Comissão 2.4 - Química do solo

NITRATE ROLE IN BASIC CATION LEACHING UNDER NO-TILL[1]

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SUMMARY

Especially under no-tillage, subsuface soil acidity has been a problem, because it depends on base leaching, which has been associated with the presence of low molecular weigth organic acids and companion anions. The objective of this study was to evaluate exchangeable base cation leaching as affected by surface liming along with annual urea side-dressing of maize and upland rice. Treatments consisted of four lime rates (0, 1500, 3000, and 6000 kg ha^{-1}) combined with four nitrogen rates (0, 50, 100, and 150 kg ha^{-1}) applied to maize (*Zea mays*) and upland rice (*Oryza sativa*), in two consecutive years. Maize was planted in December, three months after liming. In September of the following year, pearl millet (*Pennisetum glaucum*) was planted without fertilization and desiccated 86 days after plant emergence. Afterwards, upland rice was grown. Immediately after upland rice harvest, 18 months after surface liming, pH and N-NO$_3^-$, N-NH$_4^+$, K, Ca, and Mg levels were evaluated in soil samples taken from the layers 0–5, 5–10, 10–20 and 20–40 cm. Higher maize yields were obtained at higher N rates and 3000 kg ha^{-1} lime. Better results for upland rice and pearl millet yields were also obtained with this lime rate, irrespective of N levels. The vertical mobility of K, Ca and Mg was higher in the soil profiles with N fertilization. Surface liming increased pH in the upper soil layers causing intense nitrate production, which was leached along with the base cations.

Index terms: lime, nitrogen fertilization, nutrient cycling, tropical soils.

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RESUMO: *PAPEL DO NITRATO NA LIXIVIAÇÃO DE BASES EM SEMEADURA DIRETA*

A correção da acidez subsuperficial tem sido um problema, principalmente, em sistemas com semeadura direta, em que se depende da lixiviação das bases, a qual tem sido associada à presença de ácidos orgânicos e de ânions acompanhantes. O objetivo deste experimento foi avaliar a lixiviação de bases no solo em função da calagem superficial e adubação nitrogenada em cobertura no milho e arroz. Foram aplicados 0, 1.500, 3.000 e 6.000 kg ha^{-1} de calcário, combinados com 0, 50, 100 e 150 kg ha^{-1} de N aplicados no milho e arroz, cultivados em anos consecutivos. As doses totais de N ao longo do experimento foram de 0, 100, 200 e 300 kg ha^{-1}. A semeadura do milho foi realizada em dezembro, três meses após a calagem. Em setembro do ano seguinte foi semeado o milheto, sem fornecimento de fertilizantes, que foi dessecado 86 dias após a emergência. Em seguida, realizou-se a semeadura do arroz. Após a colheita do arroz e 18 meses transcorridos da calagem superficial, amostras de solo foram coletadas das camadas de 0–5, 5–10, 10–20 e 20–40 cm, para avaliação do pH, N–NO$_3^-$, N–NH$_4^+$, K, Ca e Mg. Também foram determinadas as produtividades de grãos do milho, do arroz e da matéria seca do milheto. Na presença da calagem na dose de 3.000 kg ha^{-1}, foi constatada maior produtividade de milho com doses elevadas de N. Os melhores resultados obtidos para o arroz e milheto também foram resultantes dessa dose de calagem, independentemente das doses de N. Os íons K, Ca e Mg mostraram maior mobilidade no perfil do solo na presença de adubação nitrogenada em cobertura. A calagem superficial aumentou o pH das camadas superficiais, gerando intensa nitrificação e formação de nitrato, o qual foi lixiviado no perfil do solo com as bases.

Termos de indexação: calagem, adubação nitrogenada, ciclagem de nutrientes, solos tropicais.

INTRODUCTION

In tropical soils, the agricultural production is limited by a low pH, low effective cation exchange capacity (CEC), low base saturation, Ca deficiency, toxic Al levels and predominance of kaolinite in the clay fraction (Fageria & Baligar 2008). These characteristics are not favorable for the development of most annual species because root growth and water and nutrient uptake are impaired. Liming is currently used to reduce soil acidity because it increases pH and base saturation, contributing to increased nutrient availability and Al precipitation and representing a source of Ca and Mg as well. However, lime solubility in water is low, which restricts its effects mostly to the soil layers of lime application (Fageria & Baligar, 2008).

