<0.0001	0.6482	0.5762	0.6133	0.8539
0.20–0.30	0.8568	0.9897	0.0096	<0.0001	0.5722	0.5498	0.4309	0.8022

Leveling Harrow with 28 discs (20″ diameter), a working width of 2350 mm, and a working depth of 100 mm. Corn (*Zea mays* L.) was sown approximately 3 months after lime application.

2.4. Crop management

During both growing seasons, corn was sown in the presence of fallow residue (6000 kg ha^{-1} of dry matter on the soil surface) following a glyphosate application (1800 g ha^{-1}) with a volume of 250 L ha^{-1} 20 d before sowing. Single-cross Pioneer hybrid (P30F90) was sown on December 22th (first year) and December 10th (second year) using a no-till drill to produce a population of 55,000 plants ha^{-1}. Furrow opening, fertilizer distribution, and corn seeding were performed using a mechanical seeder (Semeato Model Personale Drill-13). Sowing mineral fertilization was performed according to the recommendations of Cantarella et al. (1997) for corn crops, resulting in the application of 25 kg N ha^{-1} as urea, 89.6 kg P_2O_5 ha^{-1} as triple superphosphate and 51.2 kg K_2O ha^{-1} as potassium chloride. Mineral fertilization of 100 kg N ha^{-1} as ammonium sulfate was performed by topdressing when the corn plants reached the stage with five expanded leaves (V5), according to the recommendations of Cantarella et al. (1997). Maize was cultivated according to the needs of the crop. All pesticides applications were performed using a tractor-mounted boom sprayer (Condor 600 M14 JACTO$^{(r)}$) with a 14 m bar containing 29 nozzles (Type JA2) and a spraying pressure of 5 bars.

2.5. Sampling and analyses

A 4.5-cm diameter galvanized-steel auger was used for sampling at depths of 0–0.05, 0.05–0.10, 0.10–0.20 and 0.20–0.30 m 6, 12 and 18 months after applying lime. For each layer, five

