Journal of Agricultural Science (2017), **155**, 1093–1112.
doi:10.1017/S0021859617000235

CROPS AND SOILS RESEARCH PAPER

Liming demand and plant growth improvements for an Oxisol under long-term no-till cropping

A. C. A. CARMEIS FILHO[1], C. A. C. CRUSCIOL[2]* AND A. M. CASTILHOS[3]

[1] *São Paulo State University (UNESP), College of Agricultural Sciences, Department of Crop Science, P.O. Box: 237, 18610-307 Botucatu, State of São Paulo, Brazil*
[2] *UNESP, College of Agricultural Sciences, Department of Crop Science, P.O. Box: 237, 18610-307 Botucatu, State of São Paulo, Brazil*
[3] *UNESP, School of Veterinary Medicine and Animal Science, Department of Animal Nutrition and Breeding, P.O. Box: 560, 18618-970 Botucatu, State of São Paulo, Brazil*

(*Received 25 April 2016; revised 2 January 2017; accepted 3 March 2017; first published online 29 May 2017*)

SUMMARY

The adequate management of soil acidity has long been a challenge in no-till (NT) cropping systems. Some studies conducted in sub-tropical conditions have demonstrated the feasibility of surface liming. However, for tropical regions with dry winters, little long-term information about adequate rates and frequencies of application is available. A 12-year field trial was performed under a tropical no-tillage system with an annual crop rotation scheme. The treatments were composed of four lime rates (0, 1000, 2000 and 4000 kg/ha), estimated via the base saturation (BS) method. Surface application of lime was found to be an effective method for improving the soil fertility profile under this long-term NT cropping system. All three acidity components (pH, hydrogen + aluminium (H + Al), exchangeable Al) and some fertility attributes (phosphorus, exchangeable calcium and magnesium, and BS) were adjusted to a linear function, and better soil chemical conditions were obtained in the 4000 kg/ha treatment, even 4 years after the final application. Due to soil chemical changes, the root length density of wheat and common bean was greater at depths <0·20 m, which led to a higher grain yield, even under unfavourable weather conditions. The results indicate that the application of lime at higher rates can be an acceptable criterion for a tropical Oxisol under a no-tillage system, reducing the frequency of lime application.

INTRODUCTION

Tropical crop systems have a high capacity for food production; thus, they are characterized as one of the most important agricultural frontiers (Fageria & Baligar 2008). However, as almost 2·0 billion hectares (ha) of agricultural land in the tropics are affected by acidity (Bian *et al.* 2013), the adoption of strategies are necessary to neutralize soil acidity effects and promote greater crop growth. The primary chemical problems resulting from soil acidity include low availability of the basic cations (calcium (Ca), magnesium (Mg) and potassium (K)), phosphorus (P) deficiency and aluminium (Al) toxicity (Bronick & Lal 2005; Godsey *et al.* 2007; Castro & Crusciol 2013).

To increase crop productivity in acidic areas, liming has been considered a viable strategy. However, due to the low solubility and mobility of calcium carbonate, superficial application of the lime reaction without the use of incorporation methods usually results in restriction of lime to the uppermost layers (Caires *et al.* 2005; Soratto & Crusciol 2008). Because 75% of tropical soils are also severely affected by poor chemical fertility of the sub-soil (Sumner & Noble 2003), the limited action of surface liming can modify the root architecture, influencing water and nutrient uptake, thereby affecting plant productivity. In sub-tropical conditions, Caires *et al.* (2006) reported that sub-soil acidity does not appear to be a limiting factor for crop production in regions under an adequate water regime; however,

* To whom all correspondence should be addressed. Email: crusciol@fca.unesp.br

under unfavourable conditions, high sub-soil acidity can affect plant production substantially. In contrast, in tropical areas with a dry season, a lower organic matter content and higher than average air temperatures lead to low water storage, mainly in surface layers; thus, acidity neutralization in sub-soil layers is crucial to improve root growth and avoid water stress. Under sub-soil acidic conditions, root growth is limited to soil surface layers, since chemical attributes such as high Al activity and low availability of exchangeable bases in sub-soil layers injure meristematic cells, reducing root elongation as well as water and nutrient uptake by plants and, consequently, the productivity of crops, especially during drought periods.

The adoption of strategies to increase the downward movement of lime particles to sub-soil layers is essential to improve the sustainability of tropical crop production. de Oliveira & Pavan (1996) and Caires *et al.* (2002) reported that the carbonate reaction in sub-surface layers could vary according to lime rates and soil structure; therefore, mechanisms that induce physical displacement of lime particles into the soil play a fundamental role in alleviating sub-soil acidity. Based on a field trial conducted under sub-tropical conditions in a Typic Hapludox soil managed for 15 years under a no-till (NT) system, Caires *et al.* (2005) reported that the lime rate calculated via the base saturation (BS) method (0·70) was adequate to obtain the maximum economic yield; however, these researchers did not report the effects of surface liming below a depth of 0·20 m. In addition, interactions between topsoil chemical attributes and root growth are crucial for the formation and stabilization of aggregates, which determine the soil pore structure (Six *et al.* 2004). To improve the alkalization reaction in sub-soil layers, large amounts of lime, with a high effective calcium carbonate equivalent (ECCE), are applied (Caires *et al.* 2005); however, nutrient deficiencies can occur in the uppermost soil layers (Shuman 1986). Therefore, to increase carbonate mobility, mechanisms that improve soil structure are essential to increase the effectiveness of surface liming.

Studies conducted in tropical NT systems have detected significant changes in soil physical properties, emphasizing lower macroporosity and denser layers (Fabrizzi *et al.* 2005; Cavalieri *et al.* 2009), which are important attributes that reduce lime mobility in the soil. Because these factors are highly influenced by the soil organic matter (SOM) content, vigorous root growth should play a critical role in improving physical properties, which would induce increased physical displacement of lime to deeper soil layers (Bronick & Lal 2005). Because the roots exhibit a high capacity to increase the flux of soil organic carbon, both directly and indirectly, these structures are classified as important factors involved in the formation and stabilization of aggregates (Six *et al.* 2004). Therefore, acid management practices that improve the root architecture in topsoil layers are a prerequisite for alleviating sub-soil acidity.

A long-term field experiment was conducted under a tropical NT system to evaluate the effect of lime rates applied superficially, without previous incorporation, on root architecture, plant nutrition and technological characteristics as well as the yield of wheat and common beans cultivated in two growing seasons.

MATERIALS AND METHODS

Site description

This experiment was performed in Botucatu, São Paulo State, Southeastern Brazil (48°25′37″ W, 22° 49′50″ S, 765 m a.s.l.) during two growing seasons in an area under NT over a 12-year experimental period. The long-term (50 years) annual maximum and minimum temperatures registered in this region were 26·1 and 15·3 °C, respectively. The rainfall and the mean maximum and minimum temperatures recorded over the two growing seasons are shown in Fig. 1.

The soil is a sandy clay loam kaolinitic thermic Typic Haplorthox (Soil Survey Staff 1999), with 347, 108 and 545 g/kg of clay, silt and sand, respectively. The chemical properties of the soil were determined at multiple depths (0–0·05, 0·05–0·10, 0·10–0·20, 0·20–0·40 and 0·40–0·60 m) prior to establishing the experiment (Table 1), according to the methodologies described by van Raij *et al.* (2001).

Experimental design and establishment of treatments

A randomized complete block design was used, with four replications. Each plot covered an area of 46·8 m^2 (5·2 × 9·0 m^2). The treatments consisted of four lime rates applied to the soil surface (without incorporation): 0 (no lime), 1100 (half the recommended rate), 2700 (full recommended rate) and 4300 kg/ha of lime (double the recommended rate) were applied in 2002 (treatment establishment), and

https://doi.org/10.1017/S0021859617000235 Published online by Cambridge University Press

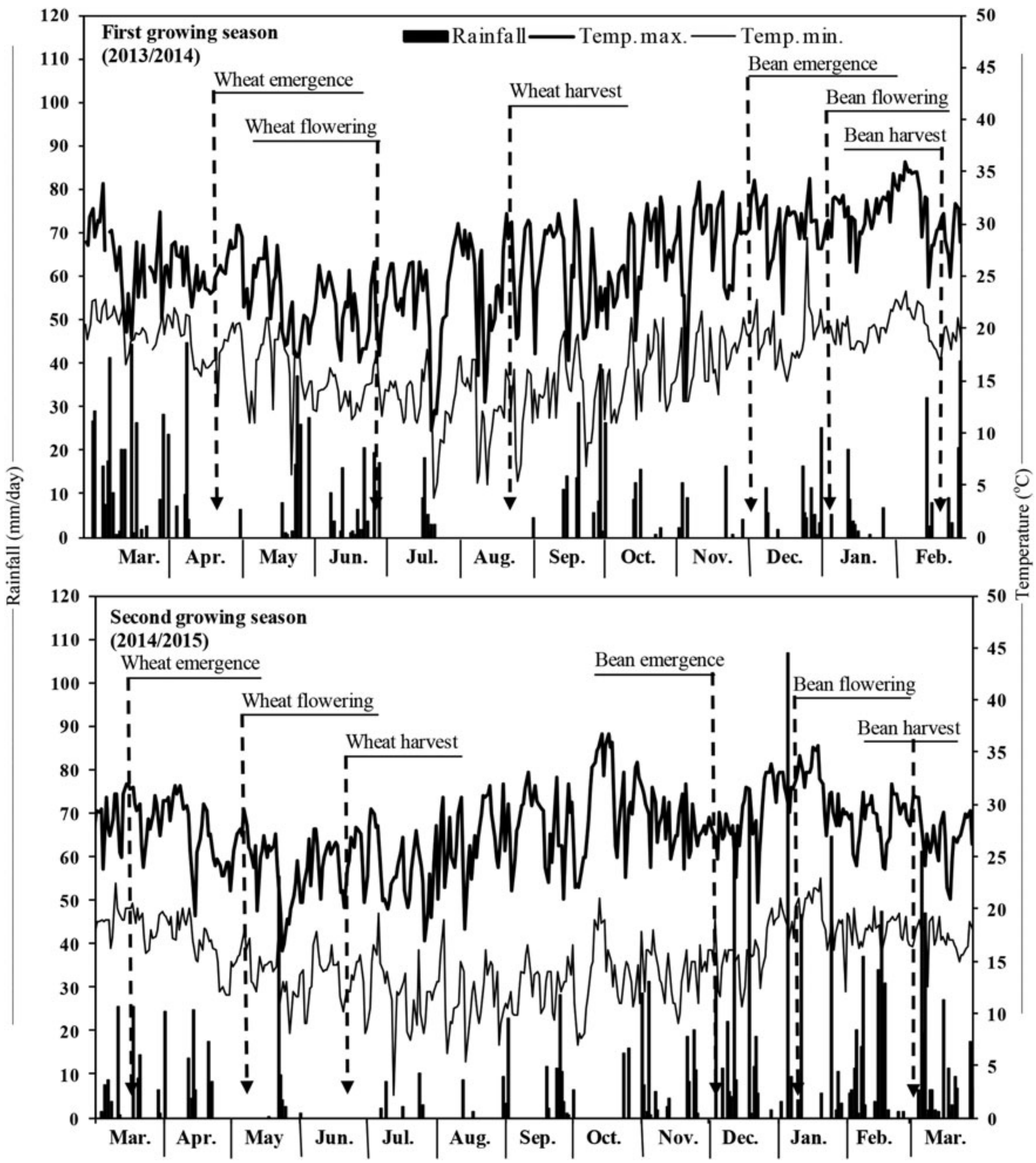

Fig. 1. Daily rainfall, maximum and minimum temperatures and growth period of crops grown at Botucatu, São Paulo State, Brazil, during 2013/14 and 2014/15.