Due to the low solubility of Ca and Mg carbonates, liming efficiency depends on the contact area between lime and soil and the reaction time and conditions, mainly soil moisture (Quaggio, 2000). To produce an adequate volume of limed soil it is therefore recommended that the lime be incorporated into the arable layer. However, in no-tillage systems, lime can only be applied on the soil surface (Caires et al., 2001) and its effects on soil properties are most significant in the surface layers (Soon & Arshad, 2005; Costa & Rosolem, 2007). In some cases, lime effects have also been detected in the subsoil (Blevins et al., 1978; Soratto & Crusciol, 2008). The magnitude of these effects in no-till systems may vary according to soil type, lime rate (Soratto & Crusciol, 2008), time after liming (Quaggio, 2000; Soratto & Crusciol, 2008), type and amount of crop residues left on the soil surface, and to soil management (Pikul & Allmaras 1986; Miyazawa et al., 2002). Anions resulting from lime dissociation (carbonate, bicarbonate, oxides, or hydroxides) do not persist in the soil solution for a long time, due to their reaction with acids, and most of Ca and Mg is bound to negative charges created due the pH increase or released by Al precipitation (Ernani et al., 2007). However, SO$_4^{2-}$ and NO$_3^-$ concentrations, from either crop residue decomposition or fertilizers, may be increased under no-tillage systems. These anions may contribute to exchangeable base cation migration in the soil profile, due to their longer persistence in the soil solution (Foloni et al., 2006; Foloni & Rosolem, 2006).

Nitrate is mobile in the soil profile, and this mobility is higher under no-tillage, where water evaporation is lower and nitrate in solution leaches to deeper layers (Eriksen et al., 2008). Besides, nitrification is favored by liming, which increases the amount of NO$_3^-$ produced from NH$_4^+$-based fertilizers (Foloni & Rosolem, 2006). Nitrogen fertilization, by increasing anion concentrations in soil solution, may raise carbonate solubilization and restore the electrochemical equilibrium of the soil solution (Lindsay, 1979), thus intensifying base cation leaching. Pearson et al. (1962) observed effects of incorporated

lime down to a depth of 60 cm in tropical soils when N fertilizers were applied to the soil surface. They also found that a lack of N fertilization may limit Ca mobility in the soil profile. There is a stronger relation between sulphate ions and soil basic cations than between nitrate ions and the basic cations, but positive correlations were observed between the amounts of SO_4^{2-} and NO_3^- and exchangeable bases leached after N application (Foloni et al., 2006).

Basic cation movement in the soil profile was related to an increase in low molecular weight organic components released from crop residues (Miyazawa et al., 2002; Franchini et al., 2003). However, these findings have been questioned, as they were not observed in other studies (Caires et al., 2008; Rosolem & Silva, 2010). Low molecular weight organic acids are rapidly metabolized or adsorbed to the soil colloidal fraction, which explains the small effect on cation mobilization, and the presence of plant residues had little effect on the mobilization of the reaction products of surface-applied lime in the soil profile (Moraes et al., 2007). Rosolem (2011) observed that both the presence of straw on the soil surface as well as increasing N rates intensified NO_3^-, NH_4^+, and K movement through the soil profile.

This shows that nutrient mobilization within the soil profile in no-tillage systems is not well understood, mainly when lime is applied to the soil surface, without incorporation. The objective of this research was to evaluate the distribution of exchangeable bases in the soil profile down to 0.40 m, as well as crop response to lime, as affected by N rates applied to maize and rice.

MATERIAL AND METHODS

The experiment was carried out in Botucatu, São Paulo State, Brazil (22º51' S, 480º26' W, 786 m asl), on a Haplorthox with 500, 140 and 360 g kg^{-1} of clay, silt and sand, respectively. Annual averages at the experimental site are 24.3 ºC in summer, 18.1 ºC in winter and rainfall of 1515 mm. In the experimental field, crops had been grown under no-tillage for two years, with maize in summer, black oat (*Avena strigosa* Schreb) in winter and pearl millet in spring. By the time this experiment was initiated, 10 t ha^{-1} of dry matter had been accumulated on the soil surface. The soil chemical analysis (Raij et al., 2001) determined the following values: pH$_{CaCl_2}$ 4.9, 25 g dm^{-3} organic matter, 16 mg dm^{-3} P$_{resin}$, 51 mmol$_c$ dm^{-3} H + Al, 2.6 mmol$_c$ dm^{-3} K, 16 mmol$_c$ dm^{-3} Ca, 10 mmol$_c$ dm^{-3} Mg, 80 mmol$_c$ dm^{-3} CEC and 36 % base saturation.

The treatments consisted of four lime rates applied to the soil surface (0, 1500, 3000, and 6000 kg ha^{-1}) and four N rates (0, 50, 100, and 150 kg ha^{-1}) side-dressed in maize and upland rice rows, in the first and second year, respectively. The fertilizer was sidedressed in

the crop rows. Thus, combined N rates were 0, 100, 200 and 300 kg ha^{-1}. Dolomitic limestone (21 % CaO and 18 % MgO, 90 % equivalent calcium carbonate, and 64 % relative efficiency) was applied in October of the first year, spread on the soil surface at the following rates: zero rate (no lime), half the rate required to increase base saturation to 60 %, recommended rate and the double lime requirement (0, 1500, 3000, and 6000 kg ha^{-1}), according to Raij et al. (1996).

