Annual crop rotation of tropical pastures with no-till soil as affected by lime surface application

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ABSTRACT

Soil acidity and low natural fertility are the main limiting factors for grain production in tropical regions such as the Brazilian Cerrado. The application of lime to the surface of no-till soil can improve plant nutrition, dry matter production, crop yields and revenue. The present study, conducted at the Lageado Experimental Farm in Botucatu, State of São Paulo, Brazil, is part of an ongoing research project initiated in 2002 to evaluate the long-term effects of the surface application of lime on the soil's chemical attributes, nutrition and kernel/grain yield of peanut (*Arachis hypogaea*), white oat (*Avena sativa* L.) and maize (*Zea mays* L.) intercropped with palisade grass (*Urochloa brizantha* cv. Marandu), as well as the forage dry matter yield of palisade grass in winter/spring, its crude protein concentration, estimated meat production, and revenue in a tropical region with a dry winter during four growing seasons. The experiment was designed in randomized blocks with four replications. The treatments consisted of four rates of lime application (0, 1000, 2000 and 4000 kg ha^{-1}), performed in November 2004. The surface application of limestone to the studied tropical no-till soil was efficient in reducing soil acidity from the surface down to a depth of 0.60 m and resulted in greater availability of P and K at the soil surface. Ca and Mg availability in the soil also increased with the lime application rate, up to a depth of 0.60 m. Nutrient absorption was enhanced with liming, especially regarding the nutrient uptake of K, Ca and Mg by plants. Significant increases in the yield components and kernel/grain yields of peanut, white oat and maize were obtained through the surface application of limestone. The lime rates estimated to achieve the maximum grain yield, especially in white oat and maize, were very close to the rates necessary to increase the base saturation of a soil sample collected at a depth of 0–0.20 m to 70%, indicating that the surface liming of 2000 kg ha^{-1} is effective for the studied tropical no-till soil. This lime rate also increases the forage dry matter yield, crude protein concentration and estimated meat production during winter/spring in the maize-palisade grass intercropping, provides the highest total and mean net profit during the four growing seasons, and can improve the long-term sustainability of tropical agriculture in the Brazilian Cerrado.

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1. Introduction

No-tillage (NT) is one of the main strategies adopted to mitigate soil degradation. In this production model, the preservation of agricultural ecosystems is the main objective; additionally, this strategy has the potential to recover areas that are already considered unproductive. Because of its adaptability and enormous benefits for soil biodiversity, NT has been adopted in various regions of the world, especially in countries such as Argentina, Australia, Brazil, Canada and the United States (Derpsch et al., 2010). The large expansion of NT systems is primarily related to the productivity gains observed in legume and cereal crops.

Soil acidity reduces the availability of nutrients such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) and increases the bioavailability of toxic elements such as aluminum (Al^{3+}) (von Uexküll and Mutert, 1995; Caires et al., 2005). Given these inappropriate conditions for

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crop development, liming is commonly employed to increase the productive potential of soil. However, the low solubility and mobility of limestone in soil cause its diminishing effect on soil acidity to occur slowly once it reaches certain depths in NT soil (Ernani et al., 2004).

In regions with a regular rainfall distribution, several reports have indicated an absence of any response of grain production to surface liming for years (Moreira et al., 2001; Caires et al., 2006a, 2008a,b,c, 2011, 2015; Joris et al., 2013). However, in the tropical regions where dry spells often occur during the rainy season and the dry winter, chemical disorders due to soil and subsoil acidity is an important factor limiting crop productivity (Marsh and Grove, 1992; Sumner, 1995; Castro and Crusciol, 2013a,b; Costa and Crusciol, 2016; Tiritan et al., 2016). This effect has been attributed to the toxic effects of Al on root growth at certain depths, inducing water stress and nutrient uptake by plants (Caires et al., 2008b). Thus, subsoil acidity alleviation can promote greater root development, increasing the plants' tolerance to water stress during dry spells.

The amount of soil organic matter has been considered an important factor to reduce free Al levels; however, tropical soils such as Oxisols and Ultisols exhibit a naturally low organic matter content. In NT systems, the addition of organic residues helps to regulate Al species in acid surface soils, but cash crops produce low amounts of straw (Alford et al., 2003; Allen et al., 2007; Zobeck and Schillinger, 2010). In addition, regions with dry winters (low and irregular rainfall), such as the Brazilian Cerrado or African Savanna, have large risks in growing a successful dry-season crop, resulting in a long fallow period without productivity (Borghi et al., 2013). In such warm conditions, straw decomposes rapidly (Nascente et al., 2013; Pariz et al., 2011a), and negatively affects success of NT system.

In NT systems, tropical forages such as palisade grass {Urochloa brizantha cv. Marandu (Hochst. ex A. Rich.) R.D. Webster [syn. Brachiaria brizantha cv. Marandu (Hochst. ex A. Rich.) Stapf]} can be available for use in the winter to spring (grazed by animals or cut and removed as fodder) and can be intercropped with grain crops in the summer (Kluthcouski and Aidar, 2003) using an integrated crop-livestock system. Therefore, intercropping maize, sorghum [Sorghum bicolor (L.) Moench], and soybean [Glycine max (L.) Merr.] with tropical perennial grasses is an excellent alternative for producing grain and forage for livestock during the dry season and for increasing the supply of straw for the continuity of NT management (Pariz et al., 2011a,b; Borghi et al., 2013; Crusciol et al., 2011, 2012, 2013, 2014, 2015; Mateus et al., 2016). Consequently, food production is increased without the requirement of cultivating additional areas, and the system is considered sustainable (Sani et al., 2011; Surve and Arvadia, 2011). Most of the agricultural research in tropical and subtropical regions has focused on developing methods to identify liming requirements for soil correction and on determining the rates and application methods that result in higher crop response (Martins et al., 2014a,b). Intercropping grain with forage crops is a new practice, and it requires more information before widespread adoption of the technology (Mateus et al., 2016). Knowledge of species competition for water, light, and nutrients is important for successful grain production and adequate forage availability (Pariz et al., 2011b). For example, understanding the changes in soil chemical attributes and their effects on grain and pasture yield is necessary for establishing and adjusting lime requirements in a crop rotation scheme under NT management (Tiritan et al., 2016).

This study aimed to evaluate the changes in the soil chemical properties, plant nutrition and kernel/grain yield of peanuts, white oat and maize intercropped with palisade grass, as well as forage dry matter yield of palisade grass in winter/spring, its crude protein concentration, estimated meat production, and revenue resulting from superficial liming under no-tillage during four growing seasons in a region with dry winters, such as that of the Brazilian Cerrado.

2. Materials and methods

2.1. Site description and climatic data

The experiment was conducted from October 2004 to October 2008 at the Lageado Experimental Farm of the College of Agricultural Sciences, FCA/UNESP, in Botucatu, São Paulo State, Brazil. The geographical coordinates of the study site are 48°23′W, 22°51′S and the elevation is 765 m. During the experimental period, rainfall was measured daily using a 50 cm tall plastic rain gauge (pluviometer) placed on the ground at a height of 1.20 m in the experimental area (Fig. 1).

The soil is classified as a Typic Hapludox (USDA, 2014), with sand, silt, and clay contents of 54, 11, and 35%, respectively, at a depth of 0–0.20 m. The area had been managed since 2002 under a no-till system: in the growing season of 2002/2003, upland rice (Oryza sativa) in the summer and black oat (Avena strigosa Schreb.) in the fall; in the growing season of 2003/2004, common bean (Phaseolus vulgaris L.) in the summer and black oat in the fall.

Prior to the beginning of the experiment (October 2002) and before the last limestone application (August 2004), eight subsamples were randomly obtained from useable areas of each plot at depths of 0–0.05, 0.05–0.10, 0.10–0.20, 0.20–0.40, and 0.40–0.60 m and were combined into one composite sample to determine the soil chemical attributes (Table 1). The soil pH was determined in a 0.01 mol L^{-1} CaCl$_2$ suspension (1:2.5 soil/solution). Soil organic matter was determined via the colorimetric method proposed by Haynes (1984) using a sodium dichromate solution. The total acidity at pH 7.0 (H + Al) was evaluated with 0.5 mol L^{-1} calcium acetate at pH 7.0 and determined through titration with a 0.025 mol L^{-1} NaOH solution. Exchangeable Al was extracted with neutral 1 mol L^{-1} KCl at a 1:10 soil/solution ratio and determined by titration with a 0.025 mol L^{-1} NaOH solution. Available P and exchangeable Ca, Mg, and K were extracted using an ion exchange resin. Exchangeable Ca^{2+}, Mg^{2+} and K$^+$ were determined using a Shimadzu AA-6300 atomic absorption/Flame-Emission spectrophotometer. Phosphorus was determined calorimetrically (Murphy and Riley, 1962) using a FEMTO 600S spectrophotometer. The cation exchange capacity (CEC) was calculated from the sum of the concentrations of the H, Al, K, Ca, and Mg cations. Given the low natural level due to the climate conditions and mineralogical composition of the soil (Leal et al., 2009), exchangeable Na was not measured. Base saturation (BS) values were calculated by dividing the sum for K, Mg, and Ca (the bases) by the CEC and multiplying the result by 100% (van Raij et al., 2001).

2.2. Experimental design

In this study, we adopted a completely randomized block experimental design with four treatments, replicated six times. The plot size was 5.4 m × 10.0 m. The plots were subjected to four rates of dolomitic limestone application: (i) Control (no lime); (ii) 1.0 Mg ha^{-1} (half the recommended dose); (iii) 2.0 Mg ha^{-1} (calculated to raise base saturation to 70%); and (iv) 4.0 Mg ha^{-1} (twice the recommended dose).

2.3. Establishment of treatments

At the beginning of the experiment (October 15, 2002), limestone rates were applied superficially. The reapplication on November 2004 was based on a soil analysis that was performed in August 2004, where the base saturation in the treatment in

Table 1
Chemical characteristics of the soil before the experiment (October 2002) and before the last application (August 2004).

Depth m	pH (CaCl$_2$)	SOM g dm^{-3}	P (resin) mg dm^{-3}	H + Al mmol$_c$ dm^{-3}	Al	K	Ca	Mg	CEC	BS %
October 2002										
0–0.05	5.0	27	17	38	4.0	1.6	28	11.7	78	53
0.05–0.10	4.9	25	12	40	3.7	1.0	31	14.2	85	54
0.10–0.20	4.3	24	7	56	9.1	0.4	21	8.2	85	34
0.20–0.40	3.9	22	6	83	17.9	0.2	18	4.8	105	22
0.40–0.60	3.9	23	4	100	24.8	0.2	19	3.7	122	18
0–0.20	*4.2*	*21*	*9*	*37*	*6.5*	*1.2*	*14*	*5.0*	*58*	*37*
August 2004										
0–0.05	5.2	27	61	32	1.6	1.3	31	15.7	79	58
0.05–0.10	4.9	26	32	35	2.3	1.3	23	11.9	71	50
0.10–0.20	4.6	25	28	44	4.8	1.1	15	7.6	68	36
0.20–0.40	4.2	23	14	58	12.9	0.7	10	4.5	73	21
0.40–0.60	4.0	23	15	78	17.6	0.6	8	3.2	90	14
0–0.20	*4.9*	*27*	*35*	*35*	*2.3*	*1.1*	*24*	*10.0*	*70*	*50*

Italic values signifies the weighted average of the first three depth.

which the limestone was applied reached 50%, which was the pre-established critical level for decreasing risk ascribed to soil acidity.