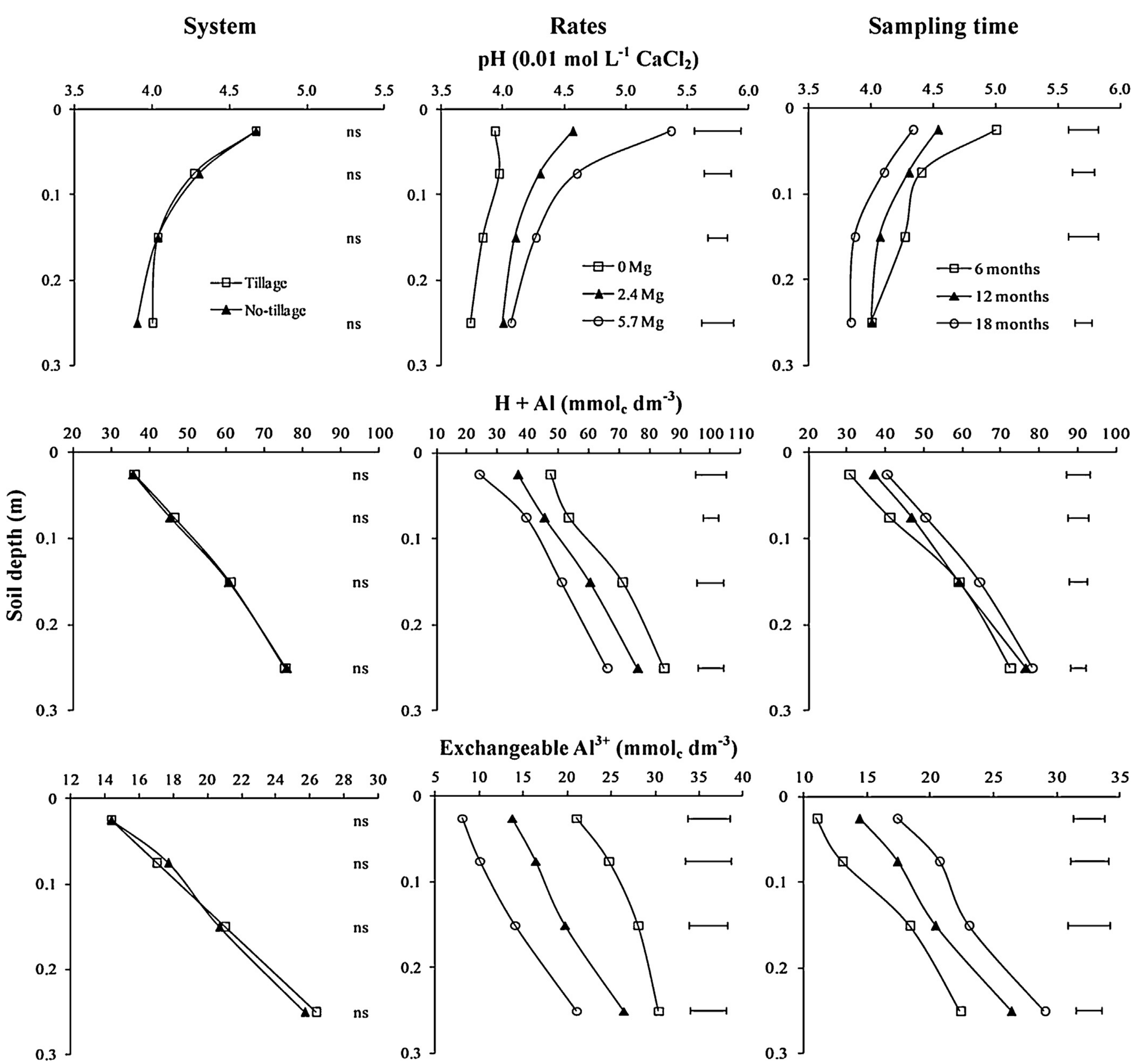

Fig. 1. pH, H+Al, and exchangeable Al^{+3} affected by system management, liming rates and sampling time. Horizontal bars indicate the Least Significant Difference ($P \leq 0.05$). ns, not significant.

subsamples were collected between the corn inter-rows (0.45 m from the plant row) of each subplot. The five subsamples were combined to form one composite sample.

The composite samples were air dried, sieved (2 mm mesh) and stored before analyzing to determine the soil pH ($CaCl_2$ 0.01 mol L^{-1}) and P, exchangeable Al^{+3}, Mg, Ca, and K, H + Al contents. In addition, the base saturation (V%) was determined according to the methodology proposed by van Raij et al. (2001).

Leaf corn sampling for nutrient concentration analysis was performed when 50% of the corn plants were in their full flowering stage. Twenty plants per subplot were randomly analyzed, and the leaf opposite the highest ear was sampled as proposed by Cantarella et al. (1997). Next, the leaf samples were washed, dried using forced air circulation at 65 °C for 72 h and ground. The N, P, K, Ca, and Mg concentrations in the leaves were determined according to the methods described by Malavolta et al. (1997). Next, N was extracted using H_2SO_4, and other nutrients were extracted using a nitro-perchloric solution. From the extracted solution, the N concentration was determined by using the Kjeldahl distiller method, and the P, K, Ca, and Mg concentrations were determined using spectrophotometry.

Grain harvest occurred seven days after the corn reached physiological maturity and was performed using a Nursery Máster Elite Wintersteiger small-plot harvester. The grain yield was measured from the usable area in each subplot. Next, the corn grain weight from the usable area was determined, and the data were transformed to grain yield in ha^{-1} (130 g kg^{-1} wet basis). Then, the final plant population was determined by counting the number of plants in the three central rows over distances of eight meters in each subplot. When determining the plant population, the plant