Maize

Maize (simple hybrid AG9010), was planted in December, in rows spaced 45 cm apart, at a plant density of 57,000 ha^{-1}. Each plot consisted of ten 6 m long rows. Rows on each side, as well as 50 cm at either end of the plots were considered borders. At planting, fertilization according to Raij et al. (1996) was applied: 30 kg ha^{-1} N, 60 kg ha^{-1} P$_2$O and 50 kg ha^{-1} K$_2$O, as urea, simple superphosphate and potassium chloride. When the plants had 6-8 leaves (Raij et al., 1996), N treatments were applied side-dressed (0, 50, 100, and 150 kg ha^{-1} as urea). The experiment was harvested in April of the following year, and grain yield was estimated (grain moisture content adjusted to 13 %).

Pearl millet

In September of the second year, pearl millet was planted using approximately 150 seeds m^{-2}, totaling 22 kg ha^{-1} of seeds (germination = 85 %). Fertilizer was not applied. Plants were chemically desiccated with glyphosate 86 days after plant emergence. Dry matter yields were determined by harvesting four 4 m long rows the day before chemical desiccation. The material was dried in a forced air oven at 60 ºC for 72 h and weighed. Then the residues were returned to their original position in the field.

Upland rice

Upland rice (cultivar IAC 202) was planted in December of the second year using 200 viable seeds m^{-2} in rows 45 cm apart. At planting, fertilizers were applied at 22 kg ha^{-1} N, 75 kg ha^{-1} P$_2$O$_5$ and 45 kg ha^{-1} K$_2$O (Cantarella & Furlani, 1997) as urea, simple superphosphate and potassium chloride, respectively. Nitrogen fertilizer was manually applied to rice, as urea, 50 % at the beginning of tillering and 50 % at the time of head differentiation (Cantarella & Furlani, 1997). Rice was harvested in April of the following year, and grain yield was estimated (grain moisture content adjusted to 13 %).

Immediately after harvest, 18 months after liming, eight soil sub-samples were taken from randomized points per plot, from the layers 0–5, 5–10, 10–20 and 20–40 cm, and mixed in one sample for each depth. The samples were immediately brought to the laboratory where they were oven-dried (40 ºC). The samples were analyzed for pH, Ca, Mg, K (Raij et al., 2001), and inorganic N was extracted with 1.0 mol L^{-1}

KCl and distilled in two steps, without and with Devarda's alloy (Keeney & Nelson, 1982).

Maize and rice leaves were sampled at flowering for foliar diagnosis. The samples were dried in a forced air oven at 65 °C for 72 h, ground, digested in nitric-perchloric acid and K, Ca, Mg and contents were determined by atomic absorption spectrophotometry, P was determined colorimetrically, S by turbidimetry and N by sulfuric acid digestion and vapor distillation (Malavolta et al., 1997).

The experimental design was a 4 x 4 factorial in complete randomized blocks, with four replications. Original data were submitted to variance analysis and means were compared using the t test (LSD, $p < 0.05$). Correlation tests were also applied to assess the relation between nitrate content and exchangeable bases for each soil depth and liming level ($p < 0.05$). For the crops grain yields, for each liming level, regression analysis was used and significant equations were adjusted.

RESULTS

No nutrient shortage, except for N, affected maize and rice yields, since the leaf concentrations determined in foliar diagnosis (results not shown) were within the adequate range (Malavolta et al., 1997). The maize, rice and millet yields were highest at 3000 kg ha^{-1} of lime, which would be the recommended rate to raise soil base saturation to 60 % to a soil depth of 20 cm (Raij et al., 1996). Maize response to N was quadratic at the highest lime rate (6000 kg ha^{-1}) and linear for the others (Figure 1a). Millet and rice responses to N were always linear up to 150 kg ha^{-1} (Figure 1b,c). A summary of ANOVA results on maize grain yield, pearl millet dry matter and rice yield is shown in table 1.

The effect of unincorporated lime on pH was higher in the top soil, 18 months after liming (Figure 2), but the highest lime rate increased pH up to 4.9 in deeper layers (Figure 2). Side dressed N fertilizer had no effect on pH (Figure 2), but increased nitrate content in the soil profile (Figure 3). However, when lime was applied at the recommended and double rates both the amount of nitrate in the top soil layer and that leached down to deeper layers were higher, mainly at the 150 kg ha^{-1} N rate (Figure 3c,d). Soil ammonium contents were decreased by liming in the top soil layers, but were increased in the soil profile by N fertilizer (Figure 4).

Potassium distribution in the soil profile was also affected, at all liming levels (Figure 5). Nitrogen application decreased K levels in the soil surface layers and increased K in the deeper layers. Calcium concentration in the top soil layers was increased by lime rates (Figure 6c,d), due to low lime solubility and mobility. However, N fertilization decreased Ca levels in the soil surface layers. In the 20–40 cm layer, the levels of this divalent cation were highest at an annual

N rate of 150 kg ha^{-1} (Figure 6), indicating a correlation between N rates and Ca mobility in deeper layers. Effects of treatments on soil Mg levels (Figure 7) were similar to those observed for K and Ca, i.e., an increase in N rates led to decreased Mg levels in surface layers and increased Mg levels in the deepest layer (20–40 cm), except at the lower lime rate (Figure 7b).