0, 1000, 2000 and 4000 kg/ha of lime, respectively, was reapplied in 2004 and 2010. In all of the applications, dolomitic limestone was used as the liming agent; its composition was 233 g/kg of CaO (calcium oxide) and 175 g/kg of MgO (magnesium oxide). The full recommended rate (*R*) was calculated to increase the BS in the topsoil (0–0·20 m) to 70% using Eqn (1), as described by Cantarella *et al.* (1998). Reapplications were performed at a rate of 2000 kg/ha in October of 2004 and 2010, when the standard treatment (full recommended rate) reached BS ≤50%:

$$R(\text{kg/ha}) = (\text{BS}_2 - \text{BS}_1)\text{CEC}/(\text{ECCE}/100) \quad (1)$$

where ECCE is the effective calcium carbonate equivalent of the dolomite; BS_2 is the estimated base saturation (70%); and BS_1 is the base saturation determined through soil chemical analysis and calculated using Eqn (2):

$$\text{BS}_1(\%) = (\text{Ca}_{\text{ex}} + \text{Mg}_{\text{ex}} + \text{K}_{\text{ex}})100/\text{CEC} \quad (2)$$

https://doi.org/10.1017/S0021859617000235 Published online by Cambridge University Press

Table 1. *Chemical characteristics of the soil before the experiment*

Depth (m)	pH ($CaCl_2$)	SOM (g/dm^3)	P resin (mg/dm^3)	H + Al ($mmol_c/dm^3$)	Al^{3+}	K^+	Ca^{2+}	Mg^{2+}	CEC	BS (%)
0–0·20	4·2	21	9·2	37	2·3	1·2	14·0	5·0	57	35

$CaCl_2$, calcium chloride; SOM, soil organic matter; P, phosphorus; H + Al, total acidity (hydrogen + aluminium); Al^{3+}, aluminium; K^+, potassium; Ca^{2+}, calcium; Mg^{2+}, manganese; CEC, cation exchange capacity, BS, base saturation.

where Ca_{ex}, Mg_{ex} and K_{ex} are the levels of basic exchangeable cations in the soil, and CEC is the total cation exchange capacity, which was calculated using Eqn (3):

$$\text{CEC}\ (\text{mmol}_c/\text{dm}^3) = \text{Ca}_{ex} + \text{Mg}_{ex} + \text{K}_{ex} + \text{total acidity}\ (\text{H} + \text{Al}) \quad (3)$$

where total acidity (H + Al) is hydrogen + aluminium.

The following crops were grown during the study period (summer crop/autumn–winter–spring crop): upland rice/black oat (2002/03), common bean/black oat (2003/04), peanut/white oat (2004/05), peanut/white oat (2005/06), maize/palisade grass (2006/07), maize/palisade grass (2007/08), soybean/black oat (2008/09), soybean/grain sorghum (2009/10), maize/cowpea (2010/11), maize/cowpea (2011/12), pearl millet/wheat (2012/13), common bean/wheat (2013/14) and common bean (2014/15).

Soil sampling and chemical analysis

Three (36 months) and 4 (48 months) years after the last application of lime, eight individual soil samples were collected randomly from between the rows in each plot (hereafter termed 'inter-row'), at depths of 0–0·05, 0·05–0·10, 0·10–0·20, 0·20–0·40 and 0·40–0·60 m to form a composite sample. The samples were subsequently dried, sieved (2-mm) and analysed according to Cantarella *et al.* (1998) and van Raij *et al.* (2001) to determine soil chemical attributes (pH, H + Al, exchangeable Al, SOM, P, exchangeable Ca, Mg and K, and BS).

Soil pH was determined in a 0·01 mol/l $CaCl_2$ (calcium chloride) suspension (1/2·5 soil/solution), and the exchangeable Al was extracted with a neutral 1 mol/l KCl (potassium chloride) solution (1/10 ratio of soil/solution) and quantified via titration with 0·025 mol/l of sodium hydroxide (NaOH) solution. Total acidity (H + Al) was determined through extraction using calcium acetate (0·5 mol/l at pH 7·0) and titration (0·025 mol/l of NaOH solution). Soil organic matter was determined via the colorimetric method using a sodium dichromate solution (Heanes 1984). Available P and exchangeable basic cations (Ca, Mg and K) were extracted using ion-exchange resin (van Raij *et al.* 1986). Phosphorus in the extractable solution was determined via the colorimetric method proposed by Murphy & Riley (1962) using a FEMTO 600S spectrophotometer (FEMTO, São Paulo, SP, Brazil). To determine the exchangeable Ca, Mg and K levels, a Shimadzu AA-6300 atomic absorption/flame-emission spectrophotometer was used. Cation exchange capacity was obtained by summing the individual basic cations (H, Al, K, Ca and Mg). The BS values were calculated by dividing the sum of the K, Mg and Ca levels (the bases) by CEC and multiplying the result by 100% (van Raij *et al.* 2001).

Crop management

Before sowing wheat and common bean (approximately 20 days), weed control was performed through glyphosate application (Roundup Original, 1800 g acid equivalents/ha, Monsanto, Brazil).

The wheat cultivar 'CD116' was sown on 18 April 2013 and 12 March 2014. The wheat seeds were sown in both growing seasons at a within-row spacing of 0·17 m, with rows of 80 seeds/m, using NT seeding (Semeato model SHM 15/17, Passo Fundo, RS, Brazil). The seeds were treated with 52 g of thiamethoxam {3-(2-chloro-thiazol-5-ylmethyl)-5-methyl-1,3,5 oxadiazinan-4-ylidene (nitro) amine}, 60 g of carboxin (5,6-dihydro-2-methyl-1,4-oxathiin-3-carboxamide) and 60 g of thiram (tetramethylthiuram disulphide) per 100 kg of seeds. Fertilization was performed at sowing with 75 kg N/ha, 70 kg phosphorus pentoxide (P_2O_5)/ha, 40 kg potassium oxide (K_2O)/ha, 1·25 kg Zn/ha and 11·25 kg S/ha. Weeds were controlled by applying 0·8 kg/ha of 2,4-D {dimethylammonium (2,4-dichlorophenoxy) acetate} and 58 g/ha of clodinafope-propargil {(R)-2-(4-(5-chloro-3-fluoro-pyridin-2-yloxy)-phenoxy)-propionic acid prop-2-ynyl ester} 10 days after sowing.

https://doi.org/10.1017/S0021859617000235 Published online by Cambridge University Press

On 28 November 2013 and 1 December 2014, the common bean cultivar 'Pérola' was sown at a density of 33 seeds/m^2 with between-row spacing of 0·45 m using a mechanical seeder (Semeato Model Personale Drill-13). The amounts of thiamethoxam, carboxin and thiram used to treat 100 kg of seeds were 105, 60 and 60 g, respectively. Base fertilization was performed at sowing with 10 kg N/ha, 50 kg P_2O_5/ha, 50 kg K_2O/ha, 1·25 kg Zn/ha and 11·25 kg S/ha. Nitrogen topdressing fertilization as ammonium nitrate (31% N) was performed at 100 kg/ha of N when the plants reached stage V_4 (third trifoliate leaf expanded) (Fernández *et al*. 1985) according to the recommendations of Ambrosano *et al*. (1997).

Root sampling and analyses

In the second growing season for wheat (2014) and common bean (2014/2015), eight root samples were collected randomly at flowering from each plot and combined to form a composite sample for determination of root characteristics (length, diameter and dry matter content). For each layer, four sub-samples were collected from plant rows and in the middle of the inter-rows of each sub-plot. A galvanized-steel probe with a 69-mm diameter cutting tip was used at depths of 0–0·05, 0·05–0·10 and 0·10–0·20 m. For samples collected at 0·20–0·40 and 0·40–0·60 m, the probe was employed with a 49-mm diameter cutting tip. Roots were carefully separated from soil and other residues by washing under a flow of swirling water over a 0·5-mm mesh sieve, according to Oussible *et al*. (1992). Root samples were then immersed in an ethyl alcohol solution in plastic pots with lids and stored at 2 °C until evaluation. To evaluate the root length density (km/m^3) and root diameter (mm), roots were digitalized using an optical scanner (Scanjet 4C/T, HP) at high resolution (600 dpi) and then analysed using the software program 'WinRhizo' version 3.8-b (Regent Instrument Inc., Quebec, Canada). Following these assessments, the root samples were dried in a forced-air oven at 60 °C for 72 h to measure root dry matter, expressed in g/m^3.

Plant sampling and analyses

At the flowering stage of both crops, leaf samples were collected to determine the nutrient concentrations, which was performed according to the method proposed by Cantarella *et al*. (1997) and Ambrosano *et al*. (1997). At the same stage, ten random plants per plot were collected to determine shoot dry matter. All of the samples were dried in a forced-air oven at 65 °C for 72 h. The plants were then weighed, the leaves ground to pass a 40-mesh (420 μm) stainless steel screen and analysed to determine the nutrient concentrations according to the methods described by Malavolta *et al*. (1997). All of the macronutrients (P, K, Ca, Mg and S) except N were extracted via nitroperchloric digestion and determined via atomic absorption spectrophotometry. Nitrogen was extracted using a H_2SO_4 (sulphuric acid) extraction solution and determined through the Kjeldahl distillation method.

At physiological maturity, 20 plants were evaluated in the plot area to determine plant height (measuring from the soil surface to the tip of the ear). Wheat was harvested on 22 August 2013 and 24 June 2014 in the first and second growing seasons, respectively, and the following parameters were determined: yield components (number of ears/m^2, obtained by counting the number of ears in 2·0 m lengths of two central rows from the usable area of each plot), number of spikelets per ear (obtained by counting the number of spikelets in 20 ears), grains/spikelet (obtained using the following function: number of grains in 20 ears/total number of spikelets in 20 ears), grains/ear (obtained by multiplying number of spikelets per ear by grains/spikelet) and 1000-grain weight (evaluated through the random collection and weighing of four samples of 1000 grains from each plot), volumetric mass (obtained by weighing four samples of grain with a volume of 0·25 litres, with the data converted to 100 litres volume) and grain yield kg/ha (130 g/kg wet basis).

Common bean was harvested manually on 17 February 2014 and 3 March 2015 in the first and second growing seasons, respectively. Yield components (final population of plants (from two central 7-m rows in each plot), number of pods per plant (obtained by counting the number of pods in ten plants), number of seeds per pod, 100-grain weight and grain yield (from seven central 7-m rows, kg/ha on 130 g/kg wet basis)) were determined.

The grain quality of the common bean grains was analysed 60 days after harvest. In each plot, four grain samples were collected randomly and then classified using sieves with oblong holes of 12/64″ × ¾″ (4·76 × 19·05 mm). After 1 min of shaking, the sieve classification (%) was calculated as the ratio between the weight of the grains retained in the sieve and the total sample weight multiplied by 100.

https://doi.org/10.1017/S0021859617000235 Published online by Cambridge University Press

Following this assessment, the retained grains (commercial grains) were ground and N content determined (Malavolta *et al.* 1997). The protein content was obtained by multiplying the N concentration in the grains by 6·25.

Statistical analysis

All data were initially tested for normality with the Shapiro–Wilk test using the UNIVARIATE procedure of SAS (version 9.3; SAS Inst. Inc., Cary, NC, USA), and the results indicated that all data were distributed normally ($W = 0·90$). The data were then analysed employing the PROC MIXED procedure of SAS and the Satterthwaite approximation to determine the degrees of freedom for the tests of fixed effects. The data were analysed using replications (lime rate) as random variables. The model statement employed for the analysis of soil, root and plant variables included the effects of lime rate, and the specified term for the repeated statement was growing seasons; replications (growing seasons × lime rate) were the subject; and the covariance structure utilized for all repeated statements was CS (compound symmetry), which provided the best fit for these analyses according to the Akaike information criterion. The results are reported as least square means and separated using the PDIFF (probability of differences) option. The lime rates were analysed via the PROC REG procedure of SAS, and the best adjustments were chosen as those with the greatest coefficients of determination and considering the results of Student's *t* tests. Error bars represent s.e. and were determined using the PROC MEAN procedure of SAS. The effects were considered statistically significant at $P < 0·05$. The data on root characteristics were considered statistically significant at $P < 0·10$. A higher probability was used for the root system evaluation because these characteristics are more variable (Fageria & Moreira 2011). According to Gregory (2006), 15–20 root samples are necessary to detect significant differences at $P < 0·10$, whereas significance at $P < 0·05$ often requires approximately 60–90 samples in each experimental unit. The figures were produced using SigmaPlot 11.

RESULTS

Soil chemical attributes

Surface application of different dolomitic limestone rates influenced the primary chemical attributes of the acidic tropical Oxisol; however, the magnitude of the effect varied according to the soil parameters, soil layer and lime rate (Supplementary Table S1, available from https://www.cambridge.org/core/journals/journal-of-agricultural-science). The reaction of different calcium carbonate rates effectively reduced the three major components of soil acidity (active (pH), total (H + Al) and exchangeable acidity (Al)), with linear adjustments for all soil layers.

Thirty-six months after the last application, regardless of soil acidification processes, there were significant ($P < 0·05$) changes in soil pH, total acidity (H + Al) and exchangeable Al, which were the most pronounced effects in the uppermost soil layers under the application of the highest lime rate (4000 kg/ha). At the second soil sampling (48 months), the lime reaction consistently alleviated soil acidity, resulting in larger pH changes in deeper soil layers under the application of the highest lime rate, with pH values ranging from 3·8 to 4·4 at the 0·20–0·40 m depth and from 3·9 to 4·2 at the 0·40–0·60 m depth, along with significant ($P < 0·05$) modifications of the other acidity components (H + Al and exchangeable Al). In addition, based on the observation of H + Al and exchangeable Al levels over time, it is important to emphasize that soil acidification was lower when the higher lime rate was applied. Large amounts of free Al were observed in unlimed soil 36 months after the last reapplication (10–20·8 $mmol_c/dm^3$, according to the soil layer), which had increased sharply 1 year later (20–32·7 $mmol_c/dm^3$). However, under the application of 4000 kg/ha, the observed exchangeable Al levels were not considered toxic at the 0–0·20 m depth, regardless of soil sampling.

Increases in SOM content were also observed following the surface application of different lime rates. Over time, greater changes in SOM levels occurred at the 0–0·05 m depth, with variations of 26·8–29·6 g/dm^3 being observed at 36 months and 24·2–28·2 g/dm^3 at 48 months after the last reapplication of calcium carbonate. After the treatment had been established for 12 years, the results showed the long-term effect of surface liming on SOM, with up to a 20% increase in the content of this fraction being observed at the 0·05–0·10 m depth and the 0·10–0·20 m depth, according to the lime rate applied. In addition, significant ($P < 0·05$) changes were observed in deeper soil layers (0·20–0·40 and 0·40–0·60 m depths), and according to the quadratic model, the highest accumulation of SOM would occur under the application of lime rates ranging from 2250 to 2300 kg/ha.

Surface liming exerted a positive effect on P availability in the soil profile, with the highest P levels being observed with the double-rate application of lime (4000 kg/ha). At both sampling times, the regression coefficients were adjusted for a linear model for all layers, except at the 0·10–0·20 m soil layer, at 48 months after the last reapplication. Regardless of the large amount of P fertilizer added in each growing season, the results showed the importance of surface liming for improving P availability, primarily in deeper soil layers, due to the low mobility of P in soil solution.

Although dolomitic lime exhibits low solubility and mobility, long-term results showed the feasibility of surface liming for increasing exchangeable Ca and Mg levels in an acid soil profile. As observed for other soil parameters, the magnitude of the effect varied according to the lime rate and soil layers, with the highest levels of Ca and Mg being observed at 0–0·05 m depths, ranging from 4·9 to 44·5 $mmol_c/dm^3$ of Ca and from 2·7 to 22·1 $mmol_c/dm^3$ of Mg, showing a persistent effect during the 48 months after the last reapplication. Despite the lower magnitude effect, the highest lime rates increased the exchangeable Ca and Mg levels by 226 and 327% in the deeper soil layer (0·40–0·60 m depth), respectively.

In contrast to what was observed for most soil parameters, 36 months after the last reapplication, lime rate did not induce changes in the levels of exchangeable K in the uppermost soil layers (0–0·05 and 0·05–0·10 m depths) but reduced K availability linearly at 0·10–0·20, 0·20–0·40 and 0·40–0·60 m depths. One year later, the same effect of lime on K levels was observed, but only in the layers above a depth of 0·20 m.

The increases in the amounts of Ca and Mg in the soil solution associated with alleviation of soil acidity contributed to a linear increase in BS. In all soil layers, the highest values were obtained with the double-rate application of lime (4000 kg/ha). However, 48 months after the last reapplication, only the soil layers at depths of 0–0·05 m and 0·05–0·10 m presented BS values close to 70%.

Wheat

Root development

The surface application of lime rates induced significant ($P < 0·05$) changes in wheat root characteristics (Table 2), linearly increasing the root length density and root dry matter in all soil layers; however, the results emphasize the benefits of lime for root growth in deeper soil layers. Compared with the control treatment (no lime), the application of the highest lime rate (4000 kg/ha) increased root growth in deeper soil layers, with an increase in root biomass from 3·2 to 70·6 g/m^3 being observed at a 0·20–0·40 m depth and from 0·9 to 28·7 g/m^3 at a 0·40–0·60 m depth. In addition, increasing lime rates reduced the root diameter linearly in the uppermost soil layer (0–0·05 m); however, the opposite effect was observed in the 0·20–0·40 and 0·40–0·60 m soil layers.

Plant nutrition and above-ground biomass

The N, Ca and S concentrations in the flag leaves and shoot dry matter of wheat were significantly ($P < 0·05$) affected by lime rate and growing season interactions, whereas for the P, K and Mg concentrations, only single effects were observed (Table 3). Regardless of the growing season, the N, Ca and Mg concentrations in the flag leaves increased linearly with lime rate (Figs 2*a, d* and 3*e*), while the leaf K concentration decreased (Fig. 2*c*), with the highest leaf concentrations of N, K, Ca and Mg being observed in the second growing season (2014). In the first growing season (2013), no effects of the applied lime rates were observed for leaf P and S concentrations, but positive effects of surface liming on the concentrations of these macronutrients were evident in the second growing season (Fig. 2*b* and *f*).

Due to the acidity in the unlimed treatment (0 kg/ha), the adverse effect of rainfall distribution in the second growing season (Fig. 1) on the growth of shoot dry matter was more evident compared with the other treatments (Fig. 3*a*). According to the quadratic model, the maximum shoot dry matter content of wheat would be achieved with estimated rates of 2576 and 2798 kg/ha.

Yield and quality characteristics

Number of ears developed/area, number of grains/spikelet, number of grains/ear, grain yield and volumetric weight were strongly affected by the interaction between lime rate and growing season (Table 3). As observed for shoot dry matter, the results regarding the number of ears per unit area and grain yield showed that the absence of lime (0 kg/ha) or the application of an insufficient rate, such as half-rate lime application (1000 kg/ha), caused wheat to be more vulnerable to adverse environmental conditions, reducing the plant productivity capacity (Fig. 3*b* and *g*). The number of spikelets/ear, and 1000-grain weight were

Table 2. *Length density, dry matter and diameter of the wheat root system as affected by surface application of lime at Botucatu, São Paulo State, Brazil*

Soil layer (m)	Lime rates (kg/ha) 0	1000	2000	4000	Equation	R^2	$P > F$
		Root length density (km/m^3)					
0–0·05	8·6	31·8	49·3	54·3	0·0109x + 16·88	0·81	<0·001
0·05–0·10	4·2	14·2	26·6	31·3	0·0067x + 7·248	0·88	<0·001
0·10–0·20	2·1	6·5	13·3	12·8	0·0027x + 3·936	0·73	<0·001
0·20–0·40	0·6	2·7	7·5	8·8	0·0021x + 1·185	0·87	<0·001
0·40–0·60	0·2	0·8	2·7	2·7	0·0007x + 0·436	0·77	<0·05
		Root dry matter (g/m^3)					
0–0·05	91·8	284·2	373·4	366·8	0·0623x + 170·09	0·66	<0·001
0·05–0·10	42·0	144·9	235·2	223·6	0·0434x + 85·528	0·69	<0·001
0·10–0·20	3·9	34·6	75·9	85·3	0·0204x + 14·289	0·85	<0·001
0·20–0·40	3·2	18·3	76·0	70·6	0·0181x + 10·354	0·71	<0·001
0·40–0·60	0·9	6·1	28·6	28·7	0·0075x + 2·9505	0·76	<0·05
		Root diameter (mm)					
0–0·05	0·30	0·26	0·23	0·23	$-2 \times 10^{-5}x + 0·281$	0·78	<0·001
0·05–0·10	0·24	0·29	0·26	0·23	–	–	ns
0·10–0·20	0·28	0·26	0·28	0·27	–	–	ns
0·20–0·40	0·24	0·29	0·30	0·34	$2 \times 10^{-5}x + 0·2525$	0·89	<0·05
0·40–0·60	0·24	0·28	0·31	0·30	$1 \times 10^{-5}x + 0·2585$	0·61	ns

ns, not significant.

decreased in the second growing season because of a low rainfall regime during important stages of wheat development; however, all of these parameters increased linearly with lime rates in both growing seasons (Fig. 3*c* and *f*). Regarding the number of grains/spikelet and number of grains/ear, the data were subjected to different polynomial adjustments according to the growing season (Fig. 3*d* and *e*). Under a more favourable rainfall distribution (first growing season), the results were adjusted to a quadratic function, with maximum grains per spikelet being obtained with an estimated rate of 2500 kg/ha of lime. However, under stress conditions (second growing season), liming resulted in a linear increase, indicating that important wheat yield components are more responsive to the application of higher rates. The lime rate did not change the volumetric weight in the first growing season, but under stress conditions, the best results were obtained under an estimated rate of 3000 kg/ha.