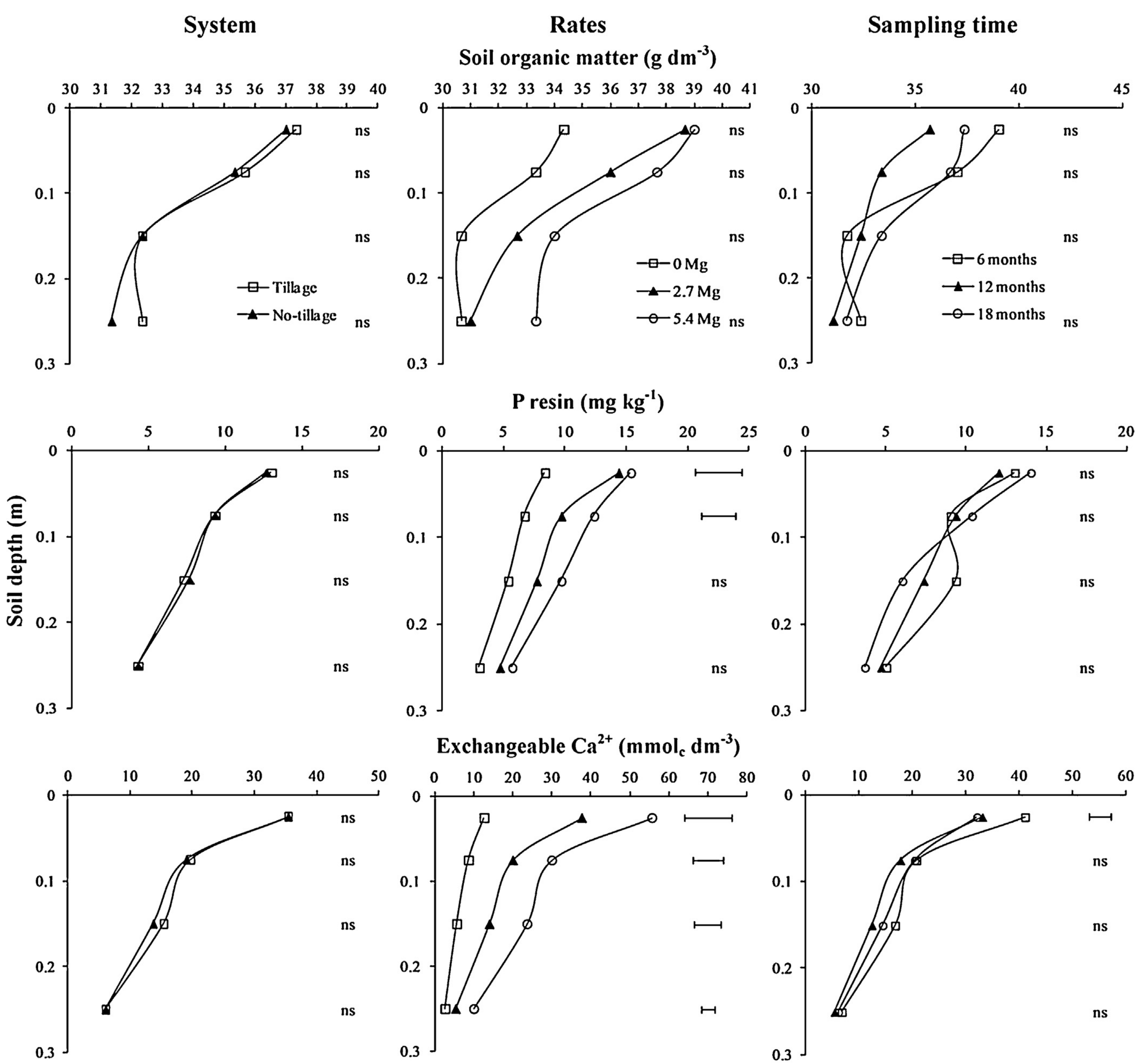

Fig. 2. Soil organic matter, phosphorus, and exchangeable Ca^{2+} affected by system management, liming rates and sampling time. Horizontal bars indicate the Least Significant Difference ($P \leq 0.05$). ns, not significant.

height, number of ears per plant, number of grains per ear, and weight of 100 grains were evaluated from 10 plants per subplot that were randomly chosen in the usable area.

2.6. Statistical analyses

All data were analyzed using the SAS Statistical Software Package. Management system, liming rates, sampling time (only for soil chemical attributes), and growing season (only for plant analysis) were all considered to have fixed effects. Mean separations were conducted using an LSD test. Effects were considered statistically significant at $P \leq 0.05$.

3. Results

3.1. Soil attributes

With respect to the chemical properties of the soil, no interaction was observed between the management systems, liming rates, and sampling time (Table 3). The single effects of these factors will be discussed separately.

Compared with superficial liming, the incorporation of the soil acidity amendment did not result in significant changes in the main soil chemical attributes, including the active acidity (pH), potential acidity (H+Al), exchangeable acidity (Al^{3+}), soil organic matter (SOM), macronutrients levels (P, Ca^{2+}, Mg^{2+} and K^{+}) and base saturation values (Figs. 1–3).