The dolomitic limestone rate (R) was calculated to increase base saturation (BS) in the topsoil (0–20 cm) to 70%, as shown in Eq. (1):

$$R\,(kg\,ha^{-1}) = (BS_2 - BS_1)CEC/(ECCE/1000) \qquad (1)$$

where BS$_2$ is the estimated base saturation (70%), and BS$_1$ is the base saturation measured in the soil analysis, as shown in Eq. (2):

$$BS_1\,(\%) = (Ca_{ex} + Mg_{ex} + K_{ex})100/CEC \qquad (2)$$

where Ca$_{ex}$, Mg$_{ex}$, and K$_{ex}$ are basic exchangeable cations, and CEC is the cation exchange capacity, calculated as indicated in Eq. (3):

$$CEC\,(mmol_c\,dm^{-3}) = Ca_{ex} + Mg_{ex} + K_{ex} + \text{total acidity at pH 7.0 (H + Al)} \qquad (3)$$

The dolomitic limestone was composed of 23.3% CaO, 17.5% MgO, and 71% effective calcium carbonate equivalents (ECCE). Among the limestone particles, 68.8, 92.4, and 99.7% passed through 50-, 20-, and 10-mesh sieves, respectively.

2.4. Crop management and the determination of plant nutrition, yield components, and crop yields

2.4.1. Peanut

The Runner IAC 886 cultivar was sown on 22 Nov., 2004 and 30 Nov., 2005. The peanut seeds were sown in both growing seasons at a spacing of 0.80 m between rows, with 12 seeds m^{-1} row using no-till seeding (Semeato, model Personale Drill 13, Passo Fundo, RS, Brazil). Every 100 kg of seeds was treated with 0.7 g of the active ingredient (a.i.) thiamethoxam {3-(2-chloro-thiazol-5-ylmethyl)-5-methyl-1,3,5-oxadiazinan-4-ylidene (nitro) amine} to control *Enneothrips flavens*. The basic fertilization (at the time of peanut sowing) in the sowing furrows consisted of 24 kg ha^{-1} of N as urea, 84 kg ha^{-1} of P$_2$O$_5$ as triple superphosphate and 48 kg ha^{-1} of K$_2$O as KCl + 0.5% Zn + 10% S (Ambrosano et al., 1997). Weeds were controlled using 0.4 kg a.i. ha^{-1} of paraquat {1,1′-dimethyl-4,4′-bipyridium} and 0.2 kg a.i. ha^{-1} of diurom {3-(3,4-dichlorophenyl)-1,1-dimethylurea} 1 d after sowing. 50% of the plants emerged by 8 d after sowing in the first growing season and by 10 d after sowing in the second.

When the peanut plants were at the full-bloom stage, 40 plants were sampled per plot (apical cluster of the main branch), according to Ambrosano et al. (1997). The material was dried in an oven at 65 °C to constant weight and then ground for macronutrient analyses. The concentrations of N, P, K, Ca, Mg, and S were determined using methods described by Malavolta et al. (1997). Nitrogen was determined by the Kjeldahl method. For the determination of other nutrients, milled plant material was mineralized

with a nitric-perchloric solution. From this solution, K, Ca, and Mg concentrations were determined using an atomic absorption spectrophotometer. P and S were measured by colorimeter methods using a spectrophotometer (Malavolta et al., 1997).

Peanut harvesting was performed manually on April 07th, 2005 and April 20th, 2006 in the first and second growing season, respectively. Yield components [the final population of plants (number of plants in the two central rows in 8-m rows extrapolated to hectare), the number of filled pods per plant (number of pods in 10 plants), the number of kernels per pod (total number of kernels in 10 plants/total number of pods in 10 plants), the 100-kernel weight (four samples of 100 kernels) and the hulled-kernel yield (kernel weight/pod weight ratio)] from each plot were determined. Pod yield (moisture content of 90 g kg^{-1}) was determined by manually harvesting the plants in the two central rows in 8-m rows. Ten peanut plants per plot were sampled for the evaluation of shoot dry matter at ground level.

2.4.2. White oat

Before sowing, the test area was desiccated by applying glyphosate (Roundup Original, 1800 g acid equivalents ha^{-1}, Monsanto Brazil). White oat cultivar 'IAC 7' was sown on April 23, 2005 and May 04, 2006. The seeds were sown in both growing seasons at a within-row spacing of 0.17 m, with 133 viable seeds m^{-2} using no-till seeding (Semeato, model Personale Drill 13, Passo Fundo, RS, Brazil). The basic fertilization (at the time of white oat sowing) in the sowing furrows consisted of 8 kg ha^{-1} of N as urea, 40 kg ha^{-1} of P$_2$O$_5$ as triple superphosphate and 20 kg ha^{-1} of K$_2$O as KCl + 7% S (Cantarella et al., 1997). After sowing was complete, 50% of the plants emerged by 8 d in the first growing season and by 7 d in the second growing season.

Full flowering of plants took place 58 and 66 days after sowing in the first and second growing seasons, respectively. At that stage, 10 plants were sampled for the evaluation of dry matter contents. Additionally, the flag leaves of 50 plants per plot were sampled (Cantarella et al., 1997) for macronutrient determination (N, P, K, Ca, Mg and S) (Malavolta et al., 1997).

White oat was harvested on September 06th, 2005 and September 09th, 2006 in the first and second growing seasons, respectively. Yield components [number of panicles per square meter (number of panicles in the two central rows in 8-m rows), number of spikelets per panicle (number of spikelets in 20 panicles), spikelet fertility (number of grain-bearing spikelets/total number of spikelets per panicle) and 1000-grain weight (four samples of 1000 grains)] from each plot were determined. Grain yield (moisture content of 130 g kg^{-1}) was determined by manually harvesting the plants in the two central rows in 8-m rows. Ten white oat plants
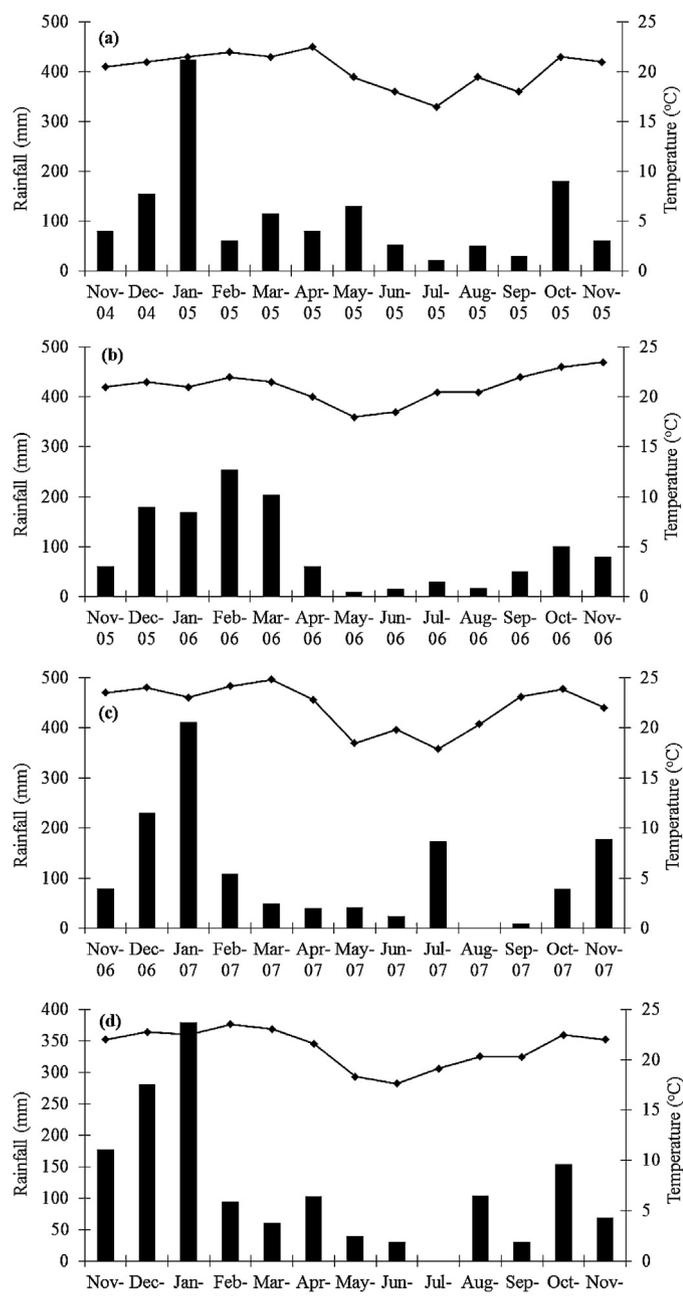
Fig. 1. Monthly rainfall (mm) and average temperature (°C) at the experimental area at Botucatu, São Paulo State, Brazil, during the period from November to November in the agricultural years of (a) 2004–2005, (b) 2005–2006, (c) 2006–2007 and 2007–2008.

per plot were sampled for the evaluation of shoot dry matter at ground level.

2.4.3. Maize and palisade grass

Before sowing, the area was desiccated by applying glyphosate (Roundup Original, 1800 g acid equivalents ha^{-1}, Monsanto Brazil). Maize was sown on December 2nd, 2006 and December 10th, 2007, at a depth of 3 cm using a no-till drill at a density of 66,000 seeds ha^{-1} and a row spacing of 0.45 m using no-till seeding (Semeato, model Personale Drill 13, Passo Fundo, RS, Brazil). The hybrid chosen was 2B570, an intermediate maturation-cycle hybrid that required good soil fertility. Every 100 kg of seeds was treated with 50 g of the a.i. carboxin {5,6-dihydro-2-methyl-1,4-oxathi-ine-3-carboxanilide} and 50 g of the a.i. thiram {Tetramethylthiuram

disulfide} to control pests (*Aspergillus flavus*, *Acremonium strictum*, *Fusarium moniliforme* and *Penicillium oxalicum*). The basic fertiliza-tion (at the time of maize sowing) in the sowing furrows consisted of 24 kg ha^{-1} of N as urea, 84 kg ha^{-1} of P$_2$O$_5$ as triple superphos-phate and 48 kg ha^{-1} of K$_2$O as KCl (Cantarella et al., 1997). Palisade grass was simultaneously sown at densities of 15.3 kg ha^{-1} seed (pure live seed = 34%). The forage seeds were mixed with base fer-tilizer (Mateus et al., 2007) and sown at depths of 8 cm below the soil surface, in the same maize rows, as described by Crusciol et al. (2012).

After sowing, 50% of the plants had emerged by 5 d in the first growing season and by 7 d in the second. During both growing seasons, the side dressing fertilization consisted of 90 kg ha^{-1} of N, applied mechanically between rows as urea. At the full-flowering stage, 10 plants per plot were sampled for the evaluation of dry matter contents. Additionally, the central third part of 30 leaves was sampled at the ear base (Cantarella et al., 1997) for macronutrient determination (N, P, K, Ca, Mg and S) (Malavolta et al., 1997).

Maize was harvested on April 1st, 2007 and March 29th, 2008 in the first and second growing seasons, respectively. Yield compo-nents [final plant population (number of plants in the two central rows in 8-m rows extrapolated to hectare), number of ears per plant (number of ears in 8-m rows/total number of plants in 8-m rows), number of grains per ear (number of grains in 10 ears) and 100-grain weight (eight samples of 100 grains)] from each plot were determined. Grain yield (moisture content of 130 g kg^{-1}) was deter-mined by manually harvesting the plants in the two central rows in 8-m rows. Ten corn plants per plot were sampled for the evaluation of shoot dry matter at ground level.