In general, there was a significant linear negative correlation between nitrate and Ca, Mg and K contents
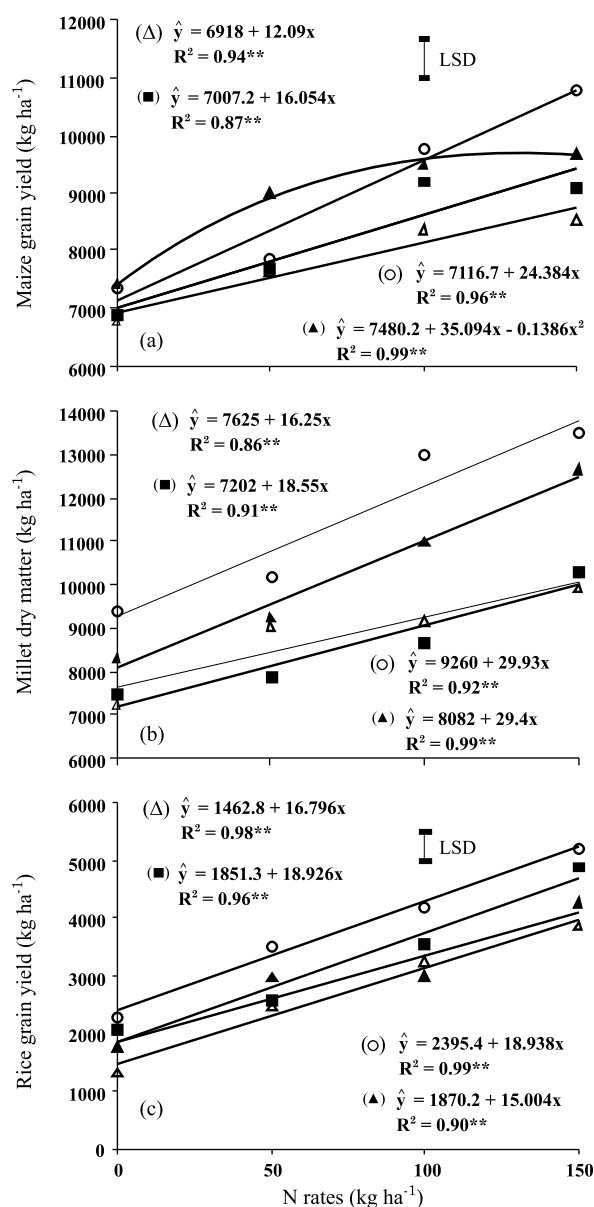

Figure 1. Maize grain yield (a), pearl millet dry matter (b) and upland rice grain yield (c) as affected by increasing N fertilization in different lime rates: 0 (Δ); 1500 (■); 3000 (O) and 6000 kg ha^{-1} (▲). * and **: significant at 5 and 1%, respectively. Vertical bars show LSD ($p < 0.05$) for the N x lime rates interaction, and there was no interaction for upland rice yield.

Table 1. ANOVA significance of maize grain yield, pearl millet dry matter and upland rice grain yield results as affected by nitrogen fertilization and liming at Botucatu, São Paulo, Brazil

Characteristic	Maize grain yield	Pearl millet dry matter	Upland rice grain yield
Limestone (LIM)	*	**	**
Nitrogen (NIT)	*	**	**
LIM × NIT	**	ns	*

* and **: significant at 5 and 1 % by the F test, respectively; ns: non significant.

in soil at each depth (Table 2). The higher the nitrate levels down to the layer of 10–20 cm, the lower the base levels. However, in the 20–40 cm layer, Ca levels showed a positive correlation with nitrate contents at all lime rates (Table 2). For Mg and K, this effect was only significant when lime was applied at 1500 and 6000 kg ha^{-1}, respectively. However, these correlations were only positive in the deepest soil layer studied, which shows that nitrate may be leached along with the bases.
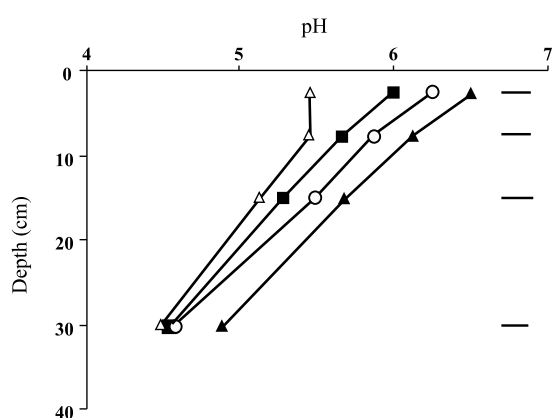
Figure 2. pH in the soil profile as affected by lime rates 0 (Δ); 1500 (■); 3000 (O) and 6000 kg ha^{-1} (▲); ▬: least significant difference at 5 % by the t test.