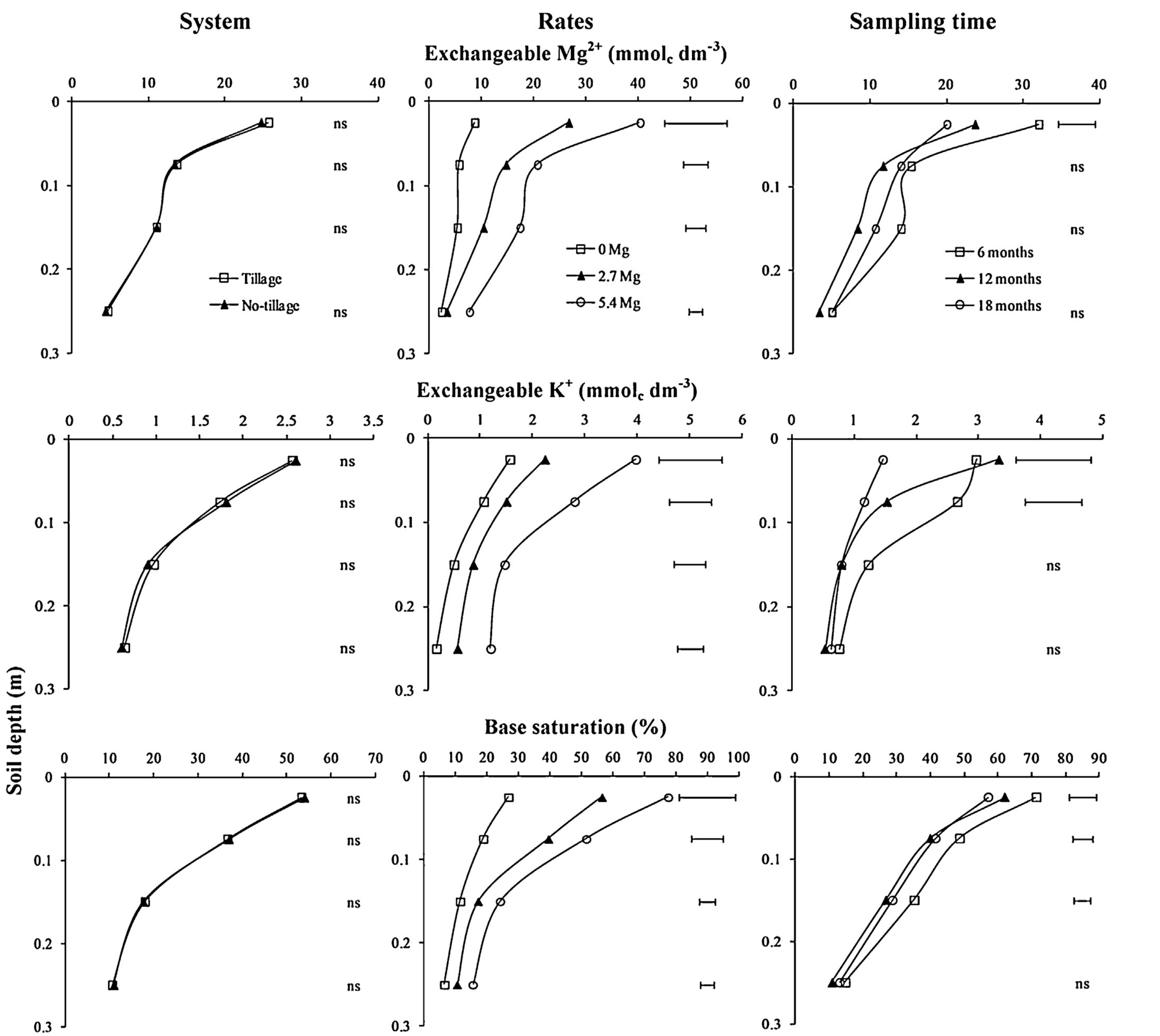

Fig. 3. Exchangeable Mg^{2+} and K^{+}, and base saturation affected by system management, liming rates and sampling time. Horizontal bars indicate the Least Significant Difference ($P \leq 0.05$). ns, not significant.

The application of the recommended rate ($5.4\,Mg\,ha^{-1}$), regardless of the system management, resulted in significant changes in the pH; exchangeable Ca^{2+}, Mg^{2+}, and K^{+} levels; and base saturation, and reduced the level of exchangeable Al^{3+} and H +Al in all of the evaluated profiles (0–0.30 m) (Figs. 1–3). Despite the less expressive effect, applying half of the rate ($2.7\,Mg\,ha^{-1}$) was sufficient for reducing acidity and increasing the levels of divalent bases (Ca^{2+} and Mg^{2+}), which resulted in significant increases in the base saturation values. However, the action of the lowest rate of lime was limited to a depth of 0.20 m.

The strongest liming action was verified after six months of treatments establishment (first sampling), which highlighted the rapid responses of the soils to soil amendment practices in all of the evaluated profiles (up to 0.30 m depth). For pH values, an increase of this index was observed at the surface layer (0–0.05 m), with a 1.1 increase in the pH scale after six months of lime application. The third sampling (18 months) showed the acidifying effects of soil during the trial period, and a decrease in this index was observed over time in all of the evaluated layers.

Regarding the levels of SOM and P, no differences were observed between the sampling time (Fig. 2). In addition, increases in basic cation levels (Ca^{2+}, Mg^{2+} and K^{+}) increased up to a depth of approximately 0.30 m relative to the original soil cation levels (before treatments establishment). Beginning from the first sampling, a decrease in exchangeable Ca^{2+}, Mg^{2+} and K^{+} levels was observed in the 0–0.05 and 0.05–0.10 m layers. In addition, a decrease in the 0.10–0.20 m layers for K^{+} was also detected.

Regarding base saturation, an index of 70% was only observed in the surface layer (0–0.05 m) six months after limestone application, regardless of the amount used (Fig. 3). After 12 months, the base saturation values decreased up to a depth of 0.20 m. However, this downward trend was not observed 18 months after applying the acidity amendment because this index remained unchanged relative to the values obtained during the second sampling.