Common bean

Root development

As observed for wheat, the amounts of lime also positively affected the root characteristics of common bean (Table 4). At 0–0·05 m and 0·10–0·20 m depths for an in-row location, the data were adjusted to a quadratic model, with estimated optimum rates of 2750 and 1714 kg/ha, respectively. In other soil layers, a linear response was identified, with the maximum root length density being recorded at a rate of 4000 kg/ha of lime. In the middle of the inter-rows (i.e. between the crop rows), a similar adjusted regression model was determined for root elongation in all soil layers.

Due to the substantial influence on root length growth, the surface application of various lime rates increased the root dry matter content in all soil profiles, with quadratic adjustments for most of the soil layers in the middle of the inter-rows and a linear response at the in-row locations. Generally, increased levels of root biomass were produced under lime rates >2800 kg/ha.

The common bean root diameter was also affected by soil acidity. At the middle of the inter-rows, the absence of lime resulted in a greater root diameter in the 0–0·05 m and 0·05–0·10 m layers. In the deeper soil layer (0·40–0·60 m depth), the alleviation of soil acidity resulted in a larger root diameter, which increased according to lime rate. A similar result was observed in the middle of the inter-rows, with the

https://doi.org/10.1017/S0021859617000235 Published online by Cambridge University Press

Table 3. *Significance determined via analysis of variance (ANOVA) for shoot dry matter (SDM), nutrient concentrations (nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S)) in flag leaves, number of ears/m² (NE), spikelets/ear (SE), grains/spikelet (GS), grains/ear (GE), 1000-grain weight (TGW), grain yield (GY) and volumetric weight (VW) in wheat as affected by the surface application of lime and different growing season at Botucatu, São Paulo State, Brazil**

	SDM	N	P	K	Ca	Mg	S	NE	SE	GS	GE	TGW	GY	VW
F probability														
Treatments (T)	<0·001	<0·001	<0·05	<0·001	<0·001	<0·001	ns	<0·001	<0·01	<0·001	<0·001	0·0005	<0·001	<0·001
Growing season (GS)	<0·001	<0·001	ns	<0·001	<0·001	<0·001	ns	<0·001	<0·001	ns	<0·001	<0·001	<0·001	<0·001
T × GS	<0·01	<0·01	ns	ns	<0·05	ns	<0·01	≤0·001	ns	≤0·001	<0·001	ns	<0·001	<0·05

ns, not significant.
* The degrees of freedom of treatments, growing season, T × GS interaction, blocks and error were 3, 1, 3, 3 and 21, respectively.

maximum root size occurring at 0·10–0·20 m and 0·20–0·40 m depths with a lime rate of 4000 kg/ha. However, according to the quadratic adjustment, the maximum root diameter at 0·40–0·60 m depth would be achieved with an estimated rate of 2500 kg/ha.

Plant nutrition and above-ground biomass

With the exception of Mg and S, the concentrations of the evaluated leaf macronutrients were influenced by interactions between lime rate and growing season (Table 5). According to the growing season, there were different polynomial adjustments for the N concentration (Fig. 4*a*). In the first growing season, the application of various lime rates increased the N concentration in the leaves linearly, but in subsequent seasons, the results were adjusted to a quadratic function, with the highest content being obtained with an estimated rate of 2600 kg/ha of lime. Regarding N concentrations, the interaction results showed that there were no differences between growing seasons under half-rate application of lime (1000 kg/ha).

Regardless of growing season, the application of various lime rates significantly ($P < 0·05$) increased P, Ca and Mg concentrations linearly in common bean leaves; however, significant ($P < 0·05$) differences in these parameters were observed between growing seasons, with higher concentrations being recorded in the first growing season (Fig. 4*b, d* and *e*). As observed for N, a significant ($P < 0·05$) interaction was found between lime rate and growing season for the concentration of K in leaves. The data were subjected to linear adjustment in the first growing season and quadratic adjustment in the second, with the maximum K concentration being obtained under an estimated rate of 2500 kg/ha (Fig. 4*c*). In both growing seasons, the S concentration in common bean leaves was not influenced by lime rate, but in contrast to most of the macronutrients, a greater leaf concentration of S was observed in the second growing season (Fig. 4*f*).

The shoot dry matter content of common bean was not influenced by the lime rate × growing season interaction, but there were single effects. The results showed that the amounts of lime applied increased shoot dry matter content linearly, with greater development of above-ground biomass being observed in the first growing season (Fig. 4*g*).

Yield and quality characteristics

Plant population, grains/pod and screenings of common bean were only influenced by lime rate,

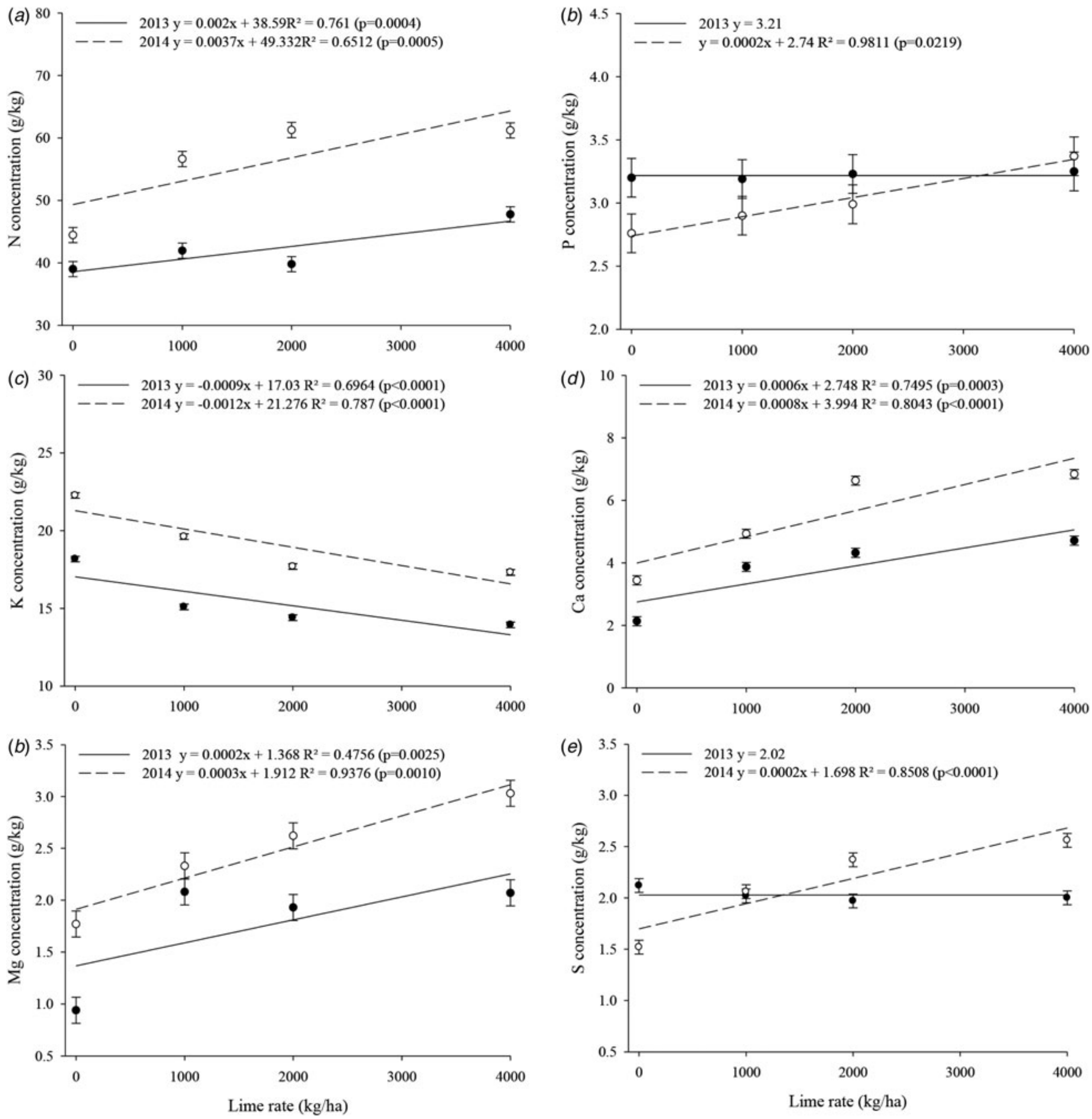

Fig. 2. (*a*) Nitrogen, (*b*) phosphorus, (*c*) potassium, (*d*) calcium, (*e*) magnesium and (*f*) sulphur concentrations in wheat flag leaves as affected by surface dolomitic lime in the 2013 (●) and 2014 (○) growing seasons. Lime was applied three times (2002, 2004 and 2010). Horizontal bars represent the least significant difference by the LSD test at $P = 0{\cdot}05$.

while the 100-grain weight and protein content were only affected by growing season. Interactions between the two factors were detected for plant survival, number of pods/plant and seed yield (Table 5). Increasing lime rates resulted in greater development of productive structures, with a linear response being observed for plant population, plant survival, number of pods/plant, seeds/pod and grain yield, regardless of the growing season (Fig. 5*a–d* and *f*). Results indicate that the higher production of pods/plant and 100-seed weight observed in the second growing season were reflected in a higher grain yield compared with the first year; however, the protein content of the seed was reduced (Fig. 5*c, e, f* and *g*). The evaluation of interactions showed that even under stress due to edapho-climatic conditions,