DISCUSSION

Species of the *Poaceae* family (grasses) are characterized by their strong response to N fertilization (Marschner, 1995), and in this experiment all three species were responsive to the highest N rate (Figure 1). The higher Ca availability in soil deeper layers as affected by N fertilization (Figure 6) may have contributed to a better root development, increasing nutrient uptake and grain yield. The lime rate of 3000 kg ha^{-1} (recommended rate to raise base saturation to 60 %) resulted in the highest grain yield and phytomass production. This also increased the response to N fertilizer (Figure 1b,c), because, when
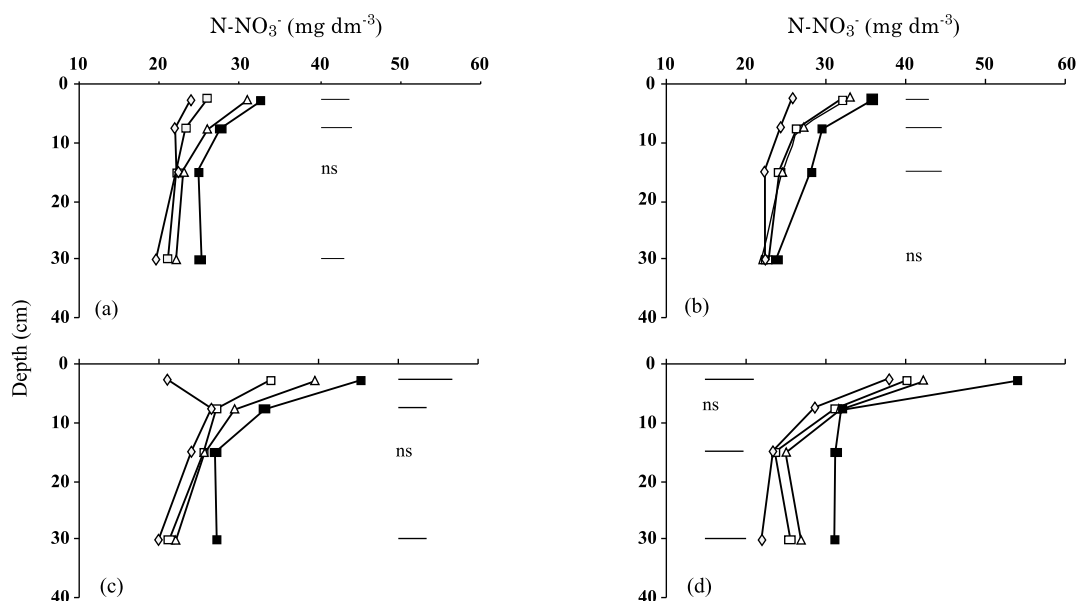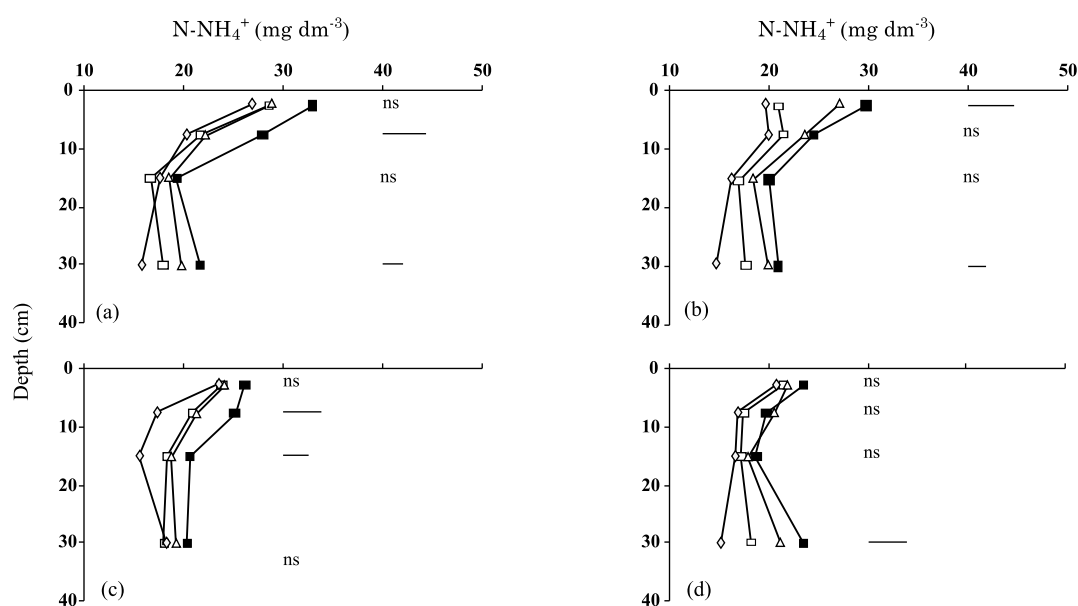

Figure 3. Nitrate (N-NO$_3^-$) levels in the soil profile as affected by nitrogen fertilization (◇): 0; (□): 50; (Δ): 100 and (■): 150 kg ha^{-1} of N, 18 months after liming (a): 0; (b): 1500; (c): 3000 and (d): 6000 kg ha^{-1} of lime). ▬: least significant difference at 5 % by the t test. ns: non significant.