The forage dry matter yield values of palisade grass were evalu-ated 70 d (first cut) and 130 d (second cut) after the maize harvests in June and August, respectively. All forage (0.25 m from the soil surface) was cut in three areas of the plots (2 m^2 for each area with a row spacing of 0.45 m) using a manual mechanical rotary mower. After cutting, all forage was removed from the plots, also using a manual mechanical rotary mower. This cutting height was used to provide faster forage regrowth. The collected material was dried using forced-air circulation at 65 °C for 72 h. The dry matter was weighed, and the data were extrapolated to kg ha^{-1}.

For a crude protein evaluation, a sub-sample of palisade grass dry matter was used to determine the nitrogen concentration. Nitrogen was determined by the Kjeldahl method. To calculate the crude protein, the following formula was used: crude protein (%) = %N × 6.25 (Malavolta et al., 1997).

2.5. Estimated meat production

Although grazing by animals was not realized for the palisade grass after the grain maize harvest in the winter/spring, meat production was estimated using the Large Ruminant Nutrition System (LRNS; http://nutritionmodels.tamu.edu/lrns.html) model. The LRNS model is based on the Cornell Net Carbohydrate and Pro-tein System (CNCPS), version 5, as described by Fox et al. (2004). The following factors were used to predict the energy and protein requirements, the performance and the dry matter intake by indi-vidual cattle fed in a group: Nellore breed, bull sex, 450 kg body weight, 52% of carcass yield, 22% Body Fat Grading System and con-tinuous grazing. For each treatment, the values of the nutritional palisade grass composition were used to predict the performance values.

The dry matter intake by individual cattle fed in a group was 10.0 kg of dry matter day^{-1}. Due to the high forage crude protein (8.4–12.0%), the average daily weight gain (ADWG) was based on the allowable metabolizable energy and protein gain. Therefore, the ADWGs were used to estimate the meat production. The dry matter herbage allowance was the double amount of dry matter

intake by individual cattle, considering a grazing efficiency of 60%, according to Braga et al. (2007).

The time of animal grazing was calculated using a method similar to that used by Crusciol et al. (2012). A period of 365 d was considered, including an average maize life cycle of 115 d, a 70-d waiting period (an important waiting period after the maize harvest and before animal grazing of palisade grass pasture), and a period of 60 d after animal grazing on palisade grass pasture for regrowth and desiccation to produce straw under NT management. Therefore, 120 d (365 d – 115 d – 70 d – 60 d) were available for animal grazing for all of the treatments (60 d in each cut). Then, the animal stocking rate was estimated from the forage dry matter yield data, the time of animal grazing (days per cut), the dry matter intake by the individual cattle fed in a group and the grazing efficiency. The animal stocking rate was multiplied by ADWG, the time of animal grazing and the carcass yield (52%) to estimate the total cattle meat produced per hectare.

2.6. Economic evaluation

An economic evaluation of each surface-applied dolomitic limestone rate was also conducted. The cost per hectare to produce each crop was calculated (CONAB, 2010). The only difference between treatments was the dolomitic limestone rates used before the peanut crop (November 2004) and the pasture costs as a function of the animal stocking rate. The average peanut, white oat and maize GY (kg ha^{-1}) and the estimated meat production (kg ha^{-1}) were calculated, and the result was multiplied by the price per kg.

The net profit realization per hectare was calculated using the following formula: (revenue – cost). The total profit and mean net profit were the sum of all growing seasons and the mean by growing season, respectively. We used the Brazilian national average prices from the last five years and converted these values to euro (€) (Agrolink, 2016).

2.7. Determination of soil chemical characteristics

Soil chemical characteristics (pH, H + Al, Al, P, Ca, Mg, K and base saturation) were evaluated at depths of 0.00–0.05, 0.05–0.10, 0.10–0.20, 0.20–0.40 and 0.40–0.60 m at twelve and twenty four months after the application of correction material. Six simple samples were collected at random from the useful area of each plot and between rows of the previous crop to form a composite sample. The samples were dried, sieved (2-mm sieves) and analyzed according to van Raij et al. (2001).

2.8. Statistical analyses

All data were initially tested for normality using the Shapiro-Wilk test from the UNIVARIATE procedure of SAS (version 9.3; SAS Inst. Inc., Cary, NC), and the results indicated that all data were distributed normally (W ≥ 0.90). The assumption for the homogeneity of variances was tested using Levene's test for residual errors. When variances could not be considered homogeneous (P ≤ 0.10), Welch's F-test was performed to determine the overall significance for the statistic of interest. The data were then analyzed using the PROC MIXED procedure of SAS and the Satterthwaite approximation to determine the degrees of freedom for the tests of fixed factors. Lime rates were considered fixed factor, and blocks were considered random factor. A repeated statement was used with growing season specified as the repeated variable and block × lime rates specified as the subject. The covariance structure used in the analyses was autoregressive, which provided the best fit according to the Akaike information criterion. Only the soil results were compared individually for each season (12 and 24 months after lime rates surface reapplication). The results are reported as the least square

means and are separated using the probability of differences option (PDIFF). The lime rates were analyzed using the PROC REG procedure of SAS, and the best adjustments were chosen as those with the greatest coefficients of determination and considering the values of the t-test. Error bars are presented as standard errors (SEs) and were determined using the PROC MEAN procedure of SAS. The growing season (only for the plant results and estimated meat production) means were compared via Fisher's protected LSD test. The effects of main factor and interaction (lime rates × growing seasons) were considered statistically significant at P < 0.05.

3. Results

3.1. Soil chemical attributes

After 12 months of superficial liming, a positive effect on the main soil properties was verified (Table 2). Notably, the potential (H + Al) and exchangeable (Al^{3+}) acidity were reduced in proportion to the applied carbonate dose; this effect was reflected in the soil pH values. The effects of superficial liming on pH levels were observed up to a depth of 0.40–0.60 m after 12 months; however, after 24 months, the effect was limited to the upper 0.20 m. Although there were no differences in pH values, reductions in potential and exchangeable acidity were observed down to 0.60 m depth after 24 months.

Liming also increased macronutrient availability in soil. Regarding the effects on the availability of phosphorus, calcium, potassium and magnesium, after 12 months, the correction raised P, Ca and Mg in all layers evaluated; however, K availability was unchanged in the deeper layers (0.20–0.40 and 0.40–0.60 m). After 24 months, the correction increased the levels of K, Ca, Mg and P at depths down to 0.60 m. The increase in the K, Ca and Mg levels was also positively reflected in base saturation values (BS%) down to 0.60 m.

3.2. Peanut, white oat, and maize nutrition

Superficial liming increased the foliar concentrations of N, P, K, Ca and Mg in peanut; the effect for K, Ca and Mg was linear, while N, P and S were better explained by a quadratic equation (Fig. 2a–e). In the first growing season, the N, P and K concentrations were lower than in the second growing season, while for the other nutrients, no effect of the growing season was observed (Table 3). The improvement of plant nutrition with liming was reflected in greater shoot dry matter production (Fig. 3a); in addition, the second growing season plants showed more vegetative development.

In the white oat crop, quadratic responses of K, Mg and S were verified (Fig. 4a–d) as well as linear responses for the Ca concentrations (Fig. 4b). However, it was observed that the second growing season showed the highest macronutrient concentration in the leaves, except for N and S (Table 4). Shoot dry matter production was influenced by both factors, with a quadratic increase being observed for liming (Fig. 5a and d) and superior results in the first growing season.

Regarding maize nutrition, higher concentrations of all macronutrients were observed in the second growing season (Table 5). Positive responses were also associated with liming for all nutrients except for P (Fig. 6). As observed for the peanut and white oat crops, shoot dry matter production in maize was also increased with liming, and the highest production occurred in the second growing season.

3.3. Peanut, white oat, and maize components and kernel/grain yield

Liming positively affected the yield components and kernel/grain yield of peanut, white oat and maize (Tables 3–5). In

Table 2
Regression equations and coefficients of determination between some soil chemical attributes and limestone rates applied 12 and 24 months before soil samples were collected from a long-term no-till soil and ANOVA significance.