3.2. Nutrient concentrations in corn leaves

The macronutrient concentrations were not changed by the soil tillage practices (Table 4). Regarding the effects of liming, the only significant effect observed was for N assimilation. No differences were observed between the quantities of lime applied (2.7 or $5.4\,Mg\,ha^{-1}$). The analysis of variance results for the nutrient concentration in the leaves did not show interactions between the management systems, liming rates, and growing season. In addition, the leaf N, K, Ca, and Mg contents were greater during the second year.

Table 4
Nitrogen, phosphorus, potassium, calcium, and magnesium concentrations in the leaves of corn as affected by two management system and lime rates in two growing season. Botucatu, State of São Paulo, Brazil.

Treatments	N	P	K	Ca	Mg
Management system			$g\,kg^{-1}$		
No-tillage	23 a	2.1 a	17.8 a	5.0 a	2.5 a
Tillage	24 a	2.2 a	16.7 a	5.0 a	2.5 a
Limestone rates					
0	21 b	2.2 a	17.4 a	4.9 a	2.5 a
2.7	24 a	2.3 a	17.3 a	5.0 a	2.3 a
5.4	25 a	2.1 a	17.1 a	5.0 a	2.5 a
Growing season					
First	22 b	2.1 a	14.9 b	3.0 b	2.1 b
Second	24 a	2.2 a	19.6 a	6.9 a	2.9 a
F probality					
Blocks	0.3456	0.2358	0.2277	0.5685	0.1728
Management system (S)	0.3376	0.4645	0.3421	0.1127	0.1258
Limestone rates (R)	0.2063	0.0922	0.5747	0.5876	0.3302
Growing season (GS)	<0.0001	0.2653	<0.0001	<0.0001	0.0012
S × R	0.3275	0.4861	0.7456	0.5562	0.4962
S × GS	0.6425	0.2953	0.5927	0.7419	0.3119
R × GS	0.3852	0.4731	0.4284	0.2048	0.7924
S × R × GS	0.7312	0.8762	0.2772	0.3741	0.5577

Means followed by different letters in the column differ statistically by the LSD test ($p \leq 0.05$).

3.3. Plant height, yield components, and corn grain yield

The manner of lime application did not affect any of the corn yield components (Table 5). Except for the plant population and number of ears per plant, the yield components and plant height benefitted from lime application. The surface application of the soil acidity amendment resulted in higher values regarding vegetative and reproductive development, regardless of the amount of lime applied. The plant height, yield components, and grain yield had values that were greater than those in the control ($0\,Mg\,ha^{-1}$). In addition, no interactions occurred between the factors, and the growing season had an isolated affect on the 100 grain-weight, with higher values during the first year.

4. Discussion

4.1. Soil attributes

Regardless of the method used for lime application into the soil, the addition of the acidity amendment improved the main soil chemical properties, with evident benefits up to a depth of 0.30 m (Figs. 1–3). Although Ca and Mg carbonates have low solubility and mobility in soil, the results showed a rapid reaction to surface liming over a relative short period. Thus, soils cultivated with perennial forage species generally produce a stable structure and good porosity (Cavalieri et al., 2009; Cavallini et al., 2010), which allows carbonate percolation through the soil profile, without the need for mechanical incorporation. In addition to the factors that determine the physical quality of soil, water availability and lime rates are important for the viability of this practice (Rheinheimer et al., 2000; Soratto and Crusciol, 2008). According to Miyazawa et al. (2002) and Calegari et al. (2013), the pluvial regime strongly interferes on reaction speed of carbonate in the sub-surface layers because water is an important vehicle for displacing limestone particles. According to Salton et al. (2008), the inclusion of perennial forage in agricultural systems is critical for increasing the soil porosity. The roots of these species formed porous channels due to the aggregation of solid particles, which likely improved the percolation of water containing suspended limestone fragments.

When comparing the effects of surface liming (no-tillage) and the incorporation of lime by plowing and disking (conventional), Rheinheimer et al. (2000) found that surface liming had limited effect on the profile of a Argisol distrophic medium-textured. By contrast, Oliveira and Pavan (1996) studied a clayey Latosol and showed that the variables related to acidity (pH and exchangeable Al^{3+}) were affected at depths of up to 0.4 m. The benefits observed in the shallow soil layers regarding the soil chemical attributes were also highlighted by Soratto and Crusciol (2008). These authors emphasize that maintaining soil structure was critical for the reaction speed of the limestone in the subsurface. Although surface liming had a limited affect on the soil profile over a short period (Pöttker and Ben, 1998; Caires et al., 2006; Caires et al., 2008), the authors noted that restrictive action can vary depending on the mobility of OH^{-} and HCO_3^{-} ions in the soil. Researchers have emphasized that certain organic and inorganic compounds can increase the affects of surface liming in shallow soils by increasing the mobility of basic cations, which can reduce the negative effect of free Al^{3+}, an important component of acidity

Table 5
Plant height (PH), plant population (PP), number of ears per plant (NEP), number of grains per ear (NGE), 100-grain weight (W100), and grain yield (GY) of corn crop as affected by two management system and lime rates application in two growing season. Botucatu, State of São Paulo, Brazil.