Table 2. Linear correlation coefficients in different layers of soil profile, among Ca, Mg and K levels and nitrate levels provided by increasing nitrogen fertilization in different liming conditions

Depth	Lime dose (kg ha⁻¹)											
	0			1500			3000			6000		
	Ca	Mg	K	Ca	Mg	K	Ca	Mg	K	Ca	Mg	K
cm												
0–5	-0.54*	-0.62**	-0.75**	-0.99*	ns	-0.68**	-0.55*	-0.76**	-0.79**	-0.95*	-0.80**	-0.65**
5–10	-0.58*	-0.57*	-0.65**	ns	ns	-0.63**	-0.62**	-0.51*	-0.74**	-0.98*	ns	ns
10–20	-0.96*	-0.81**	ns	-0.60*	ns	ns	ns	ns	ns	-0.64**	ns	-0.71**
20–40	0.96*	ns	ns	0.72*	ns	0.65*	0.96*	ns	ns	0.98**	0.57*	ns

* and ** significant at 5 and 1% by the t test, respectively; ns: non significant.

Figure 4. Ammonium (N-NH$_4^+$) levels in the soil profile as affected by nitrogen fertilization (◇): 0; (□): 50; (Δ): 100 and (■): 150 kg ha⁻¹ of N, 18 months after liming ((a): 0; (b): 1500; (c): 3000 and (d): 6000 kg ha⁻¹ of lime). ____: least significant difference at 5 % by the t test. ns: non significant.

a soil has favorable chemical properties for root growth in deeper layers, the N uptake by grasses as well as grain yields may be increased (Caires et al., 2001).

In no-till systems, the absence of tillage, along with low lime solubility, may favor the formation of a concentration gradient of nutrients in the soil profile (Ernani et al., 2007), and surface liming leads to the formation of a surface layer with reduced soil acidity over the deeper layers, proportional to time and lime rate (Conyers et al., 2003; Soratto & Crusciol, 2008). The applied lime rate is one of the factors regulating liming effects in deep layers (Soratto & Crusciol, 2008), as observed for pH in this study (Figure 2).

The charges of soil colloids are usually negative and so there is a repulsion force towards NO$_3^-$. Hence, the amount of nitrate in the soil arable layer not absorbed by plants is available for leaching and can move to deeper layers over time (Figure 3). Soil acidity inhibits nitrate

production in soils fertilized with ammonium, but nitrification is favored by liming, and NO$_3^-$ anions are formed. These anions are mobile in soil (Adams & Martin, 1984), as observed in this experiment (Figure 3). Silva & Vale (2000) found that the application of ammonium sulphate favored NO$_3^-$ formation in five soil types, and a higher effect was observed when liming was applied. According to Chung & Zasoski (1993), the activity of nitrifying bacteria is greatly influenced by soil acidity and is reduced at pH < 6.0. In this experiment, the pH was therefore favorable to nitrification in soil surface layers (Figure 2).

Cation retention to soil colloids follows a lyotrophic series determined primarily by the cation charge attraction and hydrated ion diameter. Hence, in well-drained soils the amount of divalent is generally higher than of monovalent cations, which are more affected by leaching (Raij, 1991). This can explain the
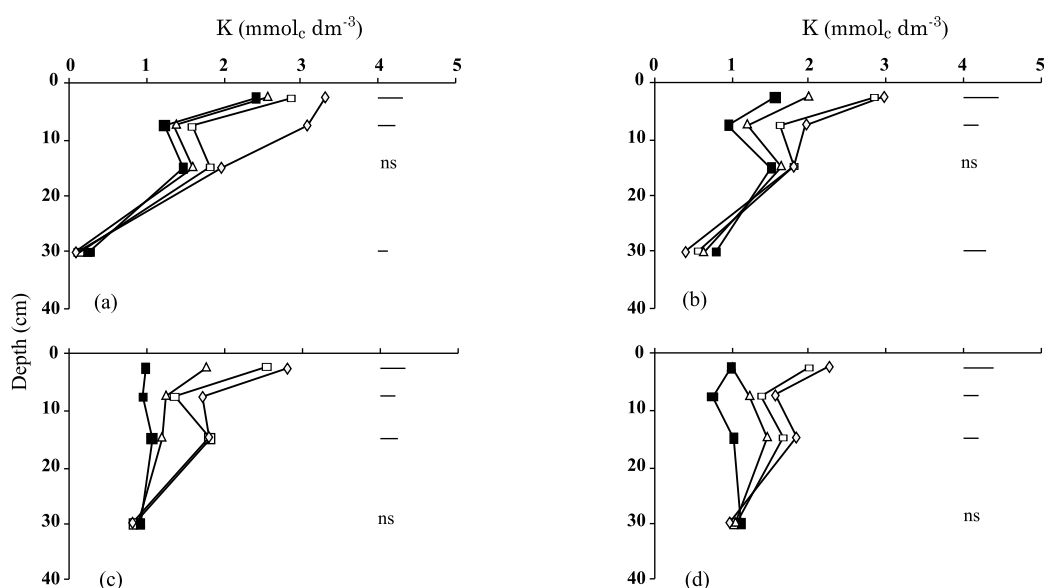
Figure 5. Potassium levels in the soil profile as affected by nitrogen fertilization (◊): 0; (□): 50; (Δ): 100 and (■): 150 kg ha⁻¹ of N, 18 months after liming ((a): 0; (b): 1500; (c): 3000 and (d): 6000 kg ha⁻¹ of lime). ___: least significant difference at 5 % by the t test. ns: non significant.