Soil depth (m)	Limestone rate, kg ha^{-1}				Regression	R^2	ANOVA (p > F)
	0	1000	2000	4000			
	pH (CaCl$_2$), 12 months						
0–0.05	4.5	4.6	5.0	5.2	$y = 0.00017x + 4.5$	87.8	0.0091
0.05–0.10	4.2	4.5	4.8	5.2	$y = 0.000243x + 4.25$	99.5	<0.0001
0.10–0.20	3.9	4.1	4.2	4.6	$y = 0.00016x + 3.895$	96.9	0.0014
0.20–0.40	3.5	3.7	3.9	4.0	$y = 0.0001x + 3.56$	89.5	0.0328
0.40–0.60	3.6	3.7	3.9	4.1	$y = 0.0001x + 3.6$	98.1	0.0064
	pH (CaCl$_2$), 24 months						
0–0.05	4.7	5.0	5.6	6.1	$y = 0.00037x + 4.74$	97.3	<0.0001
0.05–0.10	4.6	4.8	5.2	6.0	$y = 0.000358x + 4.53$	99.1	<0.0001
0.10–0.20	4.3	4.4	4.5	5.0	$y = 0.00018x + 4.27$	93.5	<0.0001
0.20–0.40	4.0	4.2	4.3	4.3	–	–	ns
0.40–0.60	4.0	4.0	4.1	4.1	–	–	ns
	H + Al, 12 months						
0–0.05	58	45	27	19	$y = -0.009671x + 53.86$	90.6	<0.0001
0.05–0.10	83	50	45	34	$y = -0.011x + 71.81$	76.7	<0.0001
0.10–0.20	85	70	53	44	$y = -0.01x + 80.37$	90.9	<0.0001
0.20–0.40	167	104	90	70	$y = 9E^{-06}x^2 - 0.0578x + 163.35$	96.5	<0.0001
0.40–0.60	145	105	80	69	$y = 7E^{-06}x^2 - 0.047x + 145.26$	99.9	0.0016
	H + Al, 24 months						
0–0.05	47	40	23	15	$y = 1E-06x^2 - 0.0141x + 48.76$	94.5	<0.0001
0.05–0.10	50	48	41	27	$y = -0.006x + 52.273$	97.1	<0.0001
0.10–0.20	71	69	54	43	$y = -0.0076x + 72.56$	94.3	<0.0001
0.20–0.40	93	83	71	63	$y = -0.00756x + 90.60$	93.0	<0.0001
0.40–0.60	109	103	96	82	$y = -0.0069x + 109.8$	99.9	<0.0001
	Exchangeable Al^{3+}, 12 months						
0–0.05	1.6	1.6	1.2	1.1	$y = -0.000131 + 1.61$	85.2	<0.0001
0.05–0.10	4.2	2.1	1.6	1.1	$y = -0.000688x + 3.44$	76.1	<0.0001
0.10–0.20	4.5	3.5	2.4	1.9	$y = -0.00064x + 4.16$	88.7	<0.0001
0.20–0.40	8.5	7.8	6.8	5.8	$y = -0.00068x + 8.40$	98.6	0.0146
0.40–0.60	9.1	8.4	7.1	6.4	$y = -0.00068x + 8.91$	93.3	<0.0001
	Exchangeable Al^{3+}, 24 months						
0–0.05	2.4	1.4	1.4	1.1	$y = 1E^{-07}x^2 - 0.0007x + 2.27$	91.0	0.0041
0.05–0.10	3.4	2.2	1.9	1.3	$y = 1E^{-07}x^2 - 0.001x + 3.2758$	97.0	0.0225
0.10–0.20	6.4	5.6	4.7	2.6	$y = -0.00095x + 6.48$	99.5	<0.0001
0.20–0.40	11.2	10.3	8.7	7.8	$y = -0.00088 + 11.02$	93.3	0.0049
0.40–0.60	13.4	12.6	12.4	11.0	–	–	ns
	P resin, 12 months						
0–0.05	27.6	36.1	41.6	50.4	$y = 0.0055x + 29.25$	97.3	<0.0001
0.05–0.10	11.4	16.5	18.9	24.7	$y = 0.0032x + 12.26$	97.7	<0.0001
0.10–0.20	8.2	8.5	10.7	12.2	$y = 0.0011x + 7.987$	93.7	<0.0001
0.20–0.40	3.8	4.6	5.1	5.8	$y = 0.00048x + 4.00$	96.0	<0.0001
0.40–0.60	3.8	5.2	5.2	9.3	$y = 0.0013x + 3.54$	92.2	<0.0001
	P resin, 24 months						
0–0.05	26	34	46	55	$y = 0.0075x + 27.08$	96.2	<0.0001
0.05–0.10	15	20	33	23	$y = -3E^{-06}x^2 + 0.0135x + 13.37$	81.1	<0.0001
0.10–0.20	5.8	7.8	12.0	12.9	$y = -5E^{-07}x^2 + 0.0039x + 5.40$	94.8	0.0071
0.20–0.40	2.4	2.7	3.1	4.2	$y = 0.00045x + 2.31$	98.1	<0.0001
0.40–0.60	2.1	2.4	2.6	2.9	$y = 0.0002x + 2.14$	94.9	0.0044
	Exchangeable K$^+$, 12 months						
0–0.05	3.4	3.5	4.8	4.2	$y = -2E^{-07}x^2 + 0.001x + 3.23$	66.0	0.0011
0.05–0.10	2.2	2.5	3.2	2.7	$y = -2E^{-07}x^2 + 0.0008x + 2.09$	85.5	0.0122
0.10–0.20	2.0	2.1	2.3	2.4	$y = 0.00011x + 2.023$	83.7	0.0132
0.20–0.40	2.0	2.2	2.2	2.2	–	–	ns
0.40–0.60	2.0	2.0	2.3	2.3	–	–	ns
	Exchangeable K$^+$, 24 months						
0–0.05	1.4	2.5	3.4	2.3	$y = -4E^{-07}x^2 + 0,0017x + 1,3647$	96.5	<0.0001
0.05–0.10	0.9	1.0	2.3	1.2	$y = -2E^{-07}x^2 + 0.0011x + 0.68$	62.1	<0.0001
0.10–0.20	0.5	0.7	1.0	0.8	$y = -6E^{-08}x^2 + 0.0003x + 0.450$	88.1	0.0018
0.20–0.40	0.3	0.4	1.0	0.5	$y = -1E^{-07}x^2 + 0.0005x + 0.19$	76.2	<0.0001
0.40–0.60	0.3	0.4	0.5	0.6	$y = 0.00008x + 0.31$	95.2	0.0009
	Exchangeable Ca^{2+}, 12 months						
0–0.05	14	28	46	66	$y = 0,013x + 15.66$	98.0	<0.0001
0.05–0.10	10	17	25	32	$y = 0.00554x + 11.28$	94.5	<0.0001
0.10–0.20	10	14	15	18	$y = 0.00183x + 10.864$	90.8	<0.0001
0.20–0.40	6.6	7.4	9.1	9.1	$y = 0.00064x + 6.90$	76.9	0.0014
0.40–0.60	6.1	7.8	9.1	10.3	$y = 0.001x + 6.536$	94.1	<0.0001

Table 2 (*Continued*)

Soil depth (m)	Limestone rate, kg ha^{-1}				Regression	R^2	ANOVA (p > F)
	0	1000	2000	4000			
	Exchangeable Ca^{2+}, 24 months						
0–0.05	17.9	35.4	60.6	82.2	$y = 0.016x + 20.58$	96.8	<0.0001
0.05–0.10	15.4	21.4	24.7	40.1	$y = 0.0061x + 14.72$	97.9	<0.0001
0.10–0.20	11.6	13.0	14.2	26.6	$y = 0.0038x + 9.73$	88.5	<0.0001
0.20–0.40	7.7	9.1	10.0	10.5	$y = 0.00067x + 8.15$	85.3	0.0029
0.40–0.60	6.3	6.6	7.5	8.4	$y = 0.0005x + 6.24$	97.5	0.0033
	Exchangeable Mg^{2+}, 12 months						
0–0.05	7.7	15.9	29.6	36.6	$y = 0.00735x + 9.582$	92.5	<0.0001
0.05–0.10	4.9	8.1	9.5	24.3	$y = 0.0048x + 3.268$	92.1	<0.0001
0.10–0.20	5.2	7.3	10.9	12.5	$y = 0.001857x + 5.73$	91.4	<0.0001
0.20–0.40	2.7	3.3	4.5	5.0	$y = 0.00059x + 2.82$	91.8	<0.0001
0.40–0.60	3.0	3.6	4.3	5.1	$y = 0.00053x + 3.055$	98.7	<0.0001
	Exchangeable Mg^{2+}, 24 months						
0–0.05	11.4	16.5	25.0	35.3	$y = 0.0061x + 11.38$	99.1	<0.0001
0.05–0.10	9.2	10.5	14.7	21.5	$y = 0.0032x + 8.37$	97.9	<0.0001
0.10–0.20	7.4	8.8	8.9	15.7	$y = 0.002x + 6.58$	88.1	<0.0001
0.20–0.40	5.0	6.0	6.0	7.1	$y = 0.00049x + 5.16$	92.7	<0.0001
0.40–0.60	3.6	3.9	4.1	4.2	$y = 0.00015x + 3.70$	87.6	0.0192
	Base saturation, 12 months						
0–0.05	30	52	75	85	$y = -0.000004\,x^2 + 0.029x + 29.26$	99.1	<0.0001
0.05–0.10	17	36	46	64	$y = 0.01123x + 20.915$	96.3	<0.0001
0.10–0.20	17	25	35	43	$y = 0.00645x + 18.53$	94.9	<0.0001
0.20–0.40	6	11	15	19	$y = 0.003x + 7.46$	95.2	<0.0001
0.40–0.60	7	11	17	20	$y = -6E^{-07}x^2 + 0.0057x + 6.90$	99.3	0.0044
	Base saturation, 24 months						
0–0.05	40	57	80	89	$y = -3E^{-06}x^2 + 0.026x + 38.16$	98.4	<0.0001
0.05–0.10	34	41	50	70	$y = 0.0092x + 32.54$	99.5	<0.0001
0.10–0.20	22	25	31	50	$y = 1E^{-06}x^2 + 0.002x + 21.48$	99.9	<0.0001
0.20–0.40	12	16	19	22	$y = 0.0025x + 13.06$	94.8	<0.0001
0.40–0.60	8	9	11	14	$y = 0.00137x + 8.40$	99.2	<0.0001

Table 3
Influence of surface-applied limestone rates on crop nutrition, shoot dry matter, yield components, and peanut pod yield in a long-term no-till soil and ANOVA significance.

Growing season	N g kg^{-1}	P	K	Ca	Mg	S	Shoot dry matter kg ha^{-1}
2004/2005	33.5 b[1]	4.7 b	18.9 b	13.6 a	5.9 a	4.0 a	3181 b
2005/2006	37.7 a	6.6 a	24.3 a	14.2 a	5.7 a	3.9 a	3746 a
ANOVA (F probability)							
Blocks	0.1622	0.5998	0.6668	0.9371	0.5038	0.7854	0.6598
Limestone rates (R)	0.0467	<0.0001	<0.0001	0.0427	0.0431	0.1050	<0.0001
Growing season (S)	0.0005	<0.0001	<0.0001	0.5094	0.6413	0.7031	<0.0001
R × S	0.3145	0.6166	0.6511	0.7509	0.9669	0.9447	0.4356

Growing season	Final population n°	Filled pods per plant n°	Kernels per pod n°	100-kernel weight g	Peanut pod yield kg ha^{-1}	Hulled-kernel yield %
2004/2005	123055 a[1]	20 a	1.2 b	47.4 b	2476 b	57 b
2005/2006	116319 a	21 a	1.6 a	53.2 a	3423 a	61 a
ANOVA (F probability)						
Blocks	0.1635	0.8043	0.6589	0.4788	0.2423	0.4102
Limestone rates (R)	0.0458	0.0004	0.2987	0.0315	0.0011	0.0182
Growing season (S)	0.2016	0.2523	<0.0001	<0.0001	0.0008	0.0415
R × S	0.5796	0.2241	0.8754	0.2844	0.2126	0.8254

[1] Means followed by different letters in the column differ statistically by the LSD test (p < 0.05).

peanut, except for the 100-kernel weight, which responded linearly (Fig. 3d), and the number of kernels per pod, which was not affected, shoot dry matter, number of plants per hectare and all reproductive parameters were explained by quadratic equations (Fig. 3a–f) and the maximum hulled-kernel yield (62%) was achieved under 2800 kg ha^{-1} of lime application. Moreover, more kernels per pod and a higher 100-kernel weight were observed in the second cropping season, with a positive impact on the kernel yield and hulled-kernel yield.

In white oat, liming also positively affected the number of panicles per square meter and the number of spikelets per panicle (Fig. 5b and c); these increases were reflected in the grain yield (Fig. 5d). All these relationships were quadratic and the maximum grain yield (3191 kg ha^{-1}) was achieved under 2000 kg ha^{-1} of lime application. Regarding the growing season, it is important to note that environmental conditions in the second growing season favored the plants' development, resulting in better growth and development of reproductive structures (number of panicles and spikelets), leading to a higher yield.