Treatments	PH	PP	NEP	NGE	W100	GY
Management system	m	n°	n°	n°	g	kg ha^{-1}
No-tillage	1.72 a	53145 a	1.05 a	501 a	29.3 a	8045 a
Tillage	1.72 a	53354 a	1.06 a	519 a	29.2 a	8141 a
Limestone rates						
0	1.62 b	52514 a	1.04 a	473 b	28.4 b	6983 b
2.7	1.76 a	53499 a	1.07 a	521 a	30.0 a	8427 a
5.4	1.75 a	53739 a	1.07 a	537 a	29.6 a	8869 a
Growing season						
First	1.70 a	53333 a	1.05 a	497 a	30.2 a	8042 a
Second	1.74 a	53167 a	1.06 a	523 a	28.4 b	8144 a
F probality						
Blocks	0.8323	0.5729	0.3556	0.6839	0.4739	0.2959
Management system (S)	0.0965	0.1148	0.4629	0.1622	0.3824	<0.0001
Limestone rates (R)	<0.0001	0.0931	0.2275	<0.0001	<0.0001	<0.0001
Growing season (GS)	0.3171	0.2277	0.6784	0.0981	<0.0001	0.2873
S × R	0.2483	0.5394	0.7239	0.4785	0.4376	0.5521
S × GS	0.4629	0.2841	0.5625	0.3367	0.6294	0.4674
R × GS	0.3529	0.2749	0.3739	0.3472	0.3698	0.2341
S × R × GS	0.3121	0.2342	0.1627	0.2849	0.3421	0.3929

Means followed by different letters in the column differ statistically by the LSD test ($p \leq 0.05$).

(Franchini et al., 2003; Castro et al., 2012). According to Caires et al. (2000), superficial liming is a viable technique because it can promote improvements in soil chemical attributes below to a depth of 0.30 m, depending on the characteristics of the soil and the environmental conditions. The changes observed in pH, potential acidity (H+Al), exchangeable Al^{3+}, Ca^{2+}, Mg^{2+} and K^{+} levels and the soil base saturation resulting from different limestone rates indicated that lime was effective for improving soil chemical attributes up to a depth of 0.30 m. The effect of liming to a depth of 0.30 m was observed in a no-tillage system in Kentucky (U.S.A.). However, the rate required to affect chemical properties of the soil at a depth of 0.3 m was three times higher than the calculated rate (Blevins et al., 1978).

Apart from the applied rate, a reduction in the various components of acidity occurred. However, the largest benefits were observed with the application of the recommended rate (Fig. 1). According to Joris et al. (2013), the effects of liming on the availability of the exchangeable Al^{3+} can vary depending on the amount of carbonate and the depth that must be achieved. At all rates of surface limestone tested, the authors observed that the Al^{3+} levels were reduced to very low levels (≤ 2 mmol$_c$ L^{-1}) in the upper soil layers (0–0.05 and 0.05–0.10 m). However, only the highest application rate (12 Mg ha^{-1}) reduced the exchangeable Al^{3+} level in the 0.10–0.20 m layer. These authors confirmed the relationship between the soil pH and exchangeable Al^{3+} that were observed by Limousin and Tessier (2007). In addition, an increase in pH encourages soluble Al^{3+} alteration to forms that are non-toxic to plants. This effect reduced the exchangeable Al^{3+} levels in the soil, which probably can explain the decreasing trend on the potential acidity (H + Al). Although, in the 0.20–0.30 m soil layer only the recommended rate resulted in a significant reduction in exchangeable Al^{3+}. This difference is probably related to minor variations in soil pH, as already indicated by Kaminski et al. (2002). In addition to the effects of the setting, it is important to note that the morphological characteristics of the root system and the kinetics of nutrient absorption by perennial forage species can also reduce the toxicity of exchangeable Al^{3+} (Wenzl et al., 2001). This effect could result from changes in the dynamics of H^{+} efflux and influx, which would promote significant changes in pH, and the precipitation of toxic elements in rhizospheric soil, as noted by Nye (1981).

The greater availability of Ca^{2+}, Mg^{2+} and K^{+} in all soil layers was only verified by implementing the recommended rate (5.4 Mg ha^{-1}). However, the highest exchangeable bases levels were observed in the 0–0.05 m layer, as noted by Conyers et al. (2003) and Soratto and Crusciol (2008). According to Mello et al. (2003), the high levels of basic cations in the surface layer resulted in pH increases at the soil surface, which increased the rate of movement of carbonate ions (accompanied with Ca and Mg) into deeper soil layers to neutralize or reduce the acidity of the sub-surface layers. The highest pH value in the surface soil probably influenced the downward movement of HCO_3^{-} ion, which was accompanied by Ca and Mg, moved to the adjacent lower layers and reacted with the acidity. According to Rheinheimer et al. (2000), when acidic cations are present, the acidity neutralization reaction will be limited to the top layer, which delays the appearance of effects in the subsurface. According to the authors, one of the main factors that contributes to the reactivity of the limestone in the subsurface is the preservation of the physical soil properties.

In addition to the physical factors, the mobility of basic cations (Ca^{2+}, Mg^{2+} and K^{+}) in the soil profile may be enhanced by the formation of water-soluble organic complexes. Changing the loading of these cations by reaction with organic compounds can facilitate the mobility of both ions through the soil. In the subsurface layer, the presence of acidic ions (H^{+} or Al^{3+}) can stimulate the release of Ca, Mg and K complexes (Miyazawa et al., 2002; Franchini et al., 2003). This reaction increases levels of basic cations which are necessary to raise root growth in acidic soils.

Unlike the soil basic cations, the soil P levels only changed in the superficial layers (0–0.05 and 0.05–0.10 m) (Figs. 1–3). The effects of liming on the availability of P are likely related to the increased action of carbonate in the surface layers, since increments of 0.7 and 1.5 pH units were observed in the 0–0.05 soil layer and increments of 0.3 and 0.6 were observed in the 0.05–0.10 soil layer with the application of 2.7 and 5.4 Mg ha^{-1}, respectively. In highly weathered soils, which are rich in Fe and Al oxides, the variations in pH determine the electrical charges on the interfaces of the organo-mineral particles. Increases in the pH index favor the development of negative charges, which increase phosphate mobility and decrease P adsorption due to ligand exchange (Parfitt, 1978; Barrow, 1985). According to Alleoni et al. (2003), this problem can also be attributed to the increased release of water-soluble organic acids in the soil. The chemical structures of these acids govern their adsorption because some molecules have preferential exchange sites and compete with phosphate, which reduces the reactions that cause P precipitation (Andrade et al., 2003). Among the main factors that influence the competition of these compounds with the colloidal complex sites, the soil pH is notable (Pavinato and Rosolem, 2008). As in the lower layers, variations in the soil pH were minor, no changes in the availability of P occurred below a depth of 0.10 m.

Despite encouraging the input of organic matter into soil (Castro et al., 2015), it is assumed that the absence of an effect is related to the time of sampling, which is probably insufficient for promoting significant changes in this attribute. The effects of the absence of tillage on the SOM were potentially related to the low level of this fraction in tropical soils (Zech et al., 1997). Moreover, the pH modification did not allow for high proliferation of mineralization organisms, which have a higher activity at neutral pH or under alkaline conditions (Rousk et al., 2009).

Independent of the management system and the amount of lime applied, greater soil chemical effects were observed for the acidity amendment practices during the first sampling (six months) (i.e., most of the limestone reacted during the first few months). These results were probably related to the high ECCE (82%) (Aguilar et al., 2009). According to Gonçalves et al. (2011), the reaction speed of the limestone and its residual effect are inverse. Consequently, greater limestone reactivity indicates that the product can be kept for a shorter period.

The changes in the various components of acidity (pH, exchangeable Al^{3+} and H+Al) observed over time were mainly associated with the action of acid reaction fertilizers, such as ammonium (Conyers et al., 1995; Crusciol et al., 2011). Although the nitrification process can be consider an important acidifying agent, greater anion NO_3^- levels in the soil solution may contribute to the migration of basic cations through the soil profile. According to Caires et al. (2015), the application of nitrogen fertilizer in soil can intensify Ca^{2+} and Mg^{2+} percolation through the soil profile. The authors observed increments of these cations at depths below 0.30 m. Although the mobility of these cations may be influenced by the formation of a complex cation-ligand, the reduction in the saturation value over the experimental period probably is related to associated to the amount of these nutrients removed by harvesting (Oliveira and Pavan, 1996).

4.2. Nutrient concentration in corn leaves

The effects of liming on the N concentration are potentially related to the availability of nitrate in the soil. According to Silva and Vale (2000), soil acidity is one of the main factors that limit the activity of nitrification organisms. Overall, the authors observed that the mean synthesis of nitrate by microorganisms was 11.6 mg kg^{-1} in acid soils, without the addition of lime; however, in amended soils, up to 62.7 mg kg^{-1} of nitrate were produced. In addition to the benefits of application on biological soil properties, liming results in better conditions for the development of root systems, even when only applied on the soil surface. These improved conditions result in greater areas of useable soil and favor increases in the uptake of nutrients, such as N (Caires et al., 2002). In addition to the factors that are favorable for increasing N availability, it is important to understand that the N leaf concentration for the corn crops are below the minimum levels that are adequate for crop growth, even in the treatments that received lime (Cantarella et al., 1997).

The absence of any treatment effect on the P, K, Ca, and Mg concentrations in corn leaves may be related to a sufficient supply of these elements through mineral fertilization and the nutrient cycling, process governed by microbiological activity. Regardless of the treatment, the concentrations of these nutrients were within the ranges considered adequate for corn crop (Cantarella et al., 1997). In soybean crops, Moreira et al. (2001) observed that the leaf P and K concentrations did not change following the immediate application of soil acidity amendments, and Caires et al. (1998) observed that surface liming does not affect the N, K, and Ca concentrations in soybean leaves.

Regarding the growing season, the leaf concentration of N was greater in the second year. This result is potentially related to the climatic conditions that occurred during each growing season, which potentially affected the N dynamics in the soil (Weber and Mielniczuk, 2009).

The K concentration during the first growing season was lower than the adequate range for the crop. However, during the second year, a generalized increase in the K concentration in the leaves occurred, which was above the minimum level considered sufficient for corn crops (Cantarella et al., 1997). The application of lime over time resulted in greater cation exchange capacities (CEC), which favored the occupation of K^+ at these bonding sites and increased the exchangeable K level in the soil surface layer (Caires et al., 1998), where the greatest corn root biomass is found (Costa et al., 2009).

Regarding the K concentration in the leaves, a difference in the Ca and Mg concentrations occurred between the growing seasons. During the first year, the leaf Ca concentration was 2.9 g kg^{-1}, and during the second year, was 6.7 g kg^{-1}. The benefits observed through the reaction time of the product may also be observed in the Mg concentration in the leaves, which were 2.2 g kg^{-1} and 3.2 g kg^{-1} in the first and second growing season, respectively. In addition to the indirect effects of pH on the availability of Ca and Mg, the dolomite is considered an important source of these cations (Amaral and Anghinoni, 2001; Moreira et al., 2001). When evaluating the effects of surface liming on soil chemical properties, Caires et al. (1999) observed greater availability of exchangeable Ca and Mg in soil 18 months after application, which was reflected by an increase in the Ca and Mg concentrations in soybean and wheat plant leaves. Although the growing seasons affected the Ca and Mg concentrations in the leaves, during both years, the values were within the range considered adequate for the crop (Cantarella et al., 1997).

4.3. Plant height, yield components and corn grain yield

Regarding of the soil management system, the favorable edaphic and climatic conditions occurred during the field experiment period, the soil type, and the use of high quantities of chemical fertilizers likely overshadowed any affects of the method of soil amendment application on corn grain yield. This finding emphasizes the importance of performing these studies over long periods and highlights the relationships of these management systems with liming.

Corn has a high demand for nutrient, as consequence, only the application of intermediate rate (2.7 Mg ha^{-1}) provided better conditions to corn growth. The soil acidity amelioration and the higher levels of exchangeable Ca^{2+} and M^{2+} in the soil contributed to the vegetative and reproductive development of the plants. Furthermore, these results were similar to those related by Pöttker & Ben (1998) and Caires et al. (2000), who affirmed that lime requirement in NTS is probably lower than that in conventional systems. The effects of improving soil chemical properties on crop development in this study were similar to those observed by Andreotti et al. (2001).

The benefits of liming on corn yield components were reflected positively in the grain yield, and the highest values were observed with lime use, regardless of the application rate. According to Ferreira et al. (2001), this result is explained by the presence of correlations between nutritional parameters and grain yield, indicating the importance of nutritional diagnosis as a tool for detecting deficiencies and predicting grain yield results. Thus, the benefits of liming on grain yield, regardless of the application rate, are likely related to improvements in the soil chemical conditions, which probably reflected in root system development and, consequently, plant nutrition. According to Caires et al. (2002), the acidity condition in subsoil layers hinders the use of soil by root systems because it confines the roots to the surface layer and, consequently, limits water and nutrient uptake by corn.

The greater grain weight observed in the second growing season could be attributed to environmental conditions. Magalhães and Jones (1990) reported that grain weight is mainly affected by genotype characteristics, which express endosperm cavity. Nevertheless, the number and capacity of endosperm cells may be strongly affected by the edaphic and climatic conditions that occurred during the growing season.

5. Conclusion

Our results demonstrate the effectiveness of surface liming on improving the main chemical attributes of tropical soils. After six months of amendment practices, which included applying limestone on soils surface with perennial forage residues (*Brachiaria decumbens* Stapf. pasture), similar results were observed between the surface and incorporation treatments, with soil mobilization up to a depth of 0.30 m. This depth is beneficial for forage roots and soil aggregation and stability. Liming increased N concentration in corn leaves, the number of grains per ear, the 100-grain weight which resulted in higher hybrid corn grain yield, regardless of application method. The surface application of lime rates showed viability to increase corn grain production in soil with limited forage productivity and low soil chemical fertility.

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