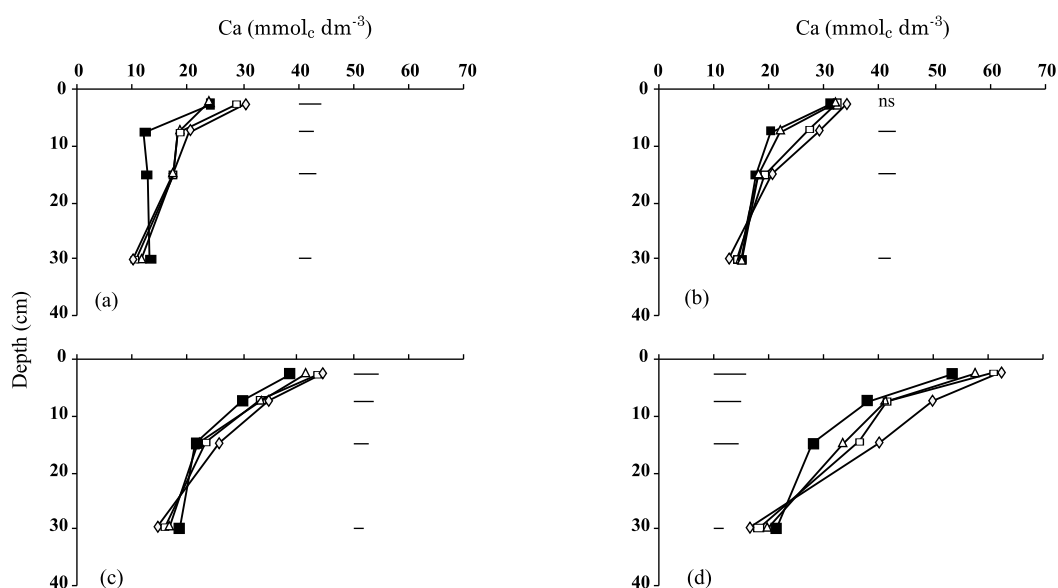**Figure 6. Calcium levels in the soil profile as affected by nitrogen fertilization (◊): 0; (□): 50; (Δ): 100 and (■): 150 kg ha⁻¹ of N, 18 months after liming ((a): 0; (b): 1500; (c): 3000 and (d): 6000 kg ha⁻¹ of lime). ___: least significant difference at 5 % by the t test. ns: non significant.**

NH_4^+ and K mobility in the soil profile observed in this study (Figure 4). According to the lyotrophic series, the leaching of K tends to be higher than of divalent bases due to its lower retention energy to soil colloids (Raij, 1991). Futhermore, K preferential displacement to deeper layers is undesirable in no-tillage systems, mainly in tropical soils with low CEC and regions with high rainfall (Garcia et al., 2008). Apart from ion pairing with nitrate in soil solution, the increase in ammonium levels (Figure 4) also provided by N fertilization may have contributed to K movement in

the soil profile (Figure 5). These cations compete for the same retention sites on soil colloids, once they have the same charge and hydrated ion size (Raij, 1991).

Nitrogen fertilization intensifies the Ca movement through the profile of limed tropical soils (Pearson et al., 1962). Foloni & Rosolem (2006) observed an effect of N fertilization on Ca mobility down to 30–50 cm when lime was incorporated, but they also found that when lime was applied to the soil surface, N fertilization increased Ca levels down to 10 cm only.
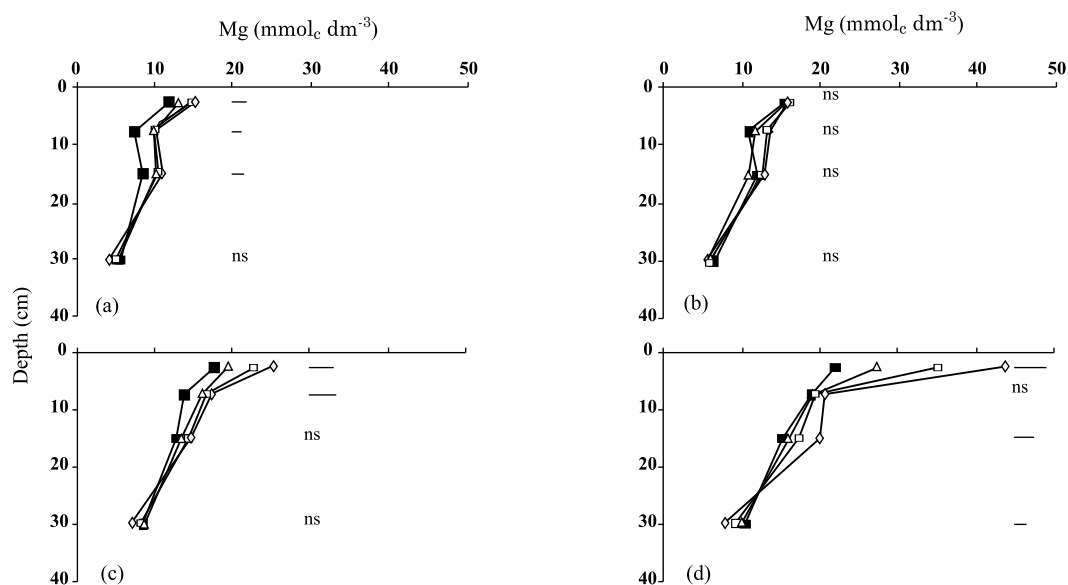
Figure 7. Magnesium levels in the soil profile as affected by nitrogen fertilization (◇): 0; (□): 50; (△): 100 and (■): 150 kg ha⁻¹ of N, 18 months after liming ((a): 0; (b): 1500; (c): 3000 and (d): 6000 kg ha⁻¹ of lime). ———: least significant difference at 5 % by the t test. ns: non significant.

In the present experiment, Ca leaching was affected by N fertilization (Figure 6). After a long period applying high N rates to eucalyptus (*Eucalyptus* spp) increased concentrations of Ca, Mg and K were found in the soil solution in the 0.3–0.6 m layer, also showing an effect of N on soil base cation mobilization (Mitchell & Smethurst, 2008).

As the accompanying anion affects base cation mobility, Ca and Mg mobility in the soil profile may differ according to the accompanying ion, as shown by Chaves et al. (1991), who reported a higher affinity of Mg^{2+} for SO_4^{2-} originated from ammonium sulphate fertilizer, for example. Nevertheless, Rosolem & Silva (2010) found that increased ammonium nitrate rates affected Mg most of all cations, in terms of mobility in soil depth. In this study, N rates commonly used for grain crops had a major effect on base cation leaching through the soil profile (Figures 5, 6, 7 and Table 2). Subsurface liming effects may depend on the release of organic acids (Miyazawa et al., 2002; Franchini et al., 2003) but a vertical movement of bases in soil was observed both with or without crop residues on the soil surface (Rosolem & Silva, 2010). For these authors, this mobility was related to N–NO_3^- released by N fertilizer, rather than to organic acids release. Besides, Moraes et al. (2007) observed no influence of different crop residues on liming effects, even with an amount of 20 t ha⁻¹ of residues on the soil surface. In this study, the higher N rates resulted in more residues on the surface, which may have produced more organic acids and eventually, Ca and Mg leaching. However, when leaching is caused by organic acids, the leaching sequence is inverted, because organic acids have a higher affinity for polyvalent cations such as Al^{3+}, Ca^{2+} and Mg^{2+}, which

may result in higher K^+ and NH_4^+ concentrations in the soil surface layer (Rosolem et al., 2004). These effects were not observed in the surface layers (Figure 5) at the highest N rate. Additionally, organic acids with 5 or 6 carbon atoms, e.g, citric, oxalic and tartaric acids, have higher affinity for these bases, and the concentration of these acids in pearl millet is low (Jones, 1998).

Another evidence for base cations being leached along with nitrate are the high correlations (Table 2), negative in surface layers and positive in the subsoil. Furthermore, organic acids produced by crop residues may have been quickly degraded by microorganisms or even adsorbed to soil colloids, resulting in lower influence on cation mobility.

Calcium deficiency and Al toxicity are the main chemical limitations for deep root development in tropical soils, and the consequences are described as nutritional and water stress (Adams & Moore 1983; Farina et al., 2000). Therefore, a high mobility of lime by products, especially Ca (Figure 6), down through the soil profile significantly affects crop yields and the viability of no tillage systems in tropical regions. Our results showed that the N–NO_3^- resulting from increased pH and N application to the soil surface may contribute significantly to reduce subsoil Al toxicity.

CONCLUSIONS

1. Maize and rice respond to sidedressed N rates up to 150 kg ha⁻¹.

2. Lime applied to the soil surface increases N-NO_3^- levels in the top soil layers and this N-NO_3^- is prone to be leached to deeper soil layers together with basic cations such as Ca, Mg and K.

3. Nitrogen application rates recommended for maize and rice production contribute to the downward movement of basic cations in the presence of lime and may reduce subsurface Al toxicity.

ACKNOWLEDGEMENTS

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