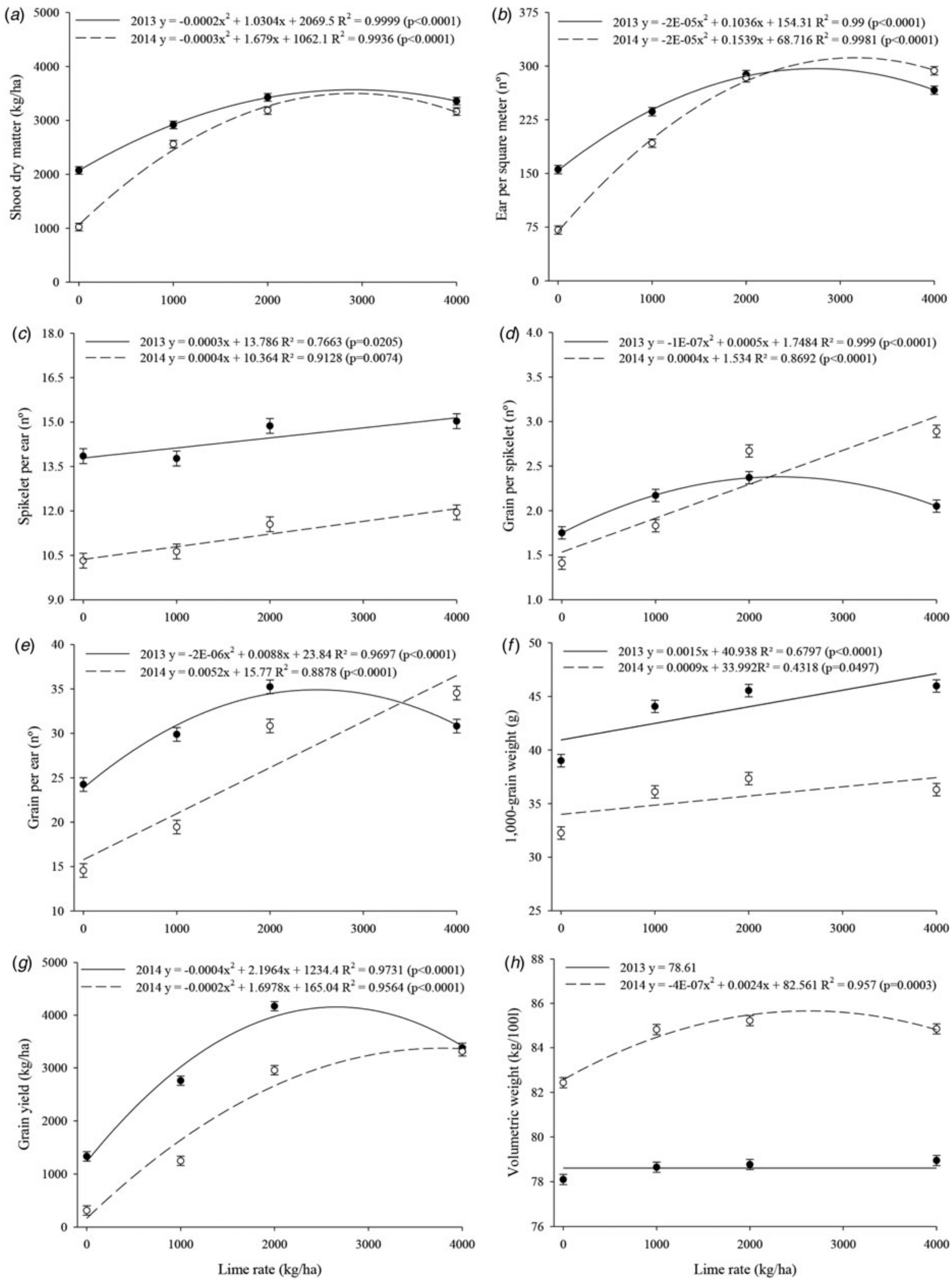

Fig. 3. (*a*) Shoot dry matter, (*b*) ear/m^2, (*c*) spikelet/ear, (*d*) grain/spikelet, (*e*) grains/ear, (*f*) 1000-grain weight, (*g*) grain yield and (*h*) volumetric weight of wheat as affected by surface dolomitic lime in the 2013 (●) and 2014 (○) growing seasons. The amendments rates were applied three times (2002, 2004 and 2010). Horizontal bars represent the least significant difference by the LSD test at $P = 0{\cdot}05$.

Table 4. *Length density, root dry matter and diameter of common bean root system within rows and in the middle of the inter-rows as affected by surface application of lime at Botucatu, São Paulo State, Brazil*

	Lime rates (kg/ha)						
Soil layers (m)	0	1000	2000	4000	Equation	R^2	$P > F$
	Root length density (in-row) (km/m^3)						
0–0·05	2·0	8·3	7·6	5·8	$-1 \times 10^{-6}x^2 + 0{\cdot}0055x + 2{\cdot}5172$	0·84	<0·001
0·05–0·10	3·8	10·0	13·8	14·3	$0{\cdot}0025x + 6{\cdot}1915$	0·75	<0·001
0·10–0·20	5·4	2·1	4·1	7·3	$7 \times 10^{-7}x^2 - 0{\cdot}0024x + 4{\cdot}9068$	0·82	<0·001
0·20–0·40	0·3	0·4	1·2	1·3	$0{\cdot}0003x + 0{\cdot}354$	0·77	<0·001
0·40–0·60	0·2	0·2	1·1	0·8	$0{\cdot}0002x + 0{\cdot}2505$	0·43	<0·001
	Root length density (inter-rows) (km/m^3)						
0–0·05	2·4	6·8	6·7	11·0	$0{\cdot}002x + 3{\cdot}2635$	0·90	<0·001
0·05–0·10	2·8	2·9	7·4	14·3	$0{\cdot}0031x + 1{\cdot}471$	0·94	<0·001
0·10–0·20	1·6	1·4	3·7	4·3	$0{\cdot}0008x + 1{\cdot}4055$	0·79	<0·001
0·20–0·40	0·6	0·3	0·8	1·0	$0{\cdot}001x + 0{\cdot}465$	0·55	<0·001
0·40–0·60	0·2	0·1	0·3	0·6	$0{\cdot}001x + 0{\cdot}0945$	0·83	<0·001
	Root dry matter (in-row) (g/m^3)						
0–0·05	23·3	78·5	81·4	41·3	$-1 \times 10^{-5}x^2 + 0{\cdot}0576x + 26{\cdot}331$	0·95	<0·001
0·05–0·10	43·8	101·4	133·9	138·5	$-1 \times 10^{-5}x^2 + 0{\cdot}067x + 44{\cdot}186$	0·99	<0·001
0·10–0·20	51·0	19·1	28·5	76·0	$1 \times 10^{-5}x^2 - 0{\cdot}0321x + 48{\cdot}365$	0·96	<0·001
0·20–0·40	6·8	2·5	12·0	11·5	$0{\cdot}0017x + 5{\cdot}221$	0·43	<0·01
0·40–0·60	0·8	0·7	9·6	5·1	$-1 \times 10^{-6}x^2 + 0{\cdot}006x - 0{\cdot}5854$	0·59	<0·001
	Root dry matter (inter-rows) (g/m^3)						
0–0·05	23·9	75·8	53·2	80·0	$0{\cdot}0108x + 39{\cdot}285$	0·52	<0·001
0·05–0·10	21·6	18·3	46·7	66·7	$0{\cdot}0126x + 16{\cdot}26$	0·89	<0·001
0·10–0·20	7·8	6·9	25·1	36·3	$0{\cdot}0079x + 5{\cdot}1885$	0·89	<0·001
0·20–0·40	2·8	1·8	20·2	27·3	$0{\cdot}0069x + 0{\cdot}998$	0·85	<0·001
0·40–0·60	1·0	0·5	1·8	3·7	$0{\cdot}0007x + 0{\cdot}4535$	0·84	<0·001
	Root diameter (in-row) (mm)						
0–0·05	0·33	0·29	0·28	0·28	$-1 \times 10^{-5}x + 0{\cdot}313$	0·54	<0·01
0·05–0·10	0·33	0·30	0·28	0·24	$-2 \times 10^{-5}x + 0{\cdot}328$	0·98	<0·001
0·10–0·20	0·30	0·33	0·25	0·30	–	–	ns
0·20–0·40	0·39	0·27	0·33	0·30	–	–	ns
0·40–0·60	0·23	0·22	0·32	0·29	$2 \times 10^{-5}x + 0{\cdot}235$	0·46	<0·001
	Root diameter (inter-rows) (mm)						
0–0·05	0·26	0·28	0·28	0·27	–	–	ns
0·05–0·10	0·24	0·25	0·24	0·24	–	–	ns
0·10–0·20	0·20	0·22	0·30	0·34	$4 \times 10^{-5}x + 0{\cdot}199$	0·93	<0·001
0·20–0·40	0·21	0·22	0·33	0·34	$4 \times 10^{-5}x + 0{\cdot}214$	0·77	<0·001
0·40–0·60	0·23	0·28	0·35	0·28	$-2 \times 10^{-8}x^2 + 0{\cdot}001x + 0{\cdot}2213$	0·88	<0·001

ns, not significant.

plots treated with lime produced higher amounts than the control treatment under better environmental conditions. In both growing seasons, the application of various lime rates increased the seed yield linearly. In the first growing season the screenings was severely affected by liming, with a linear reduction in seed size being observed according to the amount of lime applied, but no changes according to treatment were recorded in the second year.

DISCUSSION

The alleviation of soil acidity through surface application of lime without soil mobilization is considered a viable long-term practice for improving Oxisol fertility in tropical agricultural systems managed under NT cropping systems but the magnitude of the effect varies according to lime rate. In addition, reaction time (Tiritan *et al.* 2016), soil depth (Caires *et al.*

Table 5. *Significance determined via analysis of variance (ANOVA) for shoot dry matter (SDM), nutrient concentrations (nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S)) in the leaves, plant population (POP), plant survival (PS), pods/plant (PP), seeds/pod (GP), 100-grain weight (TGW), seed yield (GY), protein content (PC) and sieve classification (SC) in common bean, as affected by the surface application of lime and different growing season at Botucatu, São Paulo State, Brazil**

	SDM	N	P	K	Ca	Mg	S	POP	PS	PP	GP	TGW	GY	PC	SC
F probability															
Treatments (T)	<0·05	<0·01	<0·05	<0·05	<0·001	<0·001	ns	<0·001	<0·001	<0·001	<0·01	ns	<0·001	ns	<0·01
Growing season (GS)	<0·05	<0·001	<0·001	ns	<0·001	<0·001	<0·001	ns	<0·001	<0·001	ns	≤0·001	<0·001	≤0·001	ns
T × GS	ns	<0·01	<0·01	<0·01	<0·01	ns	ns	ns	<0·05	<0·05	ns	ns	<0·01	ns	ns

ns, not significant.
* The degrees of freedom of the treatments, growing season, T × GS interaction, blocks and error were 3, 1, 3, 3 and 21, respectively.

2005, 2008), soil characteristics (de Oliveira & Pavan 1996) and environmental conditions (Godsey *et al.* 2007) are considered important parameters that influence the feasibility of surface liming.

There are two important mechanisms that can explain the effect of surface liming on the neutralization of sub-soil acidity: (i) the downward displacement of carbonate particles through water percolation (Caires *et al.* 2005) and (ii) the reaction of organic acids with acidic components (Haynes & Mokolobate 2001). Both mechanisms can be influenced by the biological and physical effects of root growth. In an undisturbed soil, McCallum *et al.* (2004) confirmed the positive effect of root architecture on improving pore structure, through inducing the formation of large pores (>2 mm) that are responsible for increased water infiltration and are considered to play a major role in lime mobilization. In addition, according to Franchini *et al.* (2003), root activity/decomposition can also contribute to proton (H^+) consumption and Al complexation because of the reactions of organic acids such as oxalate, citrate and malate, exuded via root activity and senescence. Changes in soil pH, reduction of free Al^{3+} and higher BS in the uppermost soil layers (0–0·20 m) may be considered critical for alleviating sub-soil acidity below a depth of 0·20 m.

Even 4 years after the last reapplication of lime, use of the highest lime rate (4000 kg/ha) led to a pH value >5·0 at a 0–0·20 m depth, where the largest fractions of wheat and common bean root systems are concentrated. This lime rate also resulted in the lowest concentration of H + Al and exchangeable Al in the uppermost soil layers, which are factors that can explain the highest root length density of wheat and common beans associated with the maximum lime rate applied. Under sub-tropical conditions, Caires *et al.* (2006) reported a high correlation between these chemical attributes and root growth in surface soil layers, with increases of up to 66% in wheat root length density being observed after surface liming; however, under tropical conditions with lower annual rainfall, there is no available information about the effects of surface liming on root growth.

