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Long-term effects of lime and phosphogypsum application on tropical no-till soybean–oat–sorghum rotation and soil chemical properties

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ABSTRACT

Root growth, nutrition and crop yield can be affected by soil chemical modifications caused by superficial limestone and phosphogypsum application in a no-till system. Using this approach, this study was conducted in southeastern Brazil, continuing an experiment that has been on-going since 2002 with the objective of evaluating the residual effects of the surface application of lime and phosphogypsum on the soil chemical characteristics and the root growth, nutrition and yield of soybean, black oat and sorghum in a dry winter region cultivated in 2008/2009 and 2009/2010. The experimental design was a randomized block with 4 replications. The treatments were applied in November 2004 and were as follows: original conditions, limestone application (2000 kg ha^{-1}), phosphogypsum application (2100 kg ha^{-1}), and limestone (2000 kg ha^{-1}) + phosphogypsum (2100 kg ha^{-1}) application. Superficial liming with or without phosphogypsum reduced the surface and subsurface soil acidity 5 years after application in the no-till system. The movement of Ca^{2+} and Mg^{2+} from the surface layer into the subsoil over time was evident. The phosphogypsum application associated with liming increased the Ca^{2+} levels throughout the soil profile. Liming maintained high levels of Mg^{2+} throughout the soil profile with or without phosphogypsum application. The organic matter content increased with liming with or without phosphogypsum, indicating that in the long term, these practices can increase the C accumulation. Phosphogypsum application had a residual effect on the SO_4-S levels, and high sulphate concentrations were observed in the subsoil after 5 years. Superficial liming improved crop nutrition and, when associated with phosphogypsum, increased Ca absorption by soybean and sorghum, as reflected in the increased yields of these crops.

1. Introduction

Soil acidity is one of the factors limiting crop production, especially in tropical areas such as Brazil. The total area that is affected by acidity is estimated to be 4 billion ha, representing ~30% of the cropland worldwide (Sumner and Noble, 2003). The affected areas are mostly within countries located in the tropics; they comprise primarily Oxisols and Ultisols in South America and Oxisols in Africa (Narro et al., 2001). In Brazil, the "cerrado" (tropical savannah) is the main grain-producing region and occupies approximately 205 million ha, which is approximately 23% of the country. The soils in this region are predominantly Oxisols (46%), Ultisols (15%) and Entisols (15%), with low fertility, high aluminium saturation, and high P-fixation capacity (Fageria and Stone, 1999). Low fertility is characteristic of acidic soil; therefore, the correction of these soils is very important for the proper growth of crops (Soratto and Crusciol, 2008a,b; Soratto et al., 2010).

Liming is the most commonly used practice to neutralize soil acidity and restore production capacity, increase nutrient availability, and reduce levels of toxic elements (Caires et al., 2001; Pavan and Oliveira, 2000). In conventional tillage systems, lime is incorporated into the soil by ploughing and disking. This practice breaks up the soil aggregates, exposes the soil and increases susceptibility to erosion (Bronick and Lal, 2005). Additionally, aggregate disruption promotes the mineralization of previously protected organic matter (Caires et al., 2006a; Westerhof et al., 1999). Therefore, the interest in surface liming to control soil acidity since the implementation of no-till systems is mainly based on preserving the physical properties of the soil (Caires et al., 2011) and maintaining agricultural sustainability in tropical and subtropical regions (Caires et al., 2005).

However, in the short term, the effects of superficial liming are restricted to the soil surface (Pavan and Oliveira, 2000) because without incorporation, there is less contact between the particles

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of lime and soil colloids (Caires et al., 2005). The neutralization of the soil acidity in the subsurface with limestone is generally slow, particularly in variably charged soils (Ernani et al., 2004), because the movement of limestone to greater depths varies according to the time, dose, form, and frequency of application; soil type; climate; acid fertilizer management and crop system (Blevins et al., 1978; Caires et al., 2008b,c, 2005; de Oliveira and Pavan, 1996).

Phosphogypsum is more soluble than limestone and is composed mostly of calcium sulphate ($CaSO_4{\cdot}H_2O$); however, its addition does not change the soil pH. The phosphogypsum that is applied to the soil surface moves along the profile under the influence of percolating water (Caires et al., 1999). As a result, there is an increase in the supply of calcium and a reduction in the aluminium toxicity in the subsoil (Caires et al., 2003, 1999). Phosphogypsum is therefore an alternative for improving the root environment in the subsoil and can be used in acidic soils as a supplement for liming (Caires et al., 2003).

In the subtropical region of Brazil, where the rainfall is well distributed throughout the year, there are several reports of a lack of response of crops to the application of soil acidity correctives in no-till systems (Caires et al., 2011, 2008b,c, 2006b; Moreira et al., 2001). These findings have been attributed to the greater accumulation of organic matter and nutrients in the surface that reduce the activity of Al and consequently its toxicity by forming Al–organic complexes and to the increased ionic strength of the soil solution (Nolla and Anghinoni, 2006; Vieira et al., 2009).

It is possible the vast majority of the cerrado biome can experience increases in grain yield and fibre production with lime and phosphogypsum application in no-till systems, even on the surface, unlike what has been observed elsewhere in the subtropical region. This possibility exists because in these regions, the vast majority of cultivated areas have a low organic matter content and a low amount of straw on the surface, leading to low water storage and high evaporation of the soil water, respectively.

Thus, the probable soil acidity correction, aluminium reduction levels and base saturation elevation, especially that of calcium, in the soil profile in a short time will enable greater root depth due to the mechanisms that promote the movement of compounds produced by the dissociation of limestone and phosphogypsum. This condition will increase the water stress tolerance of plants when dry spells induce water stress, especially during off-season cultivation.

The soil acidity correction dynamics in the soil surface in no-till systems and the benefits of the joint application of limestone and phosphogypsum in long-term experiments remain poorly investigated, especially in cerrado conditions in tropical regions. However, this knowledge is important for adjusting the limestone and phosphogypsum recommendations for annual crops in no-till systems.

This study evaluated the changes in soil chemical attributes and the root growth, nutrition and productivity of soybean, black oat and sorghum resulting from limestone and phosphogypsum surface application in an established no-till system in a tropical region.

2. Materials and methods

2.1. Site description

This experiment was conducted in Botucatu, State of São Paulo, southeastern Brazil, (48°23′W, 22°51′S and 765 masl) during the 2008/2009 and 2009/2010 growing seasons. Soil at this location is classified as Rhodic Ferralsol (FAO, 2006) [kaolinitic, thermic Typic Haplorthox (Soil Survey Staff, 2014), with sandy loam texture] and had been managed since 2002 in a no-till system as follows: growing season 2002/2003, rice in the summer and black oat in the fall; growing season 2003/2004, bean in the summer and black oat in the fall; growing seasons 2004/2005 and 2005/2006, peanut in the summer and oat in the fall; and growing seasons 2006/2007 and 2007/2008, intercropped corn with *Urochloa ruziziensis*.

The climate according to Köeppen's classification is Cwa (tropical, with a dry winter and hot, rainy summer). Monthly mean values of rainfall and temperature during the experiment are shown in Fig. 1.

At the beginning of the experiment (October 2002) and before lime and phosphogypsum reapplication (August 2004), the chemical attributes of the topsoil (0–0.20 m) were determined (Table 1). In August 2004, soil samples were collected (0–0.20 m) for soil particle size distribution determination with the following results: sand, silt, and clay contents of 540, 110, and 350 g kg^{-1}, respectively. In the subsoil (0.20–0.40 m), the clay content was 360 g kg^{-1}. The bulk density at depth 0–0.20 m was 1.128 Mg m^{-3}.

2.2. Experimental design and treatments

The experimental design was a randomized complete block with 4 replications. The experimental units were 5.4 × 9 m. The treatments were as follows: original condition, lime application (Eq. (1), to increase the base saturation to 70%), phosphogypsum application (Eq. (4)), and combined lime (Eq. (1), to increase the base saturation to 70%) plus phosphogypsum (Eq. (4)) application.

At the beginning of the experiment (October 15, 2002), limestone was applied superficially at a rate of 2700 kg ha^{-1}. Phosphogypsum was applied one day after liming at a rate of 2100 kg ha^{-1}. The reapplication was based on a soil analysis that was carried out in August 2004, where the base saturation in the treatment in which the limestone was applied reached 50%, the pre-established critical level for the reapplication. Thus, on November 19, 2004, the application of limestone and phosphogypsum was performed at rates of 2000 kg ha^{-1} and 2100 kg ha^{-1}, respectively.

2.3. Dolomitic limestone and phosphogypsum characteristics

The dolomitic limestone composition was 23.3% CaO, 17.5% MgO, and 71% effective calcium carbonate equivalence (ECCE). In a physical analysis of the dolomitic limestone, 68.8, 92.4, and 99.7% of the particles passed through 50-, 20-, and 10-mesh sieves, respectively. The composition of phosphogypsum ($CaSO_4{\cdot}2H_2O$), a by-product obtained from the Brazilian phosphoric acid industry, was 20% Ca, 16% S, and a small residue of 0.1% P and F. In a physical analysis of the phosphogypsum, 60 and 90% of the particles were retained in 50- and 20-mesh sieves, respectively.

The dolomitic limestone rate (LR) was calculated to increase the base saturation in topsoil (0–20 cm) to 70% according to Eq. (1):

$$LR(\text{kg ha}^{-1}) = \frac{(BS_2 - BS_1)(CEC/BD)}{ECCE/100} \tag{1}$$

where BS_2 is the estimated base saturation (70%) and BS_1 is the base saturation as measured in the soil analysis as in Eq. (2):

$$BS_1(\%) = \frac{(Ca_{ex} + Mg_{ex} + K_{ex})100}{CEC} \tag{2}$$

where Ca_{ex}, Mg_{ex}, and K_{ex} are basic exchangeable cations, BD is bulk density at 0–0.20 m depth, and CEC is the total cation exchange capacity, as calculated by Eq. (3):

$$CEC(\text{cmol}_c\ \text{kg}^{-1}) = Ca_{ex} + Mg_{ex} + K_{ex} + \text{totalacidityatpH7.0}(H + Al) \tag{3}$$

The phosphogypsum rate (GR) was calculated using Eq. (4):

$$GR(\text{kg ha}^{-1}) = 6CL(\text{vanRaijet al., 1997}) \tag{4}$$

where CL is the clay content (g kg^{-1}) in the soil layer from 20 to 40 cm.