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Lime and gypsum application increases biological activity, carbon pools, and agronomic productivity in highly weathered soil

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ABSTRACT

The application of lime and gypsum has been recognized as an important strategy for correcting soil acidity and for improving soil fertility, soil aggregation, and agronomic productivity in highly weathered soils. We hypothesized that the combined application of lime and gypsum would create favorable conditions for biological activity and result in increased SOC storage and agronomic productivity. Thus, the aim of this study was to evaluate the long-term (*i.e.*, 15 years) impact of lime and gypsum application on the biological activity, SOC stocks, and agronomic productivity of plots under no-till soil management. The experiment was established in 1998 at a site with clayey Oxisol in southern Brazil, and was designed with a split-plot arrangement, completely randomized blocks, and three replicates. The main plot was subject to three lime treatments: (i) control (no lime); (ii) incorporated lime (IL):incorporation of 4.5 Mg lime ha^{-1} to a depth of 0–20 cm by; and (iii) surface lime (SL): surface application of 4.5 Mg lime ha^{-1}, which was equally divided among three annual applications during the first three years of the experiment. The subplots were comprised by surface applications of gypsum at 0, 3, 6, or 9 Mg ha^{-1}. Soil samples were collected in 1998, before of the experiment, and in October 2013, in order to evaluate soil enzyme activities, SOC pool stocks, crop productivity, C-biomass input, and soil fertility attributes. Both forms of lime application significant improved the stocks of several SOC pools, crop productivity, biomass-C input rates, soil fertility attributes, and enzyme activity. The SOC stocks were positively correlated with Ca^{2+} content and biomass-C input, demonstrating the potential of calcium to improve C accumulation. Enzyme activities were significantly affected by both soil fertility and SOC pools, with increases in hot water extractable organic C yielding the greatest increases in enzyme activity. In addition, we also found that gypsum application significantly increased the stocks of labile SOC pools and arylsulfatase activity. However, effects of gypsum application were less apparent than those of lime application and the combination of surface lime (4.5 Mg ha^{-1}) and gypsum (9 Mg ha^{-1}) application yielded the greatest long-term increase in the stock of total organic C stock. Thus, the results of the present study suggest that lime and gypsum application, along with no-till management and biomass-C input, constitutes an efficient strategy for improving the biological activity, C stocks, and productivity of agricultural soils.

1. Introduction

The improvement of soil aggregation is one of the main strategies for increasing C sequestration in highly weathered soils, and in the soils of tropical and subtropical native forests, C stocks are mainly governed by clay content and the presