# LIMING INFLUENCE ON SOIL CHEMICAL PROPERTIES, NUTRITIONAL STATUS AND YIELD OF ALFALFA GROWN IN ACID SOIL[1]

**Adônis Moreira[2] & Nand Kumar Fageria[3]**


## SUMMARY

**Alfalfa is an important forage crop with high nutritive value, although highly susceptible to soil acidity. Liming is one of the most efficient and prevailing practices to correct soil acidity and improve alfalfa yield. The objective of this study was to evaluate response to liming of alfalfa grown in a greenhouse on a Typic Quartzipsamment soil. The treatments consisted of four lime rates (0, 3.8, 6.6 and 10.3 Mg ha$^{-1}$) and two cuts. Alfalfa dry matter increased quadratically with increasing lime rates. In general, dry matter yield was maximized by a lime rate of 8.0 Mg ha$^{-1}$. Except for the control, the dry matter nutrient contents in the treatments were adequate. The positive linear correlation between root and nodule dry matter with lime rates indicated improvement of these plant traits with decreasing soil acidity. The soil acidity indices pH, base saturation, $Ca^{2+}$ concentration, $Mg^{2+}$ concentration, and H + Al were relevant factors in the assessment of alfalfa yield. The magnitude of influence of these soil acidity indices on yield as determined by the coefficient of determination ($R^2$) varied and decreased in the order: base saturation, H + Al, pH, Ca and Mg concentrations. Optimum values of selected soil chemical properties were defined for maximum shoot dry matter; these values can serve as a guideline for alfalfa liming to improve the yield of this forage on acid soils.**


**Index terms:** ***Medicago sativa*** **L., shoot dry matter, nodulation, soil acidity, nutrient uptake**

---

(1) Trabalho parcialmente financiado pelo CNPq. Recebido para publicação em agosto de 2009 e aprovado em abril de 2010.

(2) Pesquisador da Embrapa Amazônia Ocidental, Caixa Postal 319, CEP 69010-970 Manaus (AM). Bolsista CNPq. E-mail: adonis.moreira@cpaa.embrapa.br

(3) Pesquisador da Embrapa Arroz e Feijão. Caixa Postal 179, CEP 75375-000 Santo Antonio de Goiás (GO). Bolsista CNPq. E-mail: fageria@cnpaf.embrapa.br

**RESUMO**: *INFLUÊNCIA DA CALAGEM NAS PROPRIEDADES QUÍMICAS DO SOLO, ESTADO NUTRICIONAL E PRODUÇÃO DA ALFAFA EM UM SOLO ÁCIDO*

*A alfafa é uma importante forrageira com alto valor nutritivo, porém é altamente suscetível à acidez do solo. A calagem é uma das mais eficientes práticas para corrigir esse problema e melhorar a produtividade da alfafa. O objetivo deste trabalho foi avaliar a resposta à calagem da alfafa cultivada em Neossolo Quartzarênico em casa de vegetação. Os tratamentos consistiram de quatro doses de calcário (0; 3,8; 6,6 e 10,3 Mg ha$^{-1}$) e duas épocas de corte. A produção de matéria seca foi significativamente aumentada com a adição de calcário, com o máximo rendimento estimado obtido com a adição de 8,0 Mg ha$^{-1}$. Exceto na testemunha, o teor de nutrientes na matéria seca foi adequado. A matéria seca de raízes e de nódulos foi significativamente aumentada com a aplicação de calcário. Os índices de acidez do solo, como pH, saturação por bases, concentração de $Ca^{2+}$ e de $Mg^{2+}$ e H + Al, foram importantes na avaliação do rendimento da alfafa. Magnitudes de influência da acidez do solo desses índices no rendimento variaram, conforme determinado pelo coeficiente de determinação ($R^2$) obedeceram a seguinte ordem decrescente: saturação por bases, H + Al, pH, concentração de $Ca^{2+}$ e de $Mg^{2+}$. Os valores considerados ótimos das propriedades químicas do solo selecionados para obtenção da máxima produção estimada podem servir como referência e melhorar o rendimento de culturas forrageiras em solos ácidos.*

*Termos de indexação:* Medicago sativa *L., produção de matéria seca, nodulação, acidez do solo, absorção de nutrientes.*

## INTRODUCTION

Alfalfa is one of the most important forage crops worldwide because of its good forage quality, high forage yield in a wide range of environments, and high adaptability to different climatic conditions (Dordas, 2006; Berg et al., 2007; Zhang et al., 2008; Turan et al., 2009). Alfalfa is grown mainly for forage production while seed yield is secondary (Iannucci et al., 2002). The forage can be used directly for grazing or conserved as silage or hay and is a reliable high-quality nutrient source that could represent a significant contribution to the agricultural sector (Borreani & Tabacco, 2006).

Brazil has large cattle herds and alfalfa is an important component of forages/pastures used for cattle feeding. Most pasture in Brazil are acidic and fertility is low (Fageria & Baligar, 2008). Theoretically, soil acidity is quantified on the basis of pH and $Al^{3+}$ concentrations of soils. For crop production, however, soil acidity is a complex of numerous factors involving nutrient/element deficiencies and toxicities, low activity of beneficial microorganisms and reduced plant root growth that limit nutrient and water uptake (Fageria & Baligar, 2003). The situation is further complicated by various interactions among these factors (Foy, 1992). The practice of correcting soil acidity reduces the available contents of Al, Fe, Mn, Zn, and Cu, but increases the availability of other essential nutrients. For most crops other than alfalfa, nutritional conditions for maximum potential plant growth are most appropriate at pH values in a low acidity range (6.0 to 6.5) (Fageria, 2009). The components of the soil acidity complex have been thoroughly discussed in various publications (Foy, 1984, 1992; Tang & Rengel, 2003).

Liming is an effective and dominant practice to raise soil pH and reduce acidity-related constraints to improve crop yields (Fageria & Baligar, 2008). The quantity of lime required depends on the soil type, quality of liming material, costs and crop species or cultivars (Fageria & Baligar, 2008). Information on appropriate liming rates for alfalfa grown on acid soils in Brazil is limited. The objective of this study was to evaluate liming influence on changes in soil chemical properties and alfalfa growth in an acid soil.

## MATERIAL AND METHODS

The experiment was conducted under greenhouse conditions. The soil used in the experiment (0–20 cm depth) was a Typic Quartzipsamment (Neossolo Quartzarênico, Brazilian classification – Embrapa, 1999) from the Experimental farm of Embrapa Cattle, South-East Research Center, in São Carlos, state of São Paulo, Brazil (latitude 27 º 04 ' 39 ", longitude 53 º 00 ' 4 ", 264 m asl). The following chemical (Raij et al., 2001) and texture properties were determined (Embrapa, 1997).: pH ($CaCl_2$ 0,1 mol L$^{-1}$) = 3.8, pH (water) = 4.7, soil organic matter (SOM) = 28 g $kg^{-1}$, P (resin) = 4.0 mg $kg^{-1}$, K (resin) = 0.07 $cmol_c$ $kg^{-1}$, Ca (resin) = 0.4 $cmol_c$ $kg^{-1}$, Mg (resin) = 0.2 $cmol_c$ $kg^{-1}$, Al (KCl 1.0 mol $L^{-1}$) = 1.9 $cmol_c$ $kg^{-1}$, H + Al = 8.0 $cmol_c$ $kg^{-1}$, V (base saturation) = 7.7 %, B (hot water) = 0.42 mg $kg^{-1}$, Cu (DTPA-TEA extractant, DTPA 0.005 mol $L^{-1}$ + TEA 0.1 mol $L^{-1}$ + $CaCl_2$ 0.01 mol $L^{-1}$ at pH 7.3) = 1.8 mg $kg^{-1}$, Fe (DTPA-TEA) = 38.0 mg $kg^{-1}$, Mn (DTPA-TEA) = 1.3 mg $kg^{-1}$, Zn (DTPA-TEA) = 0.1 mg $kg^{-1}$, 860 g $kg^{-1}$ sand, 60 g $kg^{-1}$ silt and 80 g $kg^{-1}$ clay.

The experiment was conducted in clay pots filled with 3.0 $dm^3$ of air-dried soil, sieved through a 2.0 mm mesh. The experimental design was a completely randomized block with four replications in a factorial combination (2x4) of four lime rates with aboveground plant harvests repeated over time (two cuts). Dolomitic limestone (27.1 % CaO, 17.5 % MgO and effective calcium carbonate – ECC of 95 %) were incorporated 30 days before planting, at rates of 0, 3.8, 6.6 and 10.3 Mg $ha^{-1}$, respectively.

The basal application of P, K, B, Cu, Fe, Mn and Zn was supplied according to recommended solutions adapted from Allen et al. (1976) and Malavolta (1980), for greenhouse experiments (200 mg $dm^{-3}$ P as MAP, 50 mg $dm^{-3}$ K as KCl, 0.5 mg $dm^{-3}$ B as $H_3BO_3$, 1.5 mg $dm^{-3}$ Cu as $CuSO_4$, 5.0 mg $dm^{-3}$ Mn as $MnSO_4$, 5.0 mg $dm^{-3}$ Mn as $FeSO_4$ and 5.0 mg $dm^{-3}$ Zn as $ZnSO_4$). Forty-five days after planting, an additional 100 mg $dm^{-3}$ K was applied as $K_2SO_4$. The pots were irrigated daily with distilled water to replace the moisture lost by evapotranspiration and to maintain the soil near 70 % of field capacity (FC), according to the method described by Cassel & Nielsen (1986).

After scarification, the alfalfa seeds (cultivar LEN 4) were inoculated with *Sinorhizobium meliloti* and then treated with 0.01 mg $L^{-1}$ Co using, $CoSO_4$, 0.1 mg $L^{-1}$ Ni using $NiSO_4$, and 0.1 mg $L^{-1}$ Mo using $NaMoO_4$. Ten seeds were planted in each pot and after germination thinned to three plants per pot. Three months after planting (Ninety days), the plants were cut, while thirty days after the second cut was made. The harvested material was oven-dried to constant weight at 65 °C, weighed and digested (Walinga et al., 1995). The total concentration of N ($H_2SO_4$ digestion – Kjeldahl), P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn (digested with a mixture of $HNO_3$ and $HClO_4$) in the shoot dry matter – stems and leaves (Walinga et al., 1995).

Soil samples were collected from each treatment before planting (composites of the four replications) and at each harvest to determine the pH in $CaCl_2$, soil organic matter (SOM), P, K, Ca, Mg, S-$SO_4$, H + Al, base saturation (V %), B, Cu, Fe, Mn, and Zn, according to the method described by Raij et al. (2001). At the end of the experiment, roots and nodules were extracted to quantify their dry matter yield (RDM and NDM, respectively). The total concentrations of N, P, K, Ca, and Mg in the nodules were determined according to the method proposed by Walinga et al. (1995). From data of soil analysis and base saturation, the saturation of K, Ca and Mg was calculated using the following formula (Fageria, 2008):

$$\text{Saturation of K, Ca or Mg (\%)} = \left(\frac{K}{CEC}\right) \times 100, \left(\frac{Ca}{CEC}\right) \times 100 \text{ or } \left(\frac{Mg}{CEC}\right) \times 100$$

The values of K, Ca, Mg, and cation exchange capacity (CEC = ΣK, Ca, Mg, H + Al) are given in $cmol_c$ $kg^{-1}$.

The ratios Ca/K, Ca/Mg, and Mg/K were also calculated from the soil analysis data. The data were submitted to analyses of variance (ANOVA) and regression analysis (Hicks, 1973) was performed to determine adequate lime rates. All statistical inferences were based on a significance level of 0.05.

## RESULTS AND DISCUSSION

### Soil chemical properties

All soil chemical properties evaluated were significantly influenced by increasing lime rates in the range of 0 to 10.3 Mg $ha^{-1}$, except P, B and Zn (Table 1). The cut *versus* lime interactions were only significant for K, Mg, H + Al, Mn and sulfur (S-$SO_4$), indicating variation in these properties according to the date of alfalfa cut. Significant increase in the soil pH, Ca, Mg and base saturation with liming was expected. Dolomitic limestone is a source of Ca and Mg and in the presence of water the carbonates dissolve and the $OH^-$ and $HCO_3^-$ ions are released, reducing soil acidity (Havlin et al., 1999). Fageria (2001) also reported significant increase in these soil chemical properties with liming in the Brazilian Oxisols. The reduction of exchangeable K from 0.8 to 0.5 $cmol_c$ $kg^{-1}$ in the first cut and 0.4 $cmol_c$ $kg^{-1}$ in the second cut was due to a higher uptake by alfalfa plants (Moreira et al., 2008). In highly fertile soils, Lloveras et al. (2001) found extraction rates of 1.5 to 1.7 Mg $ha^{-1}$ of $K_2O$, with shoot dry matter yield of 21.5 Mg $ha^{-1}$. In the second cut there was a decrease in the soil organic matter (SOM), P, K, Ca, Mg, base saturation, S-$SO_4$ and B content, compared with the first cut. This may be associated with the uptake by the crop because alfalfa dry matter yield was higher in the second than in the first cut.

Ca/K, Mg/K, Ca and Mg saturation increased significantly with increasing lime rates in the range of 0 to 10.3 Mg $ha^{-1}$ (Table 2). The increase in these soil indices may be related to increased Ca and Mg soil contents due to liming. Moreira et al. (2005) and

**Table 1. Influence of lime rates on soil chemical properties before planting and in first and second cut**

| Lime rate | pH $CaCl_2$ | SOM | P | K | Ca | Mg | H + Al | V | S-$SO_4$ | B | Cu | Fe | Mn | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mg ha$^{-1}$ | | g kg$^{-1}$ | mg kg$^{-1}$ | cmol$_c$ kg$^{-1}$ | | | | % | mg kg$^{-1}$ | | | | | |
| | | | | | | Before planting | | | | | | | | |
| 0 | 3.8 | 20.0 | 192 .0 | 0.2 | 0.4 | 0.2 | 8.0 | 7.7 | 1.0 | 0.2 | 2.3 | 55.0 | 2.0 | 1.5 |
| 3.8 | 5.5 | 22.0 | 214 .0 | 0.2 | 1.6 | 1.4 | 3.6 | 47.0 | 2.0 | 0.4 | 1.9 | 37.0 | 1.6 | 1.6 |
| 6.6 | 5.8 | 19.0 | 165 .0 | 0.1 | 2.0 | 1.6 | 2.2 | 62.8 | 3.0 | 0.1 | 1.5 | 27.0 | 1.7 | 1.2 |
| 10.3 | 6.4 | 19.0 | 192 .0 | 0.1 | 3.3 | 2.5 | 1.6 | 78.8 | 2.0 | 0.2 | 1.4 | 19.0 | 1.2 | 1.2 |
| Average | 5.4 | 20.0 | 191 .0 | 0.2 | 1.8 | 1.4 | 3.9 | 49.1 | 2.0 | 0.2 | 1.8 | 34.5 | 1.6 | 1.4 |
| | | | | | | After first cut (a) | | | | | | | | |
| 0 | 3.9 | 34.8 | 149.0 | 0.8 | 0.4 | 0.2 | 8.3 | 14.4 | 98.0 | 0.4 | 2.9 | 121.5 | 14.4 | 4.1 |
| 3.8 | 4.7 | 30.3 | 145.8 | 0.5 | 1.4 | 1.1 | 4.6 | 38.2 | 15.0 | 0.5 | 2.8 | 68.8 | 9.5 | 4.4 |
| 6.6 | 5.4 | 31.5 | 173.8 | 0.7 | 2.9 | 2.7 | 3.1 | 66.8 | 14.8 | 0.4 | 2.2 | 52.5 | 5.8 | 3.9 |
| 10.3 | 6.1 | 30.3 | 165.5 | 0.5 | 5.0 | 4.6 | 2.0 | 82.3 | 9.0 | 0.6 | 2.0 | 32.8 | 4.0 | 4.2 |
| Average | 5.0 | 31.7 | 158.5 | 0.6 | 2.5 | 2.2 | 4.5 | 50.6 | 34.2 | 0.5 | 2.5 | 68.9 | 8.4 | 4.2 |
| | | | | | | After second cut (b) | | | | | | | | |
| 0 | 3.8 | 26.3 | 94.3 | 0.4 | 0.3 | 0.2 | 8.2 | 9.9 | 18.5 | 0.3 | 3.3 | 121.8 | 10.4 | 3.3 |
| 3.8 | 4.5 | 22.5 | 85.5 | 0.1 | 1.2 | 1.0 | 5.4 | 29.5 | 7.3 | 0.4 | 3.3 | 73.5 | 9.1 | 4.4 |
| 6.6 | 5.1 | 21.8 | 89.5 | 0.1 | 1.9 | 1.2 | 2.9 | 52.0 | 6.3 | 0.4 | 2.1 | 51.8 | 3.9 | 4.1 |
| 10.3 | 6.0 | 21.8 | 88.0 | 0.1 | 3.4 | 2.1 | 2.1 | 73.0 | 4.5 | 0.5 | 2.0 | 30.8 | 3.8 | 3.5 |
| Average | 4.9 | 23.1 | 89.3 | 0.2 | 1.7 | 1.1 | 4.7 | 41.1 | 9.2 | 0.4 | 2.7 | 69.5 | 6.8 | 3.8 |
| | | | | | | Average of first (a) and second cut (b) | | | | | | | | |
| 0 | 3.9 | 30.6 | 121.7 | 0.6 | 0.4 | 0.2 | 8.3 | 12.2 | 58.3 | 0.4 | 3.1 | 121.7 | 12.4 | 3.7 |
| 3.8 | 4.6 | 24.5 | 115.7 | 0.3 | 1.3 | 1.1 | 5.0 | 33.9 | 11.2 | 0.5 | 3.1 | 71.2 | 9.3 | 4.4 |
| 6.6 | 5.3 | 26.7 | 131.7 | 0.4 | 2.4 | 2.0 | 3.0 | 59.4 | 10.6 | 0.4 | 2.2 | 52.2 | 4.9 | 4.0 |
| 10.3 | 6.1 | 26.1 | 126.8 | 0.3 | 4.2 | 3.4 | 2.1 | 77.7 | 6.8 | 0.6 | 2.0 | 31.8 | 3.9 | 3.9 |
| Average | 5.0 | 27.0 | 124.0 | 0.4 | 2.1 | 1.7 | 4.6 | 45.8 | 21.7 | 0.5 | 2.6 | 69.2 | 7.6 | 4.0 |
| Cutting (a) | 9.68** | 119.01** | 149.17** | 257.19** | 6.91* | 17.32** | 0.51$^{NS}$ | 28.31** | 24.68** | 2.89$^{NS}$ | 3.96$^{NS}$ | 0.10$^{NS}$ | 18.43** | 4.71* |
| Lime (b) | 299.23** | 6.74** | 1.50$^{NS}$ | 24.13** | 31.13** | 31.05** | 388.25** | 258.50** | 23.53** | 1.65$^{NS}$ | 30.36** | 478.44** | 107.71** | 1.90$^{NS}$ |
| a x b | 1.01$^{NS}$ | 0.84$^{NS}$ | 1.52$^{NS}$ | 4.36* | 1.35$^{NS}$ | 6.40** | 3.29* | 1.28$^{NS}$ | 12.97** | 0.60$^{NS}$ | 2.24$^{NS}$ | 0.70$^{NS}$ | 5.18* | 0.69$^{NS}$ |
| CV (%) | 2.99 | 7.63 | 12.93 | 19.73 | 40.80 | 41.50 | 8.44 | 10.96 | 65.89 | 24.75 | 11.88 | 7.20 | 14.21 | 16.36 |

SOM, soil organic matter; V%, base saturation = å(K, Ca, Mg)/CEC; CEC, cation exchange capacity = å(Ca, Mg, K, H + Al). Cut in ANOVA= first and second cut. *, **, $^{NS}$ significant at 5 and 1 % and non significant, respectively.

**Table 2. Linear regression and coefficient of determination ($R^2$) of liming influence on Ca/K, Ca/Mg, Mg/K ratios, and Ca, Mg and K saturation before planting and after first and second cut**

| Limestone rate | Ca/K | Ca/Mg | Mg/K | Saturation Ca | Saturation Mg | Saturation K |
|---|---|---|---|---|---|---|
| Mg ha$^{-1}$ | | | | % | | |
| | | | Before planting | | | |
| 0 | 2.0 | 2.0 | 1.0 | 4.5 | 2.3 | 2.3 |
| 3.8 | 8.0 | 1.1 | 7.0 | 23.5 | 20.6 | 2.9 |
| 6.6 | 20.0 | 1.3 | 16.0 | 33.9 | 27.1 | 1.7 |
| 10.3 | 33.0 | 1.3 | 25.0 | 44.0 | 33.3 | 1.3 |
| | | | After first cut | | | |
| 0 | 0.5 | 2.0 | 0.3 | 4.1 | 2.1 | 8.0 |
| 3.8 | 2.8 | 1.3 | 2.2 | 18.4 | 14.5 | 6.6 |
| 6.6 | 4.1 | 1.1 | 3.9 | 30.8 | 28.7 | 7.4 |
| 10.3 | 10.0 | 1.1 | 9.2 | 41.3 | 38.0 | 4.1 |
| $\beta_0$ | -2.510 | 1.823 | -0.472 | 4.661 | 2.216 | 8.243 |
| $\beta_1$ | 0.889 | -0.086 | 0.844 | 3.669 | 3.595 | -0.332 |
| $R^2$ | 0.92** | 0.78** | 0.93** | 0.99** | 0.96** | 0.71** |
| | | | After second cut | | | |
| 0 | 0.8 | 1.5 | 0.5 | 3.3 | 2.2 | 4.4 |
| 3.8 | 12.0 | 1.2 | 10.0 | 15.6 | 13.0 | 1.3 |
| 6.6 | 19.0 | 1.6 | 12.0 | 31.1 | 19.7 | 1.6 |
| 10.3 | 34.0 | 1.6 | 21.0 | 44.1 | 27.3 | 1.3 |
| $\beta_0$ | 0.036 | 1.378 | 1.028 | 2.467 | 2.948 | 3.568 |
| $\beta_1$ | 3.171 | 0.018 | 1.902 | 4.069 | 2.435 | -0.274 |
| $R^2$ | 0.98** | 0.19 $^{NS}$ | 0.97** | 0.99** | 0.99** | 0.63* |

*, **, $^{NS}$: significant at 5 and 1 % and non significant, respectively.

Fageria (2006) reported similar results in Brazilian Oxisols with legumes (alfalfa and bean, respectively).

### Lime rates *versus* shoot dry matter

Shoot dry matter increased quadratically with increasing lime rates in the range of 0 to 10.3 Mg $ha^{-1}$ in the first and second cuts and in the average of both (Figure 1), with a significant interaction between cut and lime rate (F value = 6.2958, $p \leq 0.05$). In the first cut, maximum shoot dry matter was achieved with the addition of 7.3 Mg $ha^{-1}$ lime. Similarly, in the second cut, maximum shoot dry matter was achieved with 8.6 Mg $ha^{-1}$ lime. In general, maximum shoot dry matter was obtained with a lime rate of 8.0 Mg $ha^{-1}$. The higher lime rate required to achieve maximum shoot dry matter in the second cut compared to first cut can be associated with higher shoot weight and lower pH and base saturation (Table 1). The improvement in alfalfa shoot dry matter with liming in acid soils is widely reported (Adams & Pearson, 1984; Lathwell & Reid, 1984; Moreira et al., 1999). The yield increase of field crops with liming is due to improvement of the Ca and Mg soil contents and reduction of soil acidity (Fageria & Baligar, 2003; Fageria, 2009). In addition, liming also improves biological $N_2$ fixation in acid soils and enhances net mineralization of organic N (Edmeades & Ridley, 2003). Fageria (2008) reported that N deficiency was observed two weeks after sowing of common bean (*Phaseolus vulgaris*) in unlimed Oxisol plots, while no N deficiency was observed in the limed plots.

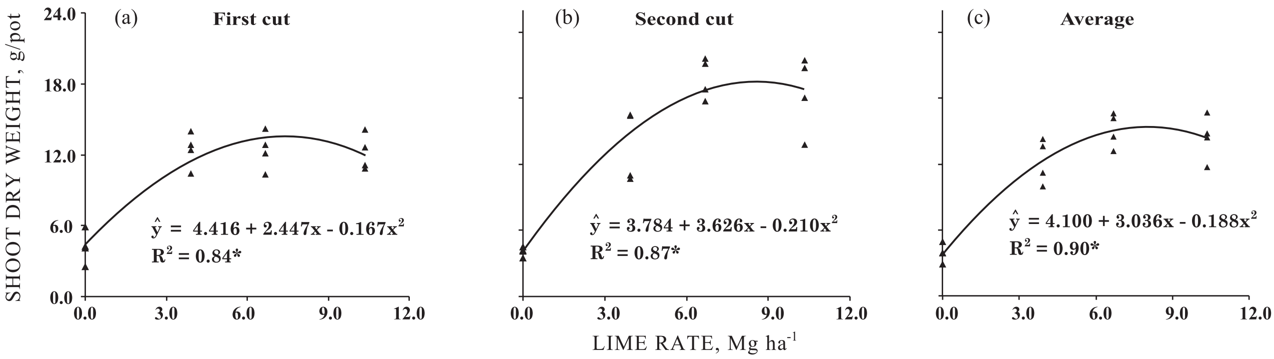


**Figure 1. Effect of lime application on alfalfa shoot dry matter yield in first and second cut and on the average of both cuts.**

**Table 3. Influence of lime rates on nutrient concentrations in alfalfa shoot dry matter**

| Lime rate | N | P | K | Ca | Mg | S | B | Cu | Fe | Mn | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mg $ha^{-1}$ | g $kg^{-1}$ | | | | | | | mg $kg^{-1}$ | | | |
| | | | | | First cut | | | | | | |
| 0 | 26.91 | 3.94 | 23.93 | 1.93 | 1.67 | 2.49 | 18.53 | 3.98 | 122.72 | 151.86 | 46.12 |
| 3.8 | 25.72 | 3.13 | 20.48 | 9.06 | 4.59 | 2.24 | 17.63 | 5.32 | 76.08 | 51.16 | 48.62 |
| 6.6 | 32.07 | 2.89 | 20.19 | 11.40 | 4.92 | 2.75 | 17.94 | 5.50 | 73.71 | 56.17 | 29.31 |
| 10.3 | 33.98 | 2.72 | 22.87 | 11.85 | 5.52 | 2.98 | 14.99 | 5.79 | 60.41 | 52.26 | 28.07 |
| Average | 29.67 | 3.17 | 21.87 | 8.56 | 4.18 | 2.62 | 17.27 | 5.14 | 83.23 | 77.86 | 38.03 |
| | | | | | Second cut | | | | | | |
| 0 | 22.55 | 3.24 | 26.00 | 1.79 | 1.59 | 3.12 | 9.03 | 3.90 | 56.18 | 149.05 | 63.96 |
| 3.8 | 30.83 | 2.82 | 16.47 | 6.89 | 3.75 | 2.09 | 8.71 | 3.88 | 45.15 | 53.51 | 29.64 |
| 6.6 | 34.95 | 2.25 | 10.17 | 6.40 | 3.40 | 1.49 | 7.31 | 3.04 | 47.25 | 30.52 | 19.12 |
| 10.3 | 37.20 | 2.17 | 8.90 | 7.10 | 3.80 | 1.71 | 7.25 | 3.29 | 37.41 | 32.26 | 17.44 |
| Average | 31.38 | 2.62 | 15.39 | 5.54 | 3.14 | 2.13 | 8.08 | 3.53 | 47.00 | 66.34 | 35.04 |
| | | | | | Average | | | | | | |
| 0 | 24.73 | 3.59 | 24.96 | 1.86 | 1.63 | 2.86 | 13.78 | 3.94 | 89.45 | 150.45 | 55.03 |
| 3.8 | 28.27 | 2.97 | 18.48 | 7.98 | 4.17 | 2.17 | 13.17 | 4.60 | 60.62 | 52.34 | 44.13 |
| 6.6 | 33.51 | 2.57 | 15.18 | 8.90 | 4.15 | 2.12 | 12.63 | 4.27 | 60.48 | 43.34 | 24.21 |
| 10.3 | 35.59 | 2.44 | 15.89 | 9.47 | 4.65 | 2.34 | 11.12 | 4.54 | 48.92 | 42.26 | 22.76 |
| Cutting (a) | 1.34 $^{NS}$ | 6.41** | 23.06** | 107.97** | 64.46** | 14.63** | 100.43** | 55.85** | 39.51** | 2.40$^{NS}$ | 2.17$^{NS}$ |
| Lime (b) | 11.16** | 5.70** | 10.88** | 147.20** | 110.85** | 7.01** | 1.54$^{NS}$ | 1.95$^{NS}$ | 8.74** | 49.46** | 60.12** |
| a x b | 1.99 $^{NS}$ | 0.16 $^{NS}$ | 6.76** | 15.79** | 8.37** | 14.37** | 0.43$^{NS}$ | 6.89** | 2.96$^{NS}$ | 0.81$^{NS}$ | 11.75** |
| CV (%) | 13.70 | 21.11 | 20.51 | 11.63 | 10.06 | 15.24 | 20.47 | 14.09 | 28.48 | 29.25 | 15.70 |

*, **, $^{NS}$ significant at 5 and 1 % and non significant, respectively.

## Macro and micronutrient uptake

Significant interaction ($p \leq 0.05$) was observed between cut and lime rate for most nutrients analyzed in alfalfa dry matter. The results of two cuts for nutrient uptake showed that the concentration of all nutrients studied in the second cut was lower than in the first cut (Table 3). Similarly to results of Moreira et al (2008), this may be due to a dilution effect, since dry matter was higher in the second than in the first cut and soil nutrient levels exported by shoot dry matter were lower. Fageria (2009) reported that nutrient concentration (nutrient content per unit dry matter) decreased with increasing shoot dry matter in crop plants. This phenomenon is known as dilution effect in plant mineral nutrition (Marschner, 1995; Fageria, 2009). In general, the N, Ca, and Mg concentrations increased with increasing lime rates. This may be associated with higher $N_2$-fixation rate by $N_2$-fixing bacteria and higher Ca and Mg uptake with increasing lime rates. The application of limestone significantly increased the N, Ca and Mg concentrations in the dry matter yield, with visual symptoms of Ca deficiency in the control. The adequate nutrient levels for alfalfa are in the range of N: 30 to 50 g kg$^{-1}$, P: 2.5 to 7.0 mg kg$^{-1}$, K: 20 to 38 mg kg$^{-1}$, Ca: 5 to 30 mg kg$^{-1}$, Mg: 2.5 to 10 mg kg$^{-1}$, S: 2.5 to 5 mg kg$^{-1}$, B: 20 to 80 mg kg$^{-1}$, Cu: 5 to 30 mg kg$^{-1}$, Fe 30 to 250 mg kg$^{-1}$, Mn: 25 to 200 g kg$^{-1}$, and Zn: 20 to 70 mg kg$^{-1}$ (Plank, 1988; Moreira et al., 2008). Using these values as reference, we observed that in the absence of liming, the N, Ca and Mg concentrations were average below the range considered suitable, the inverse was observed for K, P, Fe, Mn and Zn, but these levels declined significantly with increasing the lime rates (Table 3).

## Root and nodule dry matter and macronutrient contents in nodule dry matter

There was a significant increase in root and nodule dry matter with increasing lime rates in the range of 0 to 10.3 Mg ha$^{-1}$. The variation in root dry matter was 93 % and the variation in nodule dry matter (NDM) was 82 % with liming. Hence, RDM was relatively more sensitive to liming than NDM (Table 4). In agreement with Moreira et al. (2008), a significant effect of liming on these two variables (root and nodule dry matter) was observed. The NDM was significantly correlated with the shoot dry matter (SDM) (SDM = -0.031 + 0.029NDM, $R^2 = 0.77$; $p \leq 0.05$). As reported by Rhykerd & Overdahl (1972) regarding the sensitivity of biological $N_2$ fixation because of soil acidity, an increase of 46 % in the N content of nodules at rates of 3.8 to 10.3 Mg ha$^{-1}$ was also found. In the case of the P, Ca and Mg levels in the NDM, no influence of the limed treatments was observed (Table 4).

## Optimal soil acidity indices

The regression models (Table 5) can indicate the extent to which the dependent variable can be predicted by independent variables. On average, based on $R^2$, the soil acidity indices influencing alfalfa yield followed the order: Mg saturation, base saturation > acidity > pH and Ca saturation. Under tropical conditions, the optimum acidity indices for maximum dry matter yield were pH 5.4, base saturation 57 %, Ca saturation 40 %, and Mg saturation 24 %. Rechcigl et al. (1988) observed that alfalfa can be grown on acid soil at a pH of 5.7 (soil/water slurries) in the 0–15 cm layer.

The relative yield (%) was correlated with the exchangeable Ca, Mg and Ca + Mg (highest values estimated at 2.9, 2.0 and 4.4 cmol$_c$ kg$^{-1}$, respectively) (Figure 2). These values are independent of the Ca/Mg ratio, since studies carried out by Moreira et al. (2005) showed an absence of response in function of the Ca and Mg molar ratios at proportions of 1:0, 1:1, 2:1, 3:1, and 4:1, but that excess of Mg in soil (0:1 ratio) can cause phytotoxicity, significantly reducing alfalfa dry matter yield (Gomes et al., 2002).

**Table 4. Influence of lime treatments on root dry matter, nodule dry matter and N, P, Ca and Mg concentrations in alfalfa nodule dry matter after second cut**

| Liming rate | Dry weight | | Concentration in DW of nodules | | | |
|---|---|---|---|---|---|---|
| | Root | Nodule | N | P | Ca | Mg |
| Mg ha$^{-1}$ | g/pot | | g kg$^{-1}$ | | | |
| 0 | 3.1 | 0.05 | - | - | - | - |
| 3.8 | 10.6 | 0.45 | 52.37 | 2.60 | 2.20 | 1.90 |
| 6.6 | 13.4 | 0.58 | 62.42 | 2.98 | 2.07 | 1.90 |
| 10.3 | 17.9 | 0.50 | 76.25 | 2.78 | 2.28 | 1.47 |
| Average | 11.3 | 0.40 | 63.68 | 2.79 | 2.18 | 1.76 |
| Lime rate vs. DW of Roots | $\hat{y} = 3.850 + 1.408x$, $R^2 = 0.93^*$ | | | | | |
| Lime rate vs. DW of Nodules | $\hat{y} = 0.047 + 0.143x - 0.009x^2$ $R^2 = 0.82^*$ | | | | | |

*: significant at the 5 %. The nutrients concentrations (N, P, Ca and Mg) in the control were not analyzed due to insufficient sample quantity.

**Table 5. Significant relationship between soil chemical properties (x) and alfalfa shoot dry matter ($\hat{y}$)**

| Soil Chemical property | Regression equation | R² | Value for maximum yield |
|---|---|---|---|
| | First cut | | |
| pH ($CaCl_2$) | $\hat{y}$ = -98.008 + 40.807x - 3.742$x^2$ | 0.828* | 5.4 |
| Ca ($cmol_c\ kg^{-1}$) | $\hat{y}$ = 4.250 + 4.422x - 0.500$x^2$ | 0.611* | 4.4 |
| Mg ($cmol_c\ kg^{-1}$) | $\hat{y}$ = 5.411 + 4.247x - 0.533$x^2$ | 0.602* | 4.0 |
| H + Al ($cmol_c\ kg^{-1}$) | $\hat{y}$ = 10.680 + 1.357x - 0.253$x^2$ | 0.826* | 2.7 |
| Base saturation (%) | $\hat{y}$ = -1.821 + 0.500x - 0.004$x^2$ | 0.814* | 62.5 |
| B ($mg\ kg^{-1}$) | $\hat{y}$ = 3.935 + 19.110x - 11.957$x^2$ | 0.491* | 0.8 |
| Fe ($mg\ kg^{-1}$) | $\hat{y}$ = 16.807 - 0.095x | 0.727* | 176.9 |
| Mn ($mg\ kg^{-1}$) | $\hat{y}$ = 16.213 - 0.706x | 0.624* | 23.0 |
| Ca Saturation (%) | $\hat{y}$ = 0.897 + 0.828x - 0.014$x^2$ | 0.836* | 29.6 |
| Mg Saturation (%) | $\hat{y}$ = 3.268 + 0.769x - 0.013$x^2$ | 0.808* | 29.5 |
| Ca/K Ratio | $\hat{y}$ = 3.775 + 2.769x - 0.175$x^2$ | 0.741* | 7.9 |
| Ca/Mg Ratio | $\hat{y}$ = 19.285 - 6.163x | 0.831* | 3.1 |
| Mg/K Ratio | $\hat{y}$ = 5.004 + 2.652x - 0.186$x^2$ | 0.704* | 7.1 |
| | Second cut | | |
| pH ($CaCl_2$) | $\hat{y}$ = -162.665 + 66.705x - 6.081$x^2$ | 0.915* | 5.5 |
| Ca ($cmol_c\ kg^{-1}$) | $\hat{y}$ = 2.841 + 11.462x - 834$x^2$ | 0.749* | 3.1 |
| Mg ($cmol_c\ kg^{-1}$) | $\hat{y}$ = 0.596 + 22.303x - 6.133$x^2$ | 0.781* | 1.8 |
| H + Al ($cmol_c\ kg^{-1}$) | $\hat{y}$ = 25.820 - 2.584x | 0.848* | 10.0 |
| Base saturation (%) | $\hat{y}$ = -1.500 + 0.782x - 0.007$x^2$ | 0.823* | 5.6 |
| B ($mg\ kg^{-1}$) | $\hat{y}$ = 16.700 + 118.167x - 100.981$x^2$ | 0.507* | 0.6 |
| Fe ($mg\ kg^{-1}$) | $\hat{y}$ = 25.925 - 0.172x | 0.809* | 150.7 |
| Mn ($mg\ kg^{-1}$) | $\hat{y}$ = 26.749 - 1.882x | 0.753* | 14.2 |
| Ca Saturation (%) | $\hat{y}$ = 2.177 + 0.927x - 0.012$x^2$ | 0.850* | 38.6 |
| Mg Saturation (%) | $\hat{y}$ = 0.042 + 1.512x - 0.029$x^2$ | 0.867* | 26.1 |
| Ca/K Ratio | $\hat{y}$ = 4.549 + 0.983x - 0.015$x^2$ | 0.812* | 32.8 |
| Ca/Mg Ratio | $\hat{y}$ = -36.935 + 60.578x - 15.301$x^2$ | 0.558* | 2.0 |
| Mg/K Ratio | $\hat{y}$ = 3.483 + 1.584x - 0.037$x^2$ | 0.830* | 21.4 |
| | Average | | |
| pH ($CaCl_2$) | $\hat{y}$ = -129.463 + 53.912x - 4.919$x^2$ | 0.824* | 5.4 |
| Ca ($cmol_c\ kg^{-1}$) | $\hat{y}$ = 4.580 + 6.495x - 0.833$x^2$ | 0.702* | 3.9 |
| Mg ($cmol_c\ kg^{-1}$) | $\hat{y}$ = 6.020 + 6.623x - 0.979$x^2$ | 0.636* | 3.4 |
| H + Al ($cmol_c\ kg^{-1}$) | $\hat{y}$ = 16.020 + 0.466x - 0.231$x^2$ | 0.825* | 1.00 |
| Base saturation (%) | $\hat{y}$ = 2.823 + 0.679x - 0.006$x^2$ | 0.828* | 56.6 |
| B ($mg\ kg^{-1}$) | $\hat{y}$ = -7.859 + 76.805x - 65.876$x^2$ | 0.508* | 0.6 |
| Fe ($mg\ kg^{-1}$) | $\hat{y}$ = 21.377 - 0.134$x^2$ | 0.644* | 159.5 |
| Mn ($mg\ kg^{-1}$) | $\hat{y}$ = 20.990 - 1.166x | 0.624* | 18.0 |
| Ca Saturation (%) | $\hat{y}$ = 2.526 + 0.716x - 0.009$x^2$ | 0.796* | 39.8 |
| Mg Saturation (%) | $\hat{y}$ = 1.360 + 1.288x - 0.027$x^2$ | 0.861* | 23.8 |
| Ca/K Ratio | $\hat{y}$ = 6.315 + 0.872x - 0.013$x^2$ | 0.844* | 33.5 |
| Ca/Mg Ratio | $\hat{y}$ = -23.594 + 47.472x - 13.59$x^2$ | 0.586* | 1.7 |
| Mg/K Ratio | $\hat{y}$ = 5.732 + 1.293x - 0.030$x^2$ | 0.847* | 21.6 |

*: significant at 5 % probability.

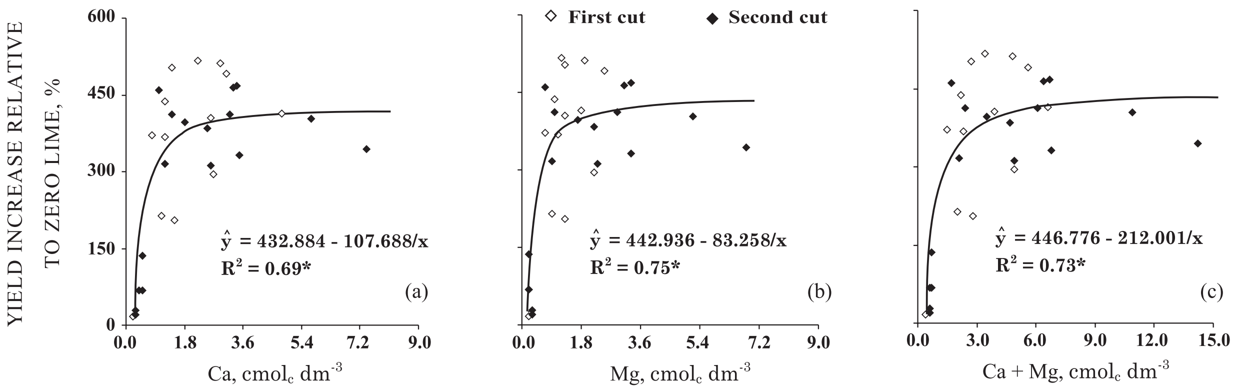


**Figure 2. Yield increase relative to zero lime: Alfalfa yield (%) of control (zero lime) influenced by concentrations of exchangeable Ca (a), Mg (b), and Ca+Mg (c) in an acid soil.**

## CONCLUSIONS

1. Liming improved alfalfa root growth and nodulation of the alfalfa root system with $N_2$-fixing bacteria.

2. Soil chemical properties such as pH, base saturation and Ca and Mg contents were increased, which may be responsible for higher alfalfa yields.

3. The optimum lime rate for a maximum alfalfa dry matter yield is estimated to be about 8.0 Mg $ha^{-1}$.

4. Optimum soil acidity indices for maximum yield alfalfa were pH 5.4, base saturation 57 %, Ca saturation 40 % and Mg saturation 24 %.

5. Alfalfa can tolerate acidity of H + Al up to 1.0 $cmol_c$ $kg^{-1}$ without reducing dry matter yield.

## LITERATURE CITED

ADAMS, F. & PEARSON, R.W. Crop responses to lime in the Southern United States. In: ADAMS, F., eds. Soil acidity and liming. Madison, American Society of Agronomy, 1984. p.212-265.

ALLEN, S.E.; TERMAN, G.L. & CLEMENTS. L.B. Greenhouse techniques for soil-plant-fertilizer research. Muscle Shoals, National Fertilizer Development Center, 1976. 55p.

BERG, W.K.; CUNNINGHAM, S.M.; BROUDER, S.M.; JOERN, B.C.; JOHNSON, K.D.; SANTINI, J.B. & VOLENCE. J.J. The long term impact of phosphorus and potassium fertilization on alfalfa yield and yield components. Crop Sci., 47:2198-2209, 2007.

BORREANI, G. & TABACCO, E. The effect of a baler chopping system of fermentation and losses of wrapped big bales of alfalfa. Agron. J., 98:1-7, 2006.

CASSEL, D.K. & NIELSEN, D.R. Field capacity and available water capacity. In: KLUTTE, A., ed. Methods of soil analysis; Physical and mineralogical methods. 2.ed. Madison, American Society of Agronomy, Soil Science Society of Agronomy, 1986. Part 1. p.901-926.

DORDAS, C. Foliar boron application improves seed set, seed yield, and seed quality of alfalfa. Agron. J., 98:907-913, 2006.

EDMEADES, D.C. & RIDLEY, A.M. Using lime to ameliorate topsoil and subsoil acidity. In: RENGEL Z., ed. Handbook of soil acidity. New York, Marcel Dekker, 2003. p.297-336.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA – EMBRAPA. Manual de métodos de análise do solo. Rio de Janeiro, National Service for Soil Survey and Soil Conservation, 1997. 212p.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA – EMBRAPA. Sistema brasileiro de classificação do solo. Brasília, SPI/Embrapa Produção e Informação, 1999. 412p.

FAGERIA, N.K. Effect of liming on upland rice, common bean, corn, and soybean production in cerrado soil. Pesq. Agropec. Bras., 36:1419-1424, 2001.

FAGERIA, N.K. Liming and copper fertilization in common bean production on an Oxisol in no-tillage system. J. Plant Nutr., 29:1219-1228, 2006.

FAGERIA, N.K. Optimum soil acidity indices for common bean production on an Oxisol in no-tillage system. Comm. Soil Sci. Plant Anal., 39:845-857, 2008.

FAGERIA, N.K. The use of nutrients in crop plants. Boca Raton, CRC Press, 2009. 430p.

FAGERIA, N.K. & BALIGAR, V.C. Fertility management of tropical acid soil for sustainable crop production. In: RENGEL, Z., ed. Handbook of soil acidity. New York, Marcel Dekker, 2003. p.359-385.

FAGERIA, N.K. & BALIGAR, V.C. Ameliorating soil acidity of tropical Oxisols by liming for sustainable crop production. Adv. Agron., 99:345-431, 2008.

FOY, C.D. Physiological effects of hydrogen, aluminum and manganese toxicity in acid soils. In: ADAMS, F., ed. Soil acidity and liming. Madison, American Society of Agronomy, 1984. p.57-97.

FOY, C.D. Soil chemical factors limiting plant root growth. Adv. Soil Sci., 19:97-149, 1992.

GOMES, F.T.; BORGES, A.C.; NEVES, J.C. & FONTES, P.C.R. Influence of limestone rates with different calcium:magnesium ratios on shoot dry matter yield and mineral composition of alfalfa. Pesq. Agropec. Bras., 37:1779-1786, 2002.

HAVLIN, J.; BEATON, J.D.; TISDALE, S.L. & NELSON, W.L. Soil fertility and fertilizers; An introduction to nutrient management. Upper Saddle River, Prentice Hall, 1999. 499p.

HICKS, C.R. Fundamental concepts in the design of experiments. New York, Rinehart and Winston, 1973. 349p.

IANNUCCI, A.; DI FONZO, N. & MARTINIELLO, P. Alfalfa (*Medicago sativa* L.) seed yield and quality under different forage management systems and irrigation treatments in a Mediterranean environment. Field Crop Res., 78:65-74, 2002.

LATHWELL, D.J. & REID, W.S. Crop response to lime in the northeastern United States. In: ADAMS, F., ed. Soil acidity and liming. Madison, American Society of Agronomy, 1984. p.305-332

LLOVERAS, J.; FERRAN, J.; BOIXADERA, J. & BONET, J. Potassium fertilization effects on alfalfa in a Mediterranean climate. Agron. J., 93:139-143, 2001.

MALAVOLTA, E. Elementos de nutrição mineral de plantas. São Paulo, Agronômica Ceres, 1980. 251p.

MARSCHNER, H. Mineral nutrition for higher plants. London, Academic Press, 1995. 889p.

MOREIRA, A.; BERNARDI, A.C.C. & RASSINI, J.B. Calagem, estado nutricional e adubação da alfafa. In: FERREIRA, R.P.; RASSINI, J.B.; RODRIGUES, A.A.; FREITAS, A.R.; CAMARGO A.C. & MENDONÇA, F.C., eds. Cultivo e utilização da alfafa nos trópicos. São Carlos, Embrapa Pecuária Sudeste, 2008. p.95-137.

MOREIRA, A.; CARVALHO, J.G. & EVANGELISTA, A.R. Influence of calcium: magnesium ratio in limestone on nodulation, dry matter yield and mineral composition of alfalfa. Pesq. Agropec. Bras., 34:249-255, 1999.

MOREIRA, A.; CARVALHO, J.G. & EVANGELISTA, A.R. Calcium and magnesium ratio in the fertility of a dystrophic Dark Red Latosol cultivated with alfalfa. Ci. Agrotec., 29:786-794, 2005.

MOREIRA, A.; HEINRICHS, R. & FREITAS, A.R. Phosphorus and magnesium ratio on soil fertility, nutritional status, and yield of alfalfa. R. Bras. Zootec., 37:984-989, 2008.

PLANCK, C.O. Alfalfa. In: PLANCK, C.O., ed. Plant analysis handbook for Georgia. Athens, University of Georgia, 1988. p.18-19.

RAIJ, B.van; ANDRADE, J.C.; CANTARELLA, H. & QUAGGIO, J.A. Análise química para avaliação dos solos tropicais. Campinas, Instituto Agronômico de Campinas, 2001. 284p.

RHYKERD, C.L. & OVERDAHL, C.J. Nutrition and fertilizer use. In: HANSON, C.H., ed. Alfalfa science and technology. Madison, American Society of Agronomy, 1972. p.437-465.

RECHCIGL, J.E.; EDMISTEN, K. L.; WOLF, D.D. & RENEAU Jr., R.B. Response of alfalfa grown on acid soil to different chemical amendments. Agr. J., 80:515-518, 1988.

TANG, C. & RENGEL, Z. Role of plant cation/anion uptake ratio in soil acidification. In: RENGEL, Z., ed. Handbook of soil acidity. New York, Marcel Dekker, 2003. p.57-81

TURAN, M.; KIZILOGLU, F.M. & KETTERINGS, Q.M. Phosphorus management of lucerne grown on calcareous soil in Turkey. J. Plant Nutr., 32:516-535, 2009.

WALINGA, I.; van der LEE, J.J.; HOUBA, V.J.G.; van VARK, W. & NOVOZAMSKY, I. Plant analysis manual. Dordrecht, Kluwer Academic Publishers, 1995. 40p.

ZHANG, T.; WANG, X.; HAN, J.; WANG, Y.; MAO, P. & MAJERUS, M. Effects of between-row and within-row spacing on alfalfa seed yields. Crop Sci., 48:794-803, 2008.