For the maize crop, the grain yield increased quadratically with lime application, due to its beneficial effects on stand establishment and the increased development of reproductive structures
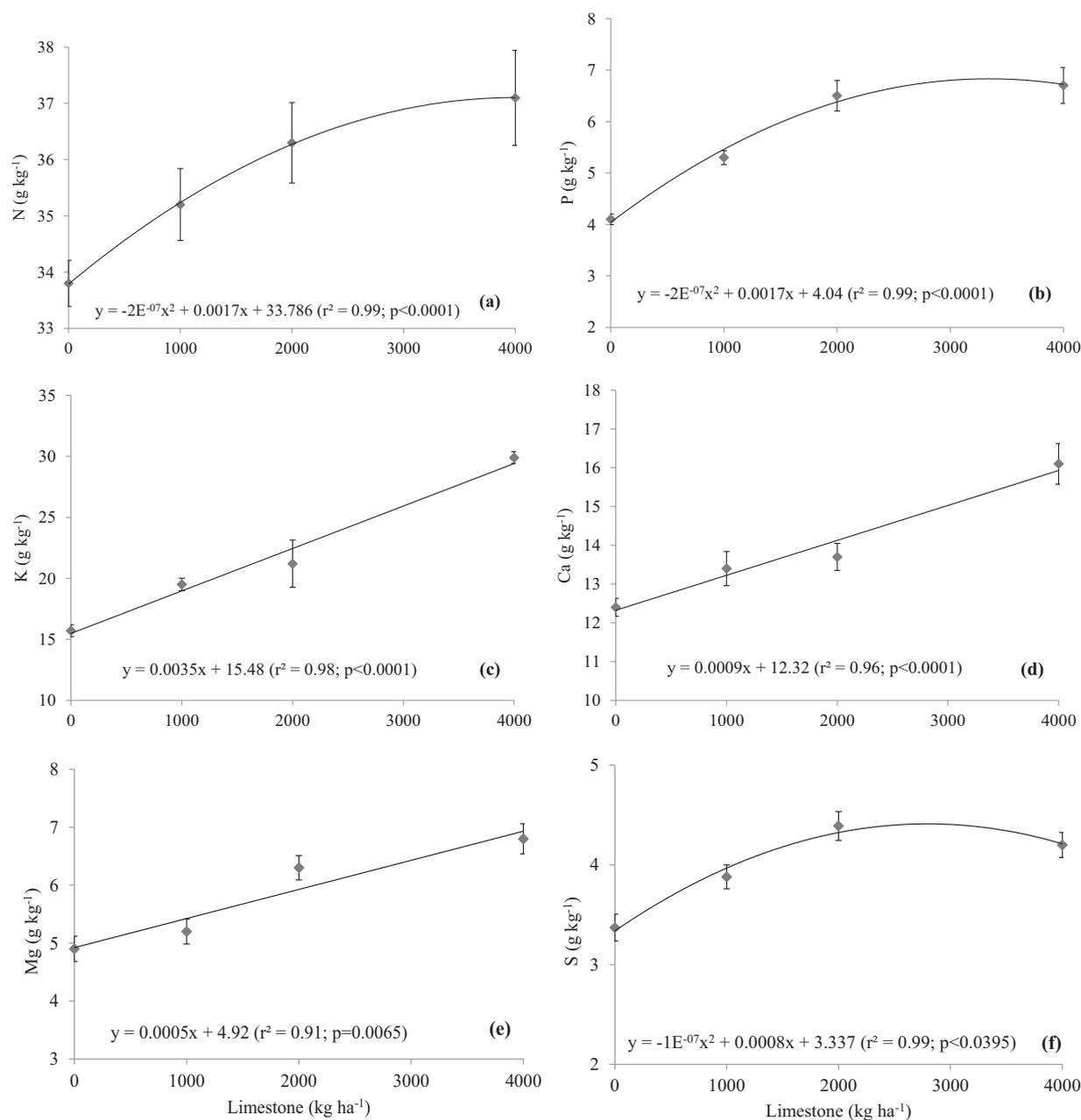
Fig. 2. (a) Nitrogen, (b) phosphorus, (c) potassium, (d) calcium, (e) magnesium and (f) sulfur concentrations in peanut (sampled from the apical cluster of the main branch) as affected by surface-applied dolomitic limestone rates in a long-term no-till soil. Bars indicate the standard error at each lime rate (n = 8; four replicates × two growing seasons).

(Fig. 7a–c). In the second growing season, the values for all production components were higher, with a significant increase in the grain yield of 2542 kg ha^{-1} being recorded.

3.4. Forage characteristics and estimated meat production

In the first and second cuttings, the forage dry matter yield was influenced by the interaction of lime rate × growing season (Table 6). In the first and second cuttings, crude protein was influenced by the lime rates. In the first and second cuttings and in the total of both cuttings, the estimated meat production was influenced by the interaction of lime rate × growing season. All results of forage dry matter yield, crude protein and estimated meat production were quadratically related to the lime rate (Figs. 8 and 9).

3.5. Economic evaluation

The lowest total profit and mean net profit (0 kg ha^{-1}, € 1198 and € 299 per ha, respectively) were achieved with no surface application of dolomitic limestone, and a rate of 2000 kg ha^{-1} of dolomitic limestone resulted in the highest total and mean net profit (€ 4064 and € 1016 per ha, respectively) (Table 7).

4. Discussion

4.1. Soil chemical attributes

Despite the low solubility and mobility of limestone in the soil, effects of superficial liming were observed at depths down to 0.60 m after 12 months, with a significant reduction in the active acid-
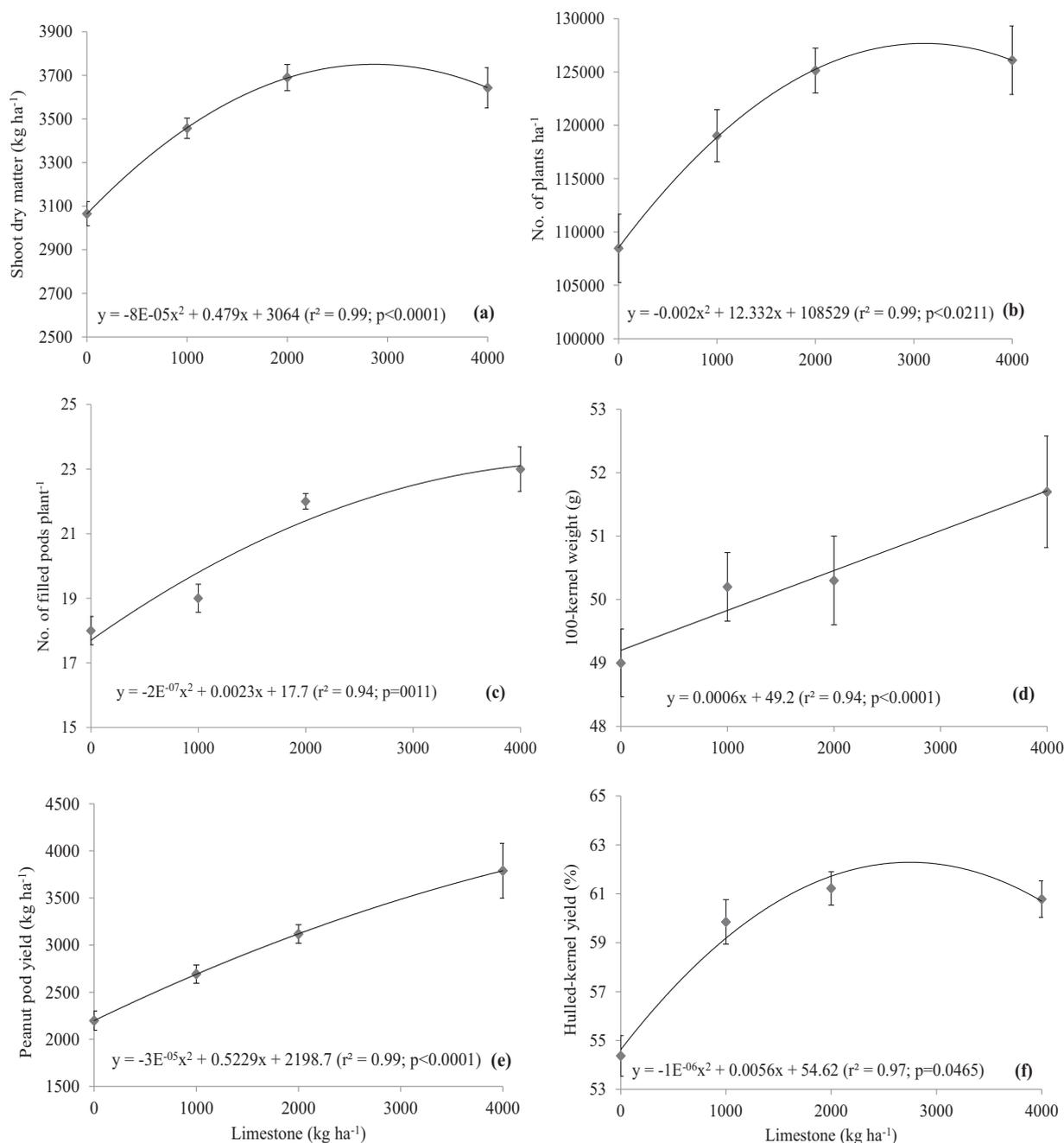
Fig. 3. (a) Shoot dry matter, (b) number of plants, (c) number of pods, (d) 100-grain weight, (e) peanut pod yield and (f) hulled-kernel yield of peanut as affected by surface-applied dolomitic limestone rates in a long-term no-till soil. Bars indicate the standard error at each lime rate (n = 8; four replicates × two growing seasons).

ity and potential and exchangeable values (Table 2). This result demonstrates the effectiveness of superficial liming in improving the chemical properties of highly acidic subsoils within a short time. Notably, even with a high base concentration in the top 0–0.05 m, under the highest applied dose (4.0 Mg ha^{-1}), the increase of the soil pH at 12 months was not excessive enough to harm the development of agricultural crops. According to Alleoni et al. (2005), this may be explained by the high buffering capacity existing in this layer, due to the accumulation of organic matter at the soil surface.

It is important to emphasize that the absence of mechanical mobilization promotes benefits related to the maintenance of aggregates and channels formed by soil biological activity. The preservation of soil physical properties is an important factor in the percolation of limestone particles into the subsoil; i.e., NT favors mobilization of the carbonate and the lime reaction at depth (Corrêa

et al., 2009; Castro et al., 2011; Briedis et al., 2012). In addition to the soil physical conditions, experimental results have emphasized the importance of soil anions on Ca^{2+} and Mg^{2+} mobility into the subsoil.

After 24 months, liming decreased total and exchangeable acidity but it did not increased pH (Table 2). At 24 months, the effect of liming decreasing potential and exchangeable (Al^{3+}) acidity in the 0.40–0.60 m and 0.20–0.40 depths was probably related to the action of water-soluble acids derived from the decomposition of the roots of previous crops, which can interfere with exchangeable and potential acidity by reducing the activity of Al^{3+} (Miyazawa et al., 2002; Soratto and Crusciol, 2007). Caires et al. (2000) found that potential acidity was reduced for up to approximately 28 months after superficial liming; however, the pH began to show decreases
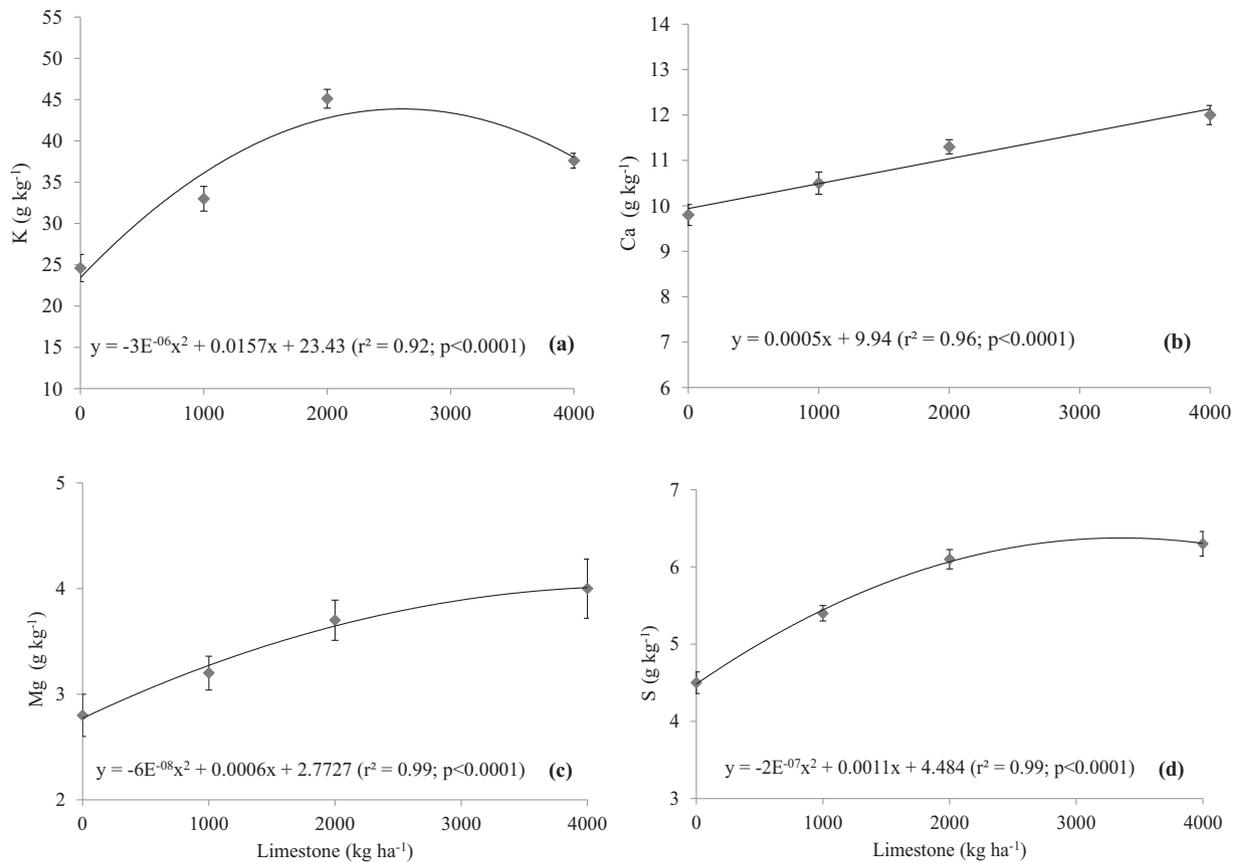
Fig. 4. (a) Potassium, (b) calcium, (c) magnesium and (d) sulfur concentrations in white oat flag leaves as affected by surface-applied dolomitic limestone rates in a long-term no-till soil. Bars indicate the standard error at each lime rate (n = 8; four replicates × two growing seasons).

Table 4
Influence of surface-applied limestone rates on crop nutrition, shoot dry matter, yield components, and white oat grain yield in a long-term no-till soil and ANOVA significance.

Growing season	N g kg^{-1}	P	K	Ca	Mg	S	Shoot dry matter kg ha^{-1}
2005	37.4 a[1]	3.5 b	29.8 b	10.1 b	2.6 b	5.6 a	5574 a
2006	34.5 b	4.9 a	40.4 a	11.7 a	4.3 a	5.6 a	5011 b
ANOVA (F probability)							
Blocks	0.5462	0.7241	0.6611	0.2412	0.1960	0.1209	0.1082
Limestone rates (R)	0.6083	0.2619	<0.0001	0.0006	0.0288	<0.0001	0.0002
Growing season (S)	0.0450	<0.0001	<0.0001	<0.0001	<0.0001	0.9354	0.0001
R × S	0.9891	0.8000	0.4311	0.7977	0.8291	0.5531	0.9928

Growing season	Panicles per square meter n°	Spikelet per panicles n°	Spikelet fertility %	1000-grain weight g	Grain yield kg ha^{-1}
2005	296 b[1]	37 b	95 a	21.3 a	2197 b
2006	336 a	52 a	94 a	20.4 a	3292 a
ANOVA (F probability)					
Blocks	0.1264	0.7143	0.7789	0.2137	0.3943
Limestone rates (R)	0.0024	0.0470	0.0865	0.1210	0.0002
Growing season (S)	0.0010	< 0.0001	0.6527	0.0641	< 0.0001
R × S	0.6818	0.7879	0.8995	0.3671	0.3604

[1] Means followed by different letters in the column differ statistically by the LSD test (p < 0.05).

from 12 months onwards. Thus, there is not always an inverse relationship between potential acidity and pH.

Due to the mineralogical attributes of Oxisols, phosphate is strongly adsorbed on Al- and Fe-(oxy) hydroxide surfaces, irrespective of the nature of the charges. However, the effect of the lime reaction on increasing phosphorus availability (Table 2) can be attributed to the competitive adsorption between OH^{-} and phosphate for the same site, resulting in lower P adsorption by oxides (Sato and Comerford, 2005). In addition, Haynes (1984) reported that the anion repulsion effect by increasing negative charges on oxides could also contribute to P bioavailability. The influence of liming on the availability of phosphorus in acid soils has also been reported by other researchers (Haynes, 1982; Jaskulska et al., 2014); however, the increased availability in the subsurface layers is notable because phosphorus generally shows limited mobility in soil, and increasing its availability contributes greatly to increasing its interception and absorption by plant roots.

Table 5

Influence of surface-applied limestone rates on crop nutrition, shoot dry matter, yield components, and maize grain yield in a long-term no-till soil and ANOVA significance.

Growing season	N g kg⁻¹	P	K	Ca	Mg	S	Shoot dry matter kg ha⁻¹
2006/2007	28 b[1]	2.3 b	24 b	3.5 b	2.9 b	1.7 b	14235 b
2007/2008	32 a	2.5 a	27 a	3.8 a	2.0 a	1.9 a	20174 a
ANOVA (F probability)							
Blocks	0.4528	0.2610	0.7628	0.6299	0.3422	0.6890	0.3432
Limestone rates (R)	<0.0001	0.8208	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Growing season (S)	<0.0001	0.0137	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
R × S	0.4632	0.9999	0.7264	0.1230	0.6977	0.4298	0.6815

Growing season	Final population n°	Ear per plant n°	Grains per ear n°	100-grain weight g	Grain yield kg ha⁻¹
2006/2007	63350 a[1]	0.80 b	348 b	36 b	6090 b
2007/2008	60332 b	0.84 a	435 a	40 a	8632 a
ANOVA (F probability)					
Blocks	0.2683	0.3282	0.3318	0.1170	0.1152
Limestone rates (R)	<0.0001	0.0711	<0.0001	0.5514	<0.0001
Growing season (S)	<0.0001	<0.0001	<0.0001	0.0019	<0.0001
R × S	0.3629	0.9999	0.0808	0.9999	0.4551

[1] Means followed by different letters in the column differ statistically by the LSD test (p < 0.05).

Table 6

Influence of surface-applied limestone rates on forage dry matter yield (FDMP), forage crude protein concentration and estimated meat production in a pasture of palisadegrass in a long-term no-till soil and ANOVA significance.

	FDMP (kg ha⁻¹)		Crude protein (%)		Estimated meat production (kg ha⁻¹)[α]		
	First cut[2]	Second cut[2]	First cut[2]	Second cut[2]	First cut[2]	Second cut[2]	Total
Growing season							
2007	4127 b[1]	4986 b	11.0 a	10.3 a	199.0 b	225.1 b	424.1 b
2008	5447 a	6581 a	10.8 b	10.1 b	266.5 a	298.9 a	565.4 a
ANOVA (F probability)							
Blocks	0.8675	0.6870	0.9745	0.5891	0.4025	0.6201	0.7001
Limestone rates (R)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Growing season (S)	<0.0001	<0.0001	0.0037	0.0440	<0.0001	<0.0001	<0.0001
R × S	0.0281	0.0242	0.9921	0.9858	0.0059	0.0002	<0.0001

[α] Estimated meat production = kg of body weight gain (cattle) per ha (estimated) × 52% of carcass yield.
[1] Means followed by different letters in the column differ statistically by the LSD test (p < 0.05).
[2] First and second cuts in June and August, respectively.

Table 7

Economic evaluation of the peanut, white oat, maize intercropped with palisadegrass and pasture as a function of the surface-applied dolomitic limestone rates in a long-term no-till soil.

Limestone rates (kg ha⁻¹)	Peanut 2004/2005	White oat 2005	Peanut 2005/2006	White oat 2006	Maize 2006/2007	Pasture (meat) 2007	Maize 2007/2008	Pasture (meat) 2008	Total[4] –	Mean[5] –
Cost[1] (€ ha⁻¹)										
0	726	206	726	206	576	131	576	131	3278	820
1000	752	206	726	206	576	212	576	215	3470	868
2000	779	206	726	206	576	328	576	344	3741	935
4000	832	206	726	206	576	288	576	300	3709	927
Revenue[2] (€ ha⁻¹)										
0	513	137	709	205	708	518	1018	669	4476	1119
1000	628	181	868	271	784	838	1127	1098	5794	1449
2000	728	233	1005	349	1002	1295	1442	1752	7805	1951
4000	885	176	1222	265	925	1135	1331	1528	7465	1866
Net profit[3] (€ ha⁻¹)										
0	−213	−69	−17	−1	131	386	442	538	1198	299
1000	−124	−25	142	65	207	625	551	882	2324	581
2000	−51	27	279	143	426	967	866	1408	4064	1016
4000	53	−30	496	59	349	847	755	1228	3756	939

[1] Mean costs and production costs of crops; the only difference was the dolomitic limestone rates used before the peanut crop (November 2004) and pasture costs as a function of the animal stocking rate.
[2] Revenue = kg of peanut, white oat and maize grain yields and estimated meat production per ha × € 0.28, € 0.08, € 0.14 and € 2.23, respectively.
[3] Net profit is the realization per ha, which was calculated using the following formula: revenue – cost.
[4] Total = sum of all growing seasons.
[5] Mean = mean by growing season.
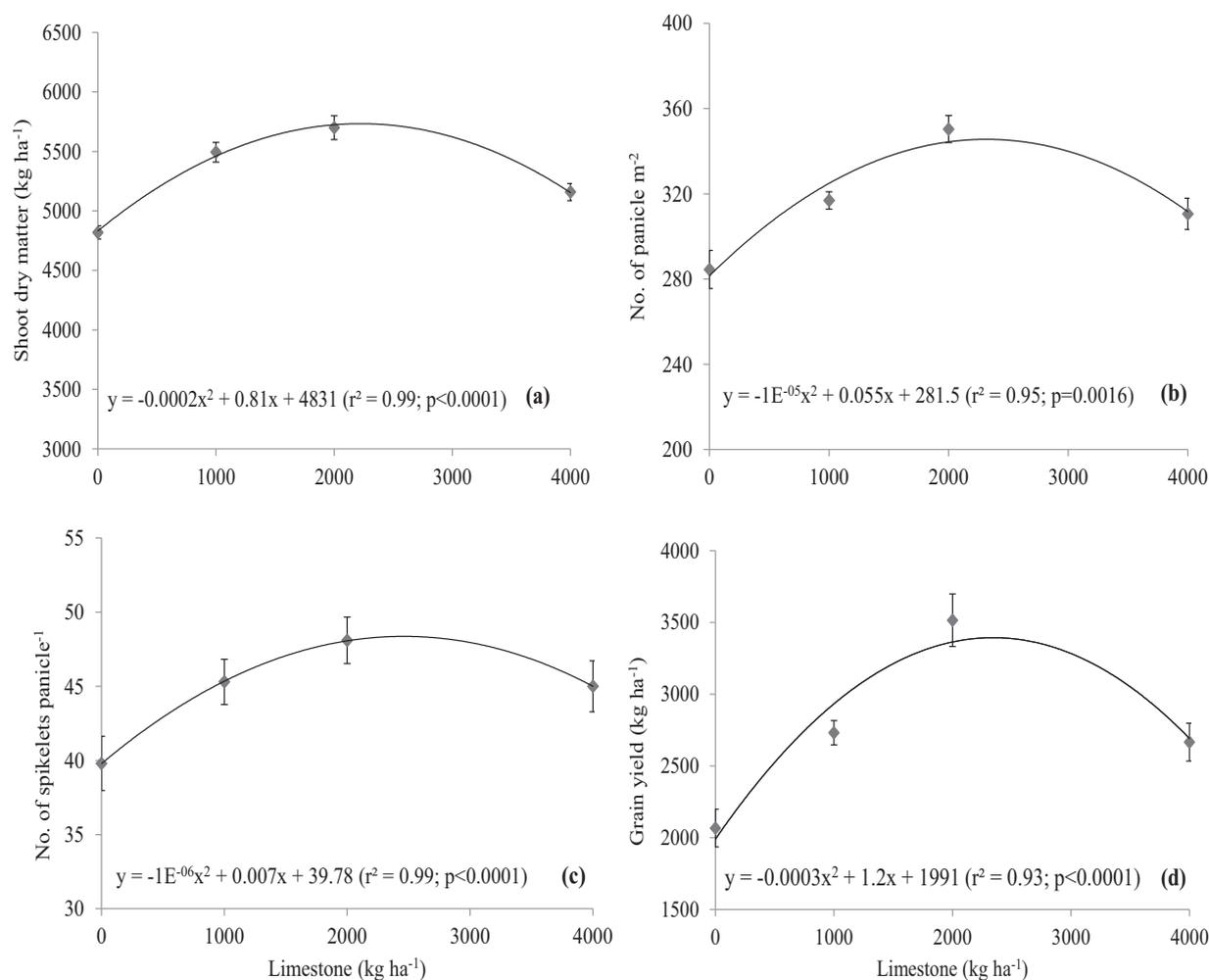
Fig. 5. (a) Shoot dry matter, (b) number of panicles per square meter, (c) number of spikelets per panicle and (d) grain yield of white oat as affected by surface-applied dolomitic limestone rates in a long-term no-till soil. Bars indicate the standard error at each lime rate (n = 8; four replicates × two growing seasons).

The K levels increased in the upper soil layers (0–0.05, 0.05–0.10 and 0.10–0.20 m) with liming after 12 months (Table 2). This increase can be explained by the increase in the soil pH, which enhanced K adsorption capacity by the soil, reduced K losses through leaching, and improved the K fertilizer efficiency (Krause, 1965). In a relatively short period, this effect was not observed in the deeper layers, possibly due to the lower lime mobility; however, after 24 months, liming increased K availability in all soil profiles, likely in response to an enhanced sorptive complex.

Regarding the increases in Ca^{2+} and Mg^{2+} availability (Table 2) observed in all layers after 12 months, it should be considered that limestone is a major source for the replacement of these nutrients in the soil. Several researchers have reported the fundamental role of this corrective process as an important Ca^{2+} and Mg^{2+} complement in cropping systems (Caires et al., 2005, 2008a,b, 2015; Soratto and Crusciol, 2008a; Fageria et al., 2010; Castro and Crusciol, 2013b). However, the present study emphasizes the increase in the levels of these nutrients in the subsoil, with significant increases observed down to a depth of 0.60 m. The displacement of exchangeable cations in the soil profile may be related to the formation of stable complexes between Ca^{2+} and Mg^{2+} and soluble organic compounds (Franchini et al., 1999), although this mechanism is not common, and to the presence and quantity of porous channels that allow the movement of limestone downward through water displacement (Amaral et al., 2004).

We highlight that after 24 months, there was a small increase in Ca^{2+} levels compared to the first sampling (12 months). This phenomenon was most likely related to the reaction of some portion of the applied limestone in the period between samplings. Furthermore, the low nutrient export by the grains may have contributed to this increase. The increase in base saturation in all of the evaluated layers was the effect of the reduction in acidity and the increased Ca and Mg levels, as evidenced by Ciotta et al. (2004).

4.2. Peanut, white oat, and maize nutrition

The highest N concentrations observed in the peanut and maize leaves (Figs. 2a and 6a) were probably related to the effects of liming on soil nitrate availability, as nitrate is one of the main forms of N absorbed by plants. The availability of nitrate may increase with an increasing pH due to liming because nitrification activity is lower at acidic pH (Islam et al., 2006) and explains the increased nitrate concentration observed in soils with acidity correction (Silva and Vale, 2000).

Observed N concentration in maize was within the range considered adequate for peanuts and maize (Ambrosano et al., 1997; Cantarella et al., 1997), independent of the lime rate applied. In the white oat crop, N concentrations were not influenced by liming (Table 3), but the N concentration was above that considered adequate (Cantarella et al., 1997).
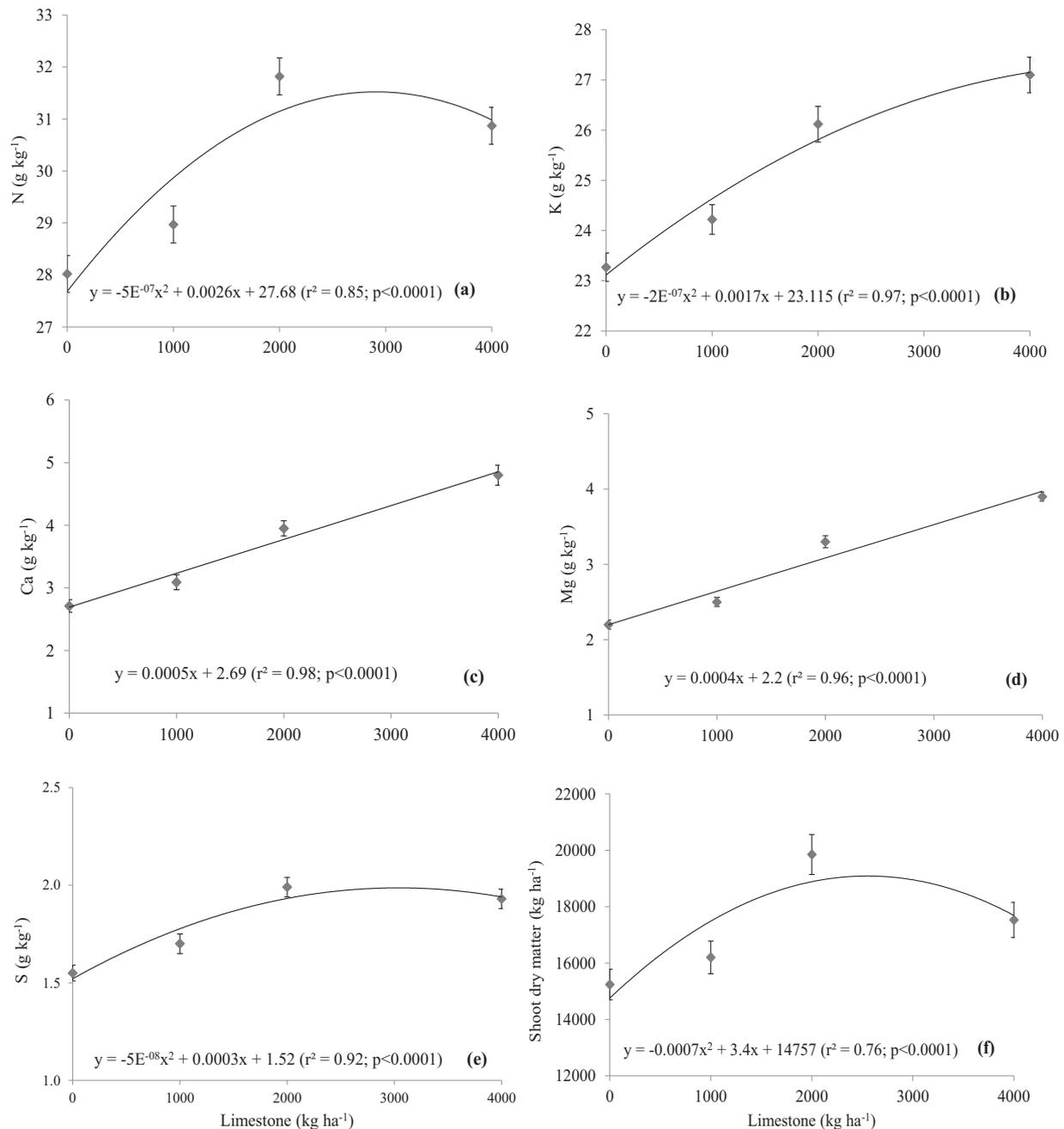
Fig. 6. (a) Nitrogen, (b) potassium, (c) calcium, (d) magnesium, and (e) sulfur concentrations in maize leaf collected from the base of the ear and (f) shoot dry matter as affected by surface-applied dolomitic limestone rates in a long-term no-till soil. Bars indicate the standard error at each lime rate (n = 8; four replicates × two growing seasons).

The P concentration was affected by liming only in the peanut crop (Fig. 2b); this effect may be related to the lower P adsorbed by Fe- and Al-(oxy) hydroxides. In other words, the recent lime application increased P bioavailability in the upper soil layers, increasing P utilization by peanut plants grown after application. In addition, the improved chemical conditions due to liming may have favored the root architecture, increasing plants' ability to extract P from soil. Considering these aspects, it was notable that the highest P concentration in peanut leaves was observed in the second growing season (Table 3), and this value was considered to be above the critical range proposed by Ambrosano et al. (1997). In the other crops, despite the increase in soil P bioavailability due to limestone application, the P concentrations in plants remained unaffected (Tables 4 and 5). However, it is important to note that the P con-

centrations in white oat and maize leaves were within the range that is considered sufficient (Cantarella et al., 1997).

The increases in K, Ca, Mg and S levels observed in peanut (Fig. 2c–f), white oat (Fig. 4a–d) and maize (Fig. 6b–e) leaves as a function of liming were related to the greater availability of these macronutrients in the soil (Table 2). The benefits of liming to shoot dry matter production (peanuts, white oat and maize) (Figs. 3a, 5a, and 6f, respectively) reflect improved soil chemical characteristics (Table 2). The increased shoot growth probably resulted from better root development, which increased the absorption capacity of nutrients and water. Caires et al. (2006b) confirmed the existence of a correlation between wheat (*Triticum* spp.) root growth and soil chemical properties, mainly regarding an increased pH, increased Ca^{2+} availability, increased base saturation, and reduced Al^{3+}.
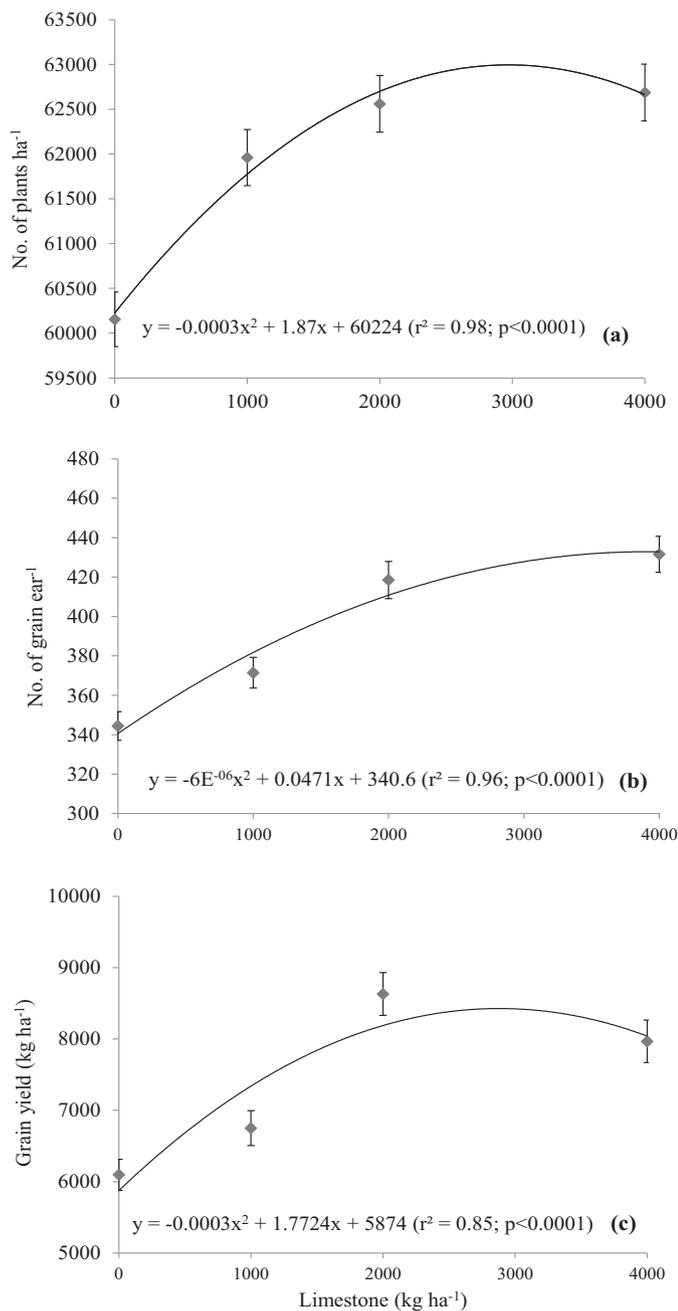
Fig. 7. (a) Number of plants per area, (b) number of grains per ear, and (c) grain yield of maize as affected by surface-applied dolomitic limestone rates in a long-term no-till soil. Bars indicate the standard error at each lime rate (n = 8; four replicates × two growing seasons).

Fig. 8. Forage dry matter yield and crude protein content in a pasture of palisade-grass in two cuts and two growing seasons as affected by surface-applied dolomitic limestone rates in a long-term no-till soil. Bars indicate the standard error at each lime rate (n = 4; four replicates – forage dry matter production; n = 8; four replicates × two growing seasons – crude protein).

4.3. Peanut, white oat, and maize components and kernel/grain yields

The positive results of surface liming on yield components and the kernel/grain yield (peanuts, white oat and maize) (Figs. 3, 5, and 7) were the result of reduced acidity and increased soil nutrient availability (Table 2). These results are in accordance with those observed by Caires et al. (2000), who reported correlations between cumulative grain production and soil chemical properties, especially regarding increases in pH, exchangeable Ca^{2+}, and base saturation as well as reductions in exchangeable Al^{3+}.

The increase in white oat grain yields observed after liming (Fig. 5d) was similar to the results presented by Castro and Crusciol (2013b), who reported positive effects on white oat yield compo-

nents due to reduced acidity and also minimizes the harmful effects of acidity on crop development and thereby increases the number of panicles per area and the number of spikelets per panicle, with significant effects on the grain yield.

As observed for the other species, the significant increases in the maize yield are justified by the chemical changes brought about by liming (Table 2). Castro and Crusciol (2013a,b) also demonstrated the benefits of these changes on the yield components responsible for determining the grain yield. According to Caires et al. (2000), the morphological parameters of maize roots are modified by superficial lime application in NT. These authors observed a reduction in the relative root length in the soil surface layer (0–0.10 m) and an increase in the subsoil (0.20–0.60 m) as a function of increasing doses of liming. In other words, in higher-acidity conditions, the maize root system is restricted to the surface, which makes plants vulnerable to water deficits. Similar effects may have occurred dur-
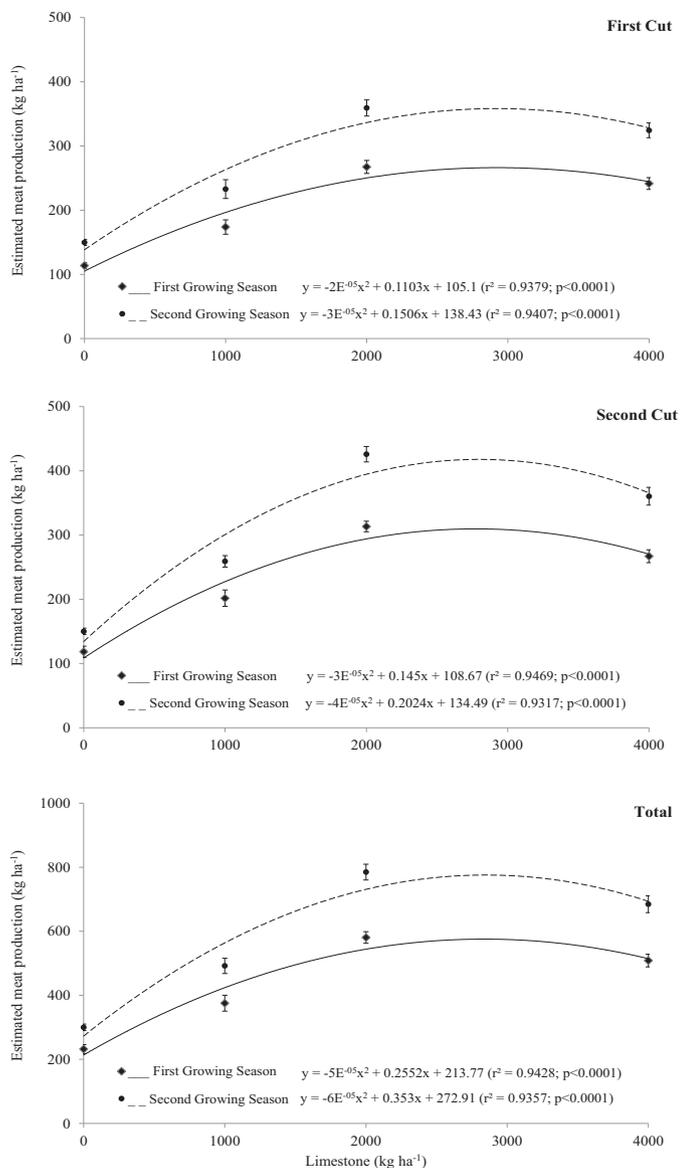
Fig. 9. Estimated meat production in a pasture of palisade grass in two cuts and total in two growing seasons as affected by surface-applied dolomitic limestone rates in a long-term no-till soil. Bars indicate the standard error at each lime rate (n = 4; four replicates).

ing maize development because dry spells occurred in February 2007 and 2008 (Fig. 1c and d).

However, attention should be paid to the use of higher doses of lime, which caused reductions in white oat and maize grain yields in this study (Figs. 5d and 7c). These results are similar to those reported by Caires et al. (2000) and Soratto and Crusciol (2008b), who attributed this effect to the lower availability of some micronutrients, especially cationic micronutrients, whose solubility decreases with an increasing pH. We note that the lime rates estimated to achieve the maximum grain yield, especially in white oat and maize, were very close to those calculated to adjust the base saturation of a soil sample collected at the 0–0.20 m depth to 70%, indicating that this surface liming recommendation is effective for the studied tropical no-till soil.

The higher kernel/grain yield (peanut, white oat and maize) observed in the second growing season (Tables 3–5) may have resulted from soil and weather conditions during the plants' development, which greatly affected crop productivity (Fig. 1).

4.4. Forage characteristics and estimated meat production

The forage dry matter yield and estimated meat production were highest in the second growing season (2008) compared to the first growing season (2007) (Table 6 and Fig. 8); as a function of the stimulus from tilling after the first cut, the forage dry matter yield was higher during the second cut in both growing seasons. The low temperatures and low rainfall, mainly during August and September in the first growing season (2007), contributed to the lower forage dry matter yield. According to Costa et al. (2005), the optimal temperature range for palisade grass development was between 30 and 35 °C, and its growth was greatly reduced between 10 and 15 °C. In addition, Costa et al. (2005) reported that low rainfall, which is characteristic of regions with dry winters, such as the Brazilian Cerrado during June and July, is another cause of the reduced palisade grass development observed in our trial for the first cutting. The observed two-year-average crude protein concentration of approximately 8.2–12.5% is higher than the crude protein of 7% reported by van Soest (1994) as the minimum concentration required for maintaining microbial populations in the rumen of cattle.

The forage dry matter yield (2573–6642 kg ha^{-1} in the first cut and 3397–8767 kg ha^{-1} in the second cut) in this study (Table 6; Fig. 8) can be considered high during this season (winter/spring). The forage dry matter yield can be used as an index for mechanical cutting or in the fields for grazing by animals (Pariz et al., 2011b) and to increase the estimated meat production (Fig. 9) and revenue of the farmer. Typically, during this time of the year (June to September), the availability of forage in areas with dry winters is limited (Borghi et al., 2013). Sowing tropical forage after a maize grain harvest does not provide sufficient fodder during the autumn, winter and part of the spring in regions with dry winters, such as the Brazilian Cerrado or African Savanna. However, in this intercropping system, the rain that falls after the maize is harvested (in April and May) allows for adequate development of palisade grass.

The forage dry matter yield, crude protein concentrations and estimated meat production increased quadratically as a function of the lime rate (Figs. 8 and 9). This result indicates that when low rates of surface limestone are used for maize intercropped with palisade grass, the forage dry matter yield is also low in the winter/spring, consequently reducing the estimated meat production. In the subtropical Brazilian regions, the surface limestone (application or reapplication) in an integrated crop-livestock system (soybean-beef cattle) also increased the forage dry matter yield [mix of black oat + Italian ryegrass (*Lolium multiflorum*)] and reduced the long-term soil acidification, with a higher base saturation and lower aluminum saturation, mainly in the grazed areas compared to the non-grazed areas (Martins et al., 2014a, 2014b, 2016).

4.5. Economic evaluation

The surface application of no dolomitic limestone resulted in a negative net profit for peanut and white oat in both growing seasons (Table 7). This result demonstrates the importance of the limestone practice in an annual crop rotation of tropical pastures under no-till. All treatments resulted in a positive total profit and a mean net profit, mainly using 2000 kg ha^{-1} of limestone. An integrated crop-livestock system using maize intercropped with palisade grass is a good option in a tropical agricultural system because in addition to maize grain produce in summer/autumn, the farmers can use the forage dry matter yield of palisade grass (Table 6 and Fig. 8) for animal fodder in winter/spring. The pasture of palisade grass in winter/spring provided a higher net profit compared to white oat. Thus, 232–785 kg of meat per ha could be produced in both cuts (Fig. 9), with net profits of € 386–1408 per ha, depending on the surface limestone rate applied-reapplied in the crop rotation (a rate of 2000 kg ha^{-1} of limestone results in higher

net profits, as a function of higher forage dry matter and estimated meat production).

Therefore, our data indicated that an annual crop rotation of a tropical pasture under no-till using maize intercropped with palisade grass is a promising option for farmers and liming can improve crop-livestock systems involving the crop rotation studied.

5. Conclusions

The surface application of limestone in a tropical no-till soil effectively reduced soil acidity from the surface down to a depth of 0.60 m, resulting in greater availability of P and K near the soil surface. The Ca and Mg availability in the soil also increased with the limestone application rates up to a depth of 0.60 m. Nutrient absorption was enhanced by liming, especially regarding the plant uptake of K, Ca and Mg. Significant increases in the yield components and kernel/grain yields of peanuts, white oat and maize were obtained with surface application of limestone. The lime rates estimated to achieve the maximum grain yield, especially in white oat and maize, were very close to the rates that are necessary to raise the base saturation of a soil sample collected at the 0–0.20 m depth to 70%. This lime rate also increases the forage dry matter yield, the crude protein concentration and the estimated meat production during winter/spring in the maize-palisade grass intercropping, provides the highest total and mean net profit during the four growing seasons and can improve the long-term sustainability of tropical agriculture in the Brazilian Cerrado.

Acknowledgements

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