Aluminium toxicity is one of the most limiting factors for root growth, inducing notable damage to root morphology (Parker *et al.* 1988). In addition to showing an inhibitory effect on root elongation, exchangeable Al induces physical modifications of the cell membrane, inducing thicker root formation. This physiological effect is irreversible and can

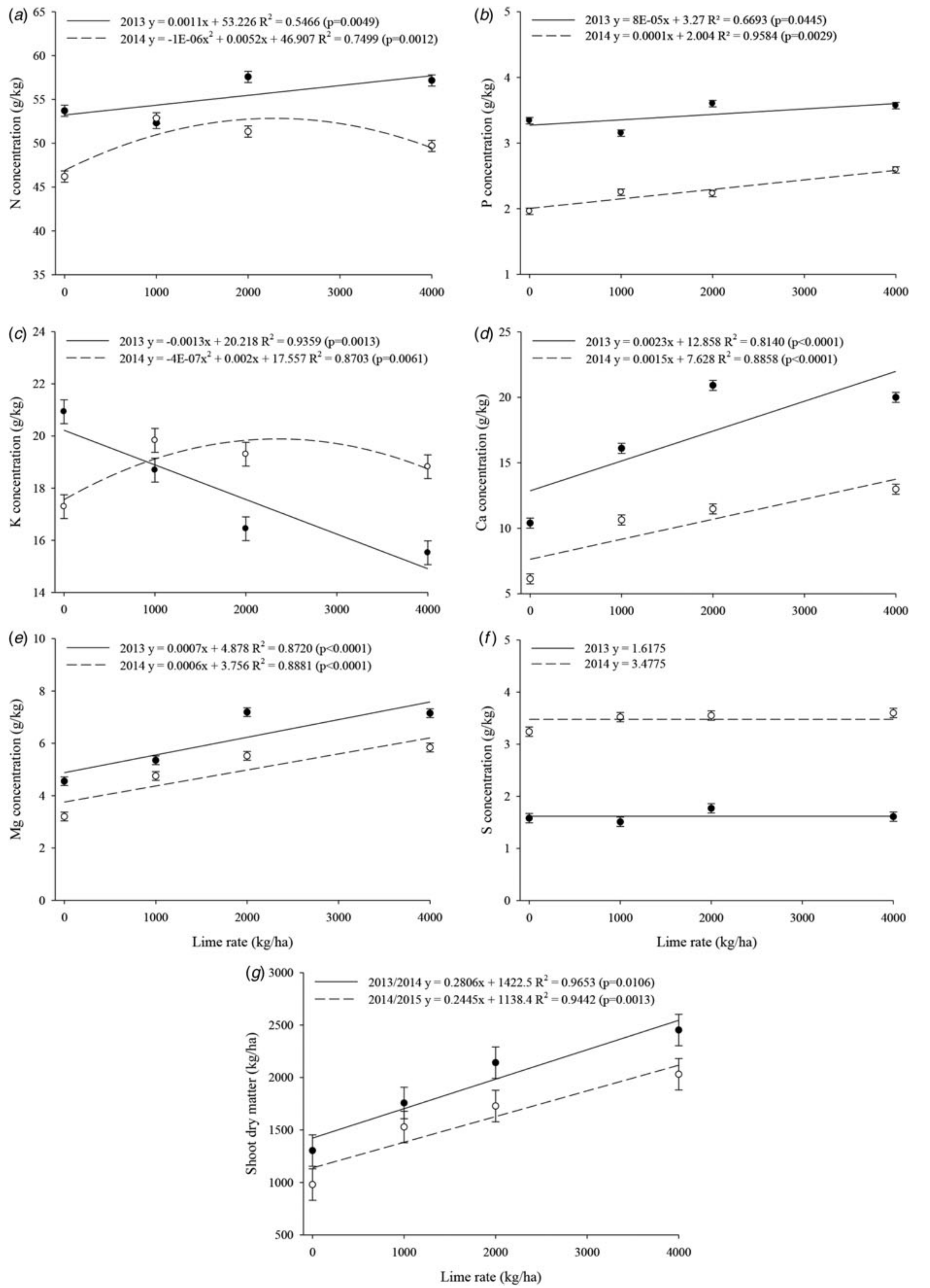

Fig. 4. (*a*) Nitrogen, (*b*) phosphorus, (*c*) potassium, (*d*) calcium, (*e*) magnesium and (*f*) sulphur concentration in leaves, and (*g*) shoot dry matter, of common bean as affected by surface dolomitic lime in the 2013 (●) and 2014 (○) growing seasons. The amendments rates were applied three times (2002, 2004 and 2010). Horizontal bars represent the least significant difference by the LSD test at $P = 0{\cdot}05$.

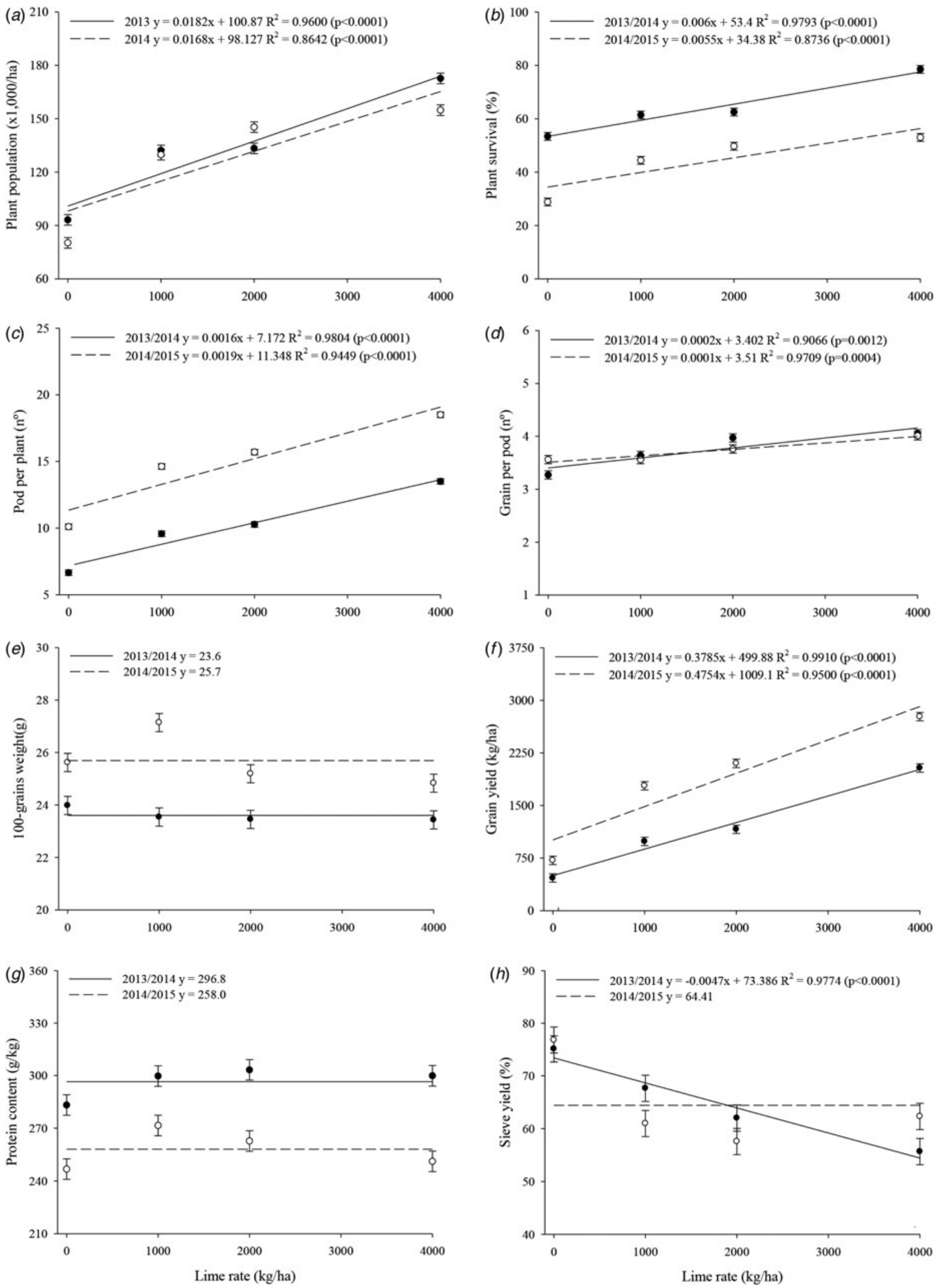

Fig. 5. (*a*) Plant population, (*b*) plant survival, (*c*) pods/plant, (*d*) grain/pod, (*e*) 100-grain weight, (*f*) seed yield, (*g*) protein content and (*h*) sieve classification of common bean as affected by surface dolomitic lime in the 2013/14 (●) and 2014/15 (○) growing seasons. The amendments rates were applied three times (2002, 2004 and 2010). Horizontal bars represent the least significant difference by the LSD test at $P = 0{\cdot}05$.

https://doi.org/10.1017/S0021859617000235 Published online by Cambridge University Press

drastically reduce water and nutrient uptake by plants (Pan *et al.* 2001). Regardless of crop species, the current results suggest that the surface application of lime was essential to reduce the diameter of roots developing in the soil surface. In a trial conducted in sub-tropical soil, Caires *et al.* (2002) also reported an effect of lime, in which wheat root diameter was reduced at a depth of 0·10–0·20 m; however, in this case, the effect was not observed in the uppermost soil layers and, due to the short-term nature of the trial, the authors did not emphasize effects on root characteristics in deeper layers. Under tropical conditions, the current results suggested the opposite effect of liming on root diameter in deeper soil layers, usually below 0·20 m depth. This effect can be related to root longevity, which changes according to soil depth. The more favourable chemical conditions (due to the application of higher lime rates) associated with reduced variation of temperature and soil moisture probably contributed to the longevity of roots growing in deeper soil layers, inducing the formation of root structures with larger diameters (Baddeley & Watson 2005).

Due to the linear effect of applied lime rates on soil chemical parameters, similar adjustments were observed for root dry matter results. The quadratic effect observed for common bean root dry matter, except at 0·20–0·40 m depths, may be explained by the variations in the soil's chemical conditions, which can stimulate changes in common bean root architecture; in addition, interactions between the root length density and root diameter may also contribute to this effect.

The greater root length density and root dry matter caused significant increases in SOM content at 0–0·20 m depth. According to Briedis *et al.* (2012), increases in organic carbon content below a depth of 0·025 m may be attributable to root activity, due to the high potential to produce large quantities of biomass and organic compounds in the soil. In addition, in a medium-textured, dystrophic Red Latosol, Briedis *et al.* (2012) reported increases in total organic carbon stock in the 0–0·20 m layer of up to 15% after surface liming. In the current study, 48 months after the last reapplication, results showed significant changes below a depth of 0·10 m, emphasizing that double-rate lime application (4000 kg/ha) resulted in a slight reduction in SOM content in the sub-soil compared with full-rate lime application (2000 kg/ha). This effect may be the result of an elevated pH, which stimulates microbial activity and the decomposition of organic particulate fractions (Haynes & Swift 1988). However, based on mineral–SOM interactions, significant changes have been related to the soil's physical quality (Jastrow 1996; Six *et al.* 2004; Garcia *et al.* 2013), influencing water flow and affecting the physical displacement of lime particles to sub-soil layers. The long-term benefits of surface liming were essential to increase SOM accumulation in the topsoil layers (0–0·20 m), indicating that in addition to being an important tool for improving soil fertility in areas severely affected by acidity, this strategy may help to make tropical crop systems more sustainable.

The effect of acidity alleviation on P, Ca and Mg availability can be explained by the charge characteristics of Oxisols. In most tropical soils, negative charge densities are defined by the variation in pH, increasing with soil solution alkalinization (Uehara & Gillman 1980). The effects of lime dissolution on increasing pH levels include contributing to the deprotonation of acidic groups (e.g., carboxyl, enol and phenolic OH), increasing negative charges and decreasing positive charges. These reactions increase CEC, inducing lower chemisorption of phosphate (PO_4^{2-}) and higher retention of Ca and Mg. Fageria & Baligar (2008) reported positive effects of liming on reducing P fixation; however, at pH levels >6·5, lower P availability can occur due to the reaction of P with cations, such as Ca, inducing precipitated forms of P. Despite the Ca–P reaction, the quadratic effect observed in the 0·10–0·20 m layers 48 months after the last reapplication was most likely a consequence of the effect of the highest lime rates (2000 and 4000 kg/ha) on higher root density and P uptake rate. No quadratic effect was observed in the uppermost soil layers (0–0·05 m and 0·05–0·10 m depths) because of the high rates of phosphate continuously added to the sowing furrows.

In addition to the CEC effect, levels of exchangeable Ca and Mg increased linearly due to the chemical composition of dolomitic lime (calcium and magnesium carbonates), with the largest amounts of these cations in the soil being provided with maximum rate of application. In addition to the acidity alleviation effect, downward displacement of Ca to deeper layers must be considered essential for improving root growth in the sub-soil (Caires *et al.* 2006).

Although the effect of lime increased CEC, the addition of Ca and Mg by liming influenced K mobility, which was variable according to the amount of applied lime. This reaction can be explained by the competition between cations for exchange sites. In addition, because polyvalent cations exhibit a higher chemical affinity for negative sites, monovalent cations such as K are displaced and leach into sub-soil layers (Phillips *et al*. 1988), which was below 0·60 m depth in this case. The absence of an effect of lime at 0–0·10 m depth 36 months after the last reapplication of lime can be explained by K dynamics in soil, which can change according to rainfall distribution, crop species, phenological development stage and amounts of organic residues on the soil surface, recognized as an important K reserve (Garcia *et al*. 2008). Rosolem *et al*. (2005) reported that shoot residues of pearl millet, a species cultivated between wheat and common bean crops, could accumulate up to 122·2 kg/ha of K, according to the amount of K applied to the soil to support 8 t/ha of shoot dry matter.

The effects of lime rates on increasing soil pH and the negative sites (CEC) associated with Ca^{2+} and Mg^{2+} addition caused by calcium/magnesium carbonate dissociation explain the significant changes observed in soil BS. Notably, there was a strong effect of applied lime rates on variations in BS below a depth of 0·30 m. Although lime is characterized by low mobility, a higher SOM content in the uppermost soil layers (0–0·20 m) can contribute to improving cation mobility, due to reactions with organic-soluble compounds (Franchini *et al*. 2003). In areas with dry-season periods, as in tropical regions, surface liming is an important strategy for improving sub-soil chemical fertility, which is necessary for root growth as well as water and nutrient uptake during periods of drought.

Due to the effect of lime on macronutrient availability in the soil, concentrations of all macronutrients in wheat leaves, except for K, P and S in the first growing season, increased according to lime rates applied. Although applied lime rates increased P levels linearly in the soil, the concentration of P in leaves was not affected by soil amendment application in the first growing season. Compared with the second growing season, better rainfall distribution during the first year, associated with large amounts of phosphate fertilizer applied to the topsoil layer, did not affect P uptake by plants, even under acidic conditions. In contrast, under a prolonged drought period, liming can improve root system architecture, increasing P uptake from sub-surface layers. However, in all treatments, including unlimed plots, P concentration in the flag leaves was considered appropriate (2·1–3·3 g/kg) (Cantarella *et al*. 1997). The effect of liming on improving the N and S concentrations in leaves is most likely a result of microbial and enzyme activities due to pH changes. According to Haynes & Swift (1988), alkalization has significant effects on S and N mineralization and nitrification reactions, which are considered important indicators of S and N availability in the soil. In addition, because the dissolution of lime increased Ca and Mg in all soil profiles, higher concentrations of these nutrients were observed in wheat leaves; however, due to the action of Ca and Mg on the competitive inhibition mechanism, K uptake was reduced, and the concentration of this monovalent ion in leaf tissue was lower.

Based on a short-term trial conducted in a dystrophic clay Rhodic Hapludox under sub-tropical conditions, Caires *et al*. (2002) reported that a single full-rate application of lime (estimated through the BS method) on the soil surface was insufficient to increase macronutrient concentrations in wheat leaves; however, a higher Mg concentration in flag leaves was only observed when lime was incorporated into the soil.

Although the current results suggested significant long-term effects of lime rate on wheat nutrition, the concentrations of N, Ca, Mg, K and S were above or within the adequate range in all treatments (Cantarella *et al*. 1997). The adequate concentration of most nutrients in wheat leaves under soil conditions with the highest acidity may result in decreased plant growth, thus reducing the nutrient requirements of the plants compared with lime-amended plots.

The wheat shoot dry matter data showed positive effects of surface liming on reducing the effect of unfavourable climatic conditions. In the second growing season (2014/15), the lower and irregular rainfall registered during the vegetative stage (155 mm), which is associated with higher soil acidity conditions, severely affected wheat shoot dry matter production. However, the growing season showed no effect when full and double rates of dolomitic lime were applied, which may be related to the superior chemical conditions of deeper soil layers (below 0·30 m depth), which is essential for root growth and water absorption, reducing water stress during long drought periods. Regarding the environmental effect, this factor can also explain the higher concentrations of N, K, Ca and Mg observed in wheat flag leaves in the second growing season (2014/15), as the lower above-ground shoot growth most likely resulted in a higher concentration of these nutrients in leaf tissue.

For common bean, regression models adjusted for the concentrations of N, K, Ca and Mg in the first growing season were similar to those for wheat. In the first year, it is important to emphasize that in all treatments, including the control (without lime application), N, P, Ca and Mg concentrations in common bean leaves were within or above the range considered appropriate (Ambrosano *et al.* 1997). Despite lower rainfall conditions in the first growing season (95 mm) compared with the second year (402 mm) during the vegetative stage, lower concentrations of N, P, Ca and Mg in common bean leaves observed in the second growing season may be related to the occurrence and severity of *Sclerotium rolfsii* Sacc., negatively affecting macronutrient uptake, shoot dry matter production and plant survival. This pathogen causes economic damage in several agricultural species, mainly in tropical regions due to the high temperatures (30–35 °C) and high soil moisture in these areas, which provide favourable conditions for parasite growth (Abeygunawardena & Wood 1957). Despite the observed parasitism, the higher S concentration observed in common bean leaves in the second growing season may be related to the effects of soil moisture on sulphur mineralization, inducing higher levels of S in the soil (Ghani *et al.* 1991). Although common bean is considered a species with a high demand for S (Soratto *et al.* 2013), the concentration of S was not altered because of the influence of several factors, including: (i) the high supply of S via mineral fertilization (11·3 kg/ha per cycle), (ii) S mineralization and (iii) the nutrient requirements of different plant populations.

Considering that there was no application of any Ca source in the control treatment for 12 years and that there is a higher demand for Ca compared with Mg (Soratto *et al.* 2013), Ca concentration in leaves was below or reached the minimum level within the adequate range. In the other treatments, the Ca ranges were considered appropriate (Ambrosano *et al.* 1997). As observed for wheat, increases in Ca and Mg uptake in common bean leaves, but a reduction in the K concentration according to the amounts of lime applied were only observed in the first growing season. Different effects of applied lime rates on K concentration may be attributed to changes in the Ca/K ratio in the soil and edapho-climatic factors during vegetative stages. With the exception of the control treatment in the first growing season, all other treatments showed K levels below the adequate range (20–24 g/kg) (Ambrosano *et al.* 1997). Similar results were obtained by Soratto & Crusciol (2008).

Considering the effects on improving soil chemical fertility and plant nutrition, surface liming estimated via the BS method increased the grain yields of wheat and common bean. As observed for wheat shoot dry matter, the alleviation of soil acidity in deeper soil layers was fundamental to reducing the negative effects of unfavourable environmental conditions and improving production stability in this tropical region. In general, higher acidity conditions inhibiting root growth cause plants to be more susceptible to water stress during dry periods, reducing wheat grain yield. In a trial conducted in a sub-tropical wheat production area, Caires *et al.* (2008) found that plant response to the liming reaction was intensified during the occurrence of low soil moisture, due to changes in ion concentrations in the soil solution, primarily increasing the levels of ions considered toxic for plant growth, such as exchangeable Al.

The quadratic adjustment for the volumetric weight in the second growing season can be explained by the compensatory mechanisms of the yield components. The linear increase observed for the number of spikelets per ear most likely influenced the number of grains produced per plant, increasing photoassimilate competition among these structures and negatively influencing grain volume. According to the regression equation, the highest volumetric weights were obtained with the application of lime at levels above the recommended rate calculated via the BS method. With the exception of grain quality, the best results for grain yield, were observed in the first growing season due to the better rainfall distribution during the wheat growth cycle.

As observed for wheat, improvements in soil chemical attributes and root growth were critical for the development of yield production in common bean. Under sub-tropical conditions, Caires *et al.* (2008) found that soil acidity conditions are not a soybean growth-limiting factor in areas without water restrictions; however, the long-term results suggested that even under an adequate water supply (772 mm in the second growing cycle), the applied lime rates were beneficial for tropical soil fertility, favouring the nutrition and yield of common bean. One year after surface liming, Soratto & Crusciol (2008) reported a maximum common bean yield with the application of lime below the amounts recommended by the BS method; however, long-term results showed positive influences of higher rates. Even under a high incidence and severity of *S. rolfsii* Sacc., the application of lime rates linearly increased plant population, plant survival and the number of pods/plant and seeds/pod, thus increasing the seed yield.

Despite the lower plant survival in the second growing season due to the occurrence of disease, the plasticity and adaptation of this common bean cultivar associated with higher water availability during the growing cycle favoured a greater reproductive development, i.e. pods and seeds. Because the number of pods/plant is one of the major production components (Soratto & Crusciol 2008), the common bean yield was also greater. Considering the higher seed production/plant, photoassimilate partitioning between pods increased, affecting the seed protein content. In addition, this event can explain the linear effect of lime rate on reducing the screening levels in the first growing season.

It is noteworthy that the long-term results confirmed the feasibility of surface liming for improving soil chemical attributes and crop production in an Oxisol in a tropical region with dry winter and frequent dry spells during the wet season. The application of higher lime rates than those estimated via the BS method (70%) effectively prolonged the benefits of acidity management over time. In addition, the higher residual effect can allow the application frequency of soil acidity amendments in the soil to be reduced, increasing crop production in a tropical Oxisol managed under no-tillage systems. Four years after the last reapplication of lime, the highest rate applied resulted in a greater yield of the annual crops. Due to effect on yield, lime can compromise crop quality; however, the effects were variable according to crop species.

The authors would like to thank the São Paulo Research Foundation (FAPESP, Proc. 2013/18462-0 and 2014/16712-2) for providing financial support and the National Council for Scientific and Technological Development (CNPq) for granting an award for excellence in research to the second author.

SUPPLEMENTARY MATERIAL

The supplementary material for this article can be found at https://doi.org/10.1017/S0021859617000235

REFERENCES

Abeygunawardena, D. V. W. & Wood, R. K. S. (1957). Factors affecting the germination of sclerotia and mycelial growth of *Sclerotium rolfsii* Sacc. *Transactions of the British Mycological Society* **40**, 221–231.

Ambrosano, E. J., Tanaka, R. T., Mascarenhas, H. A. A., Van Raij, B. V., Quaggio, J. A. & Cantarella, H. (1997). Legumes and oilseeds. In *Recommendations for Fertilization and Liming in the State of São Paulo* (Eds B. Van Raij, H. Cantarella, J. A. Quaggio & A. M. C. Furlani), pp. 189–203. Campinas: Instituto Agronômico.

Baddeley, J. A. & Watson, C. A. (2005). Influences of root diameter, tree age, soil depth and season on fine root survivorship in *Prunus avium*. *Plant and Soil* **276**, 15–22.

Bian, M., Zhou, M., Sun, D. & Li, C. (2013). Molecular approaches unravel the mechanism of acid soil tolerance in plants. *Crop Journal* **1**, 91–104.

Briedis, C., de Moraes Sá, J. C., Caires, E. F., Navarro, J. D. F., Inagaki, T. M., Boer, A., Neto, C. Q., de Oliveira Ferreira, A., Canalli, L. B. & dos Santos, J. B. (2012). Soil organic matter pools and carbon-protection mechanisms in aggregate classes influenced by surface liming in a no-till system. *Geoderma* **170**, 80–88.

Bronick, C. J. & Lal, R. (2005). Soil structure and management: a review. *Geoderma* **124**, 3–22.

Caires, E. F., Alleoni, L. R. F., Cambri, M. A. & Barth, G. (2005). Surface application of lime for crop grain production under a no-till system. *Agronomy Journal* **97**, 791–798.

Caires, E. F., Churka, S., Garbuio, F. J., Ferrari, R. A. & Morgano, M. A. (2006). Soybean yield and quality as a function of lime and gypsum applications. *Scientia Agricola* **63**, 370–379.

Caires, E. F., Feldhaus, I. C., Barth, G. & Garbuio, F. J. (2002). Lime and gypsum application on the wheat crop. *Scientia Agricola* (*Piracicaba, Brazil*) **59**, 357–364.

Caires, E. F., Pereira Filho, P. R. S., Zardo Filho, R. & Feldhaus, I. C. (2008). Soil acidity and aluminium toxicity as affected by surface liming and cover oat residues under a no-till system. *Soil Use and Management* **24**, 302–309.

Cantarella, H., Van Raij, B. & Camargo, C. E. O. (1997). Cereals. In *Recommendations for Fertilization and Liming in the State of São Paulo* (Eds B. Van Raij, H. Cantarella, J. A. Quaggio & A. M. C. Furlani), pp. 189–203. Campinas: Instituto Agronômico.

Cantarella, H., Van Raij, B. & Quaggio, J. A. (1998). Soil and plant analyses for lime and fertilizer recommendations in Brazil. *Communications in Soil Science and Plant Analysis* **29**, 1691–1706.

Castro, G. S. A. & Crusciol, C. A. C. (2013). Effects of superficial liming and silicate application on soil fertility and crop yield under rotation. *Geoderma* **195–196**, 234–242.

Cavalieri, K. M. V., da Silva, A. P., Tormena, C. A., Leão, T. P., Dexter, A. R. & Häkansson, I. (2009). Long-term effects of no-tillage on dynamic soil physical properties in a Rhodic Ferralsol in Paraná, Brazil. *Soil and Tillage Research* **103**, 158–164.

de Oliveira, E. L. & Pavan, M. A. (1996). Control of soil acidity in no-tillage system for soybean production. *Soil and Tillage Research* **38**, 47–57.

Fabrizzi, K. P., García, F. O., Costa, J. L. & Picone, L. I. (2005). Soil water dynamics, physical properties and corn and wheat responses to minimum and no-tillage systems in the southern Pampas of Argentina. *Soil and Tillage Research* **81**, 57–69.

Fageria, N. K. & Baligar, V. C. (2008). Ameliorating soil acidity of tropical oxisols by liming for sustainable crop production. *Advances in Agronomy* **99**, 345–399.

Fageria, N. K. & Moreira, A. (2011). The role of mineral nutrition on root growth of crop plants. *Advances in Agronomy* **110**, 251–331.

Fernández, F., Gepts, P. & López, M. (1985). Etapas de desarollo en la planta de frijol. In *Frijol: Investigación y Producción* (Eds M. López, F. Fernández & A. van Choonhoven), pp. 61–78. Cali: CIAT.

Franchini, J. C., Hoffmann-Campo, C. B., Torres, E., Miyazawa, M. & Pavan, M. A. (2003). Organic composition of green manure during growth and its effect on cation mobilization in an acid Oxisol. *Communications in Soil Science and Plant Analysis* **34**, 2045–2058.

Garcia, R. A., Crusciol, C. A. C., Calonego, J. C. & Rosolem, C. A. (2008). Potassium cycling in a corn-brachiaria cropping system. *European Journal of Agronomy* **28**, 579–585.

Garcia, R. A., Li, Y. & Rosolem, C. A. (2013). Soil organic matter and physical attributes affected by crop rotation under no-till. *Soil Science Society of America Journal* **77**, 1724–1731.

Ghani, A., McLaren, R. G. & Swift, R. S. (1991). Sulphur mineralisation in some New Zealand soils. *Biology and Fertility of Soils* **11**, 68–74.

Godsey, C. B., Pierzynski, G. M., Mengel, D. B. & Lamond, R. E. (2007). Management of soil acidity in no-till production systems through surface application of lime. *Agronomy Journal* **99**, 764–772.

Gregory, P. J. (2006). Development and growth of root systems. In *Plant Roots: Growth, Activity and Interaction with Soils* (Ed. P. J. Gregory), pp. 45–79. Oxford: Blackwell.

Haynes, R. J. & Mokolobate, M. S. (2001). Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the mechanisms involved. *Nutrient Cycling in Agroecosystems* **59**, 47–63.

Haynes, R. J. & Swift, R. S. (1988). Effects of lime and phosphate additions on changes in enzyme activities, microbial biomass and levels of extractable nitrogen, sulphur and phosphorus in an acid soil. *Biology and Fertility of Soils* **6**, 153–158.

Heanes, D. L. (1984). Determination of total organic-C in soils by an improved chromic acid digestion and spectrophotometric procedure. *Communications in Soil Science and Plant Analysis* **15**, 1191–1213.

Jastrow, J. D. (1996). Soil aggregate formation and the accrual of particulate and mineral-associated organic matter. *Soil Biology and Biochemistry* **28**, 665–676.

Malavolta, E., Vitti, G. C. & Oliveira, S. A. (1997). *Evaluation of Nutritional Status of Plants: Principles and Applications (in Portuguese)*. Piracicaba, Brazil: Potafós.

McCallum, M. H., Kirkegaard, J. A., Green, T. W., Cresswell, H. P., Davies, S. L., Angus, J. F. & Peoples, M. B. (2004). Improved sub-soil macroporosity following perennial pastures. *Australian Journal of Experimental Agriculture* **44**, 299–307.

Murphy, J. & Riley, J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta* **27**, 31–36.

Oussible, M., Crookston, R. K. & Larson, W. E. (1992). Subsurface compaction reduces the root and shoot growth and grain yield of wheat. *Agronomy Journal* **84**, 34–38.

Pan, J. W., Zhu, M. Y. & Chen, H. (2001). Aluminum-induced cell death in root-tip cells of barley. *Environmental and Experimental Botany* **46**, 71–79.

Parker, D. R., Zelazny, L. W. & Kinraide, T. B. (1988). Aluminum speciation and phytotoxicity in dilute hydroxy-aluminum solutions. *Soil Science Society of America Journal* **52**, 438–444.

Phillips, I. R., Black, A. S. & Cameron, K. C. (1988). Effect of cation exchange on the distribution and movement of cations in soils with variable charge. II. Effect of lime or phosphate on potassium and magnesium leaching. *Fertilizer Research* **17**, 31–46.

Rosolem, C. A., Calonego, J. C. & Foloni, J. S. S. (2005). Potassium leaching from millet straw as affected by rainfall and potassium rates. *Communications in Soil Science and Plant Analysis* **36**, 1063–1074.

Shuman, L. M. (1986). Effect of liming on the distribution of manganese, copper, iron, and zinc among soil fractions. *Soil Science Society of America Journal* **50**, 1236–1240.

Six, J., Bossuyt, H., Degryze, S. & Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research* **79**, 7–31.

Soil Survey Staff (1999). *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*, 2nd edn. U.S. Department of Agriculture Handbook 436. Washington, D.C.: Natural Resources Conservation Service.

Soratto, R. P. & Crusciol, C. A. C. (2008). Dolomite and phosphogypsum surface application effects on annual crops nutrition and yield. *Agronomy Journal* **100**, 261–270.

Soratto, R. P., Fernandes, A. M., dos Santos, L. A. & Job, A. L. G. (2013). Nutrient extraction and exportation by common bean cultivars under different fertilization levels: I – macronutrients. *Revista Brasileira de Ciencia do Solo* **37**, 1027–1042.

Sumner, M. E. & Noble, A. D. (2003). Soil acidification: the world story. In *Handbook of Soil Acidity* (Ed. Z. Rengel), pp. 1–28. New York: Marcel Dekker Inc.

Tiritan, C. S., Büll, L. T., Crusciol, C. A. C., Carmeis Filho, A. C. A., Fernandes, D. M. & Nascente, A. S. (2016). Tillage system and lime application in a tropical region: soil chemical fertility and corn yield in succession to degraded pastures. *Soil and Tillage Research* **155**, 437–447.

Uehara, G. & Gillman, G. P. (1980). Charge characteristics of soils with variable and permanent charge minerals: I. Theory. *Soil Science Society of America Journal* **44**, 250–252.

Van Raij, B., Andrade, J. C., Cantarella, H. & Quaggio, J. A. (2001). *Chemical Analysis for Fertility Evaluation of Tropical Soils (in Portuguese)*. Campinas, Brazil: Instituto Agronômico.

Van Raij, B., Quaggio, J. A. & da Silva, N. M. (1986). Extraction of phosphorus, potassium, calcium, and magnesium from soils by an ion-exchange resin procedure. *Communications in Soil Science and Plant Analysis* **17**, 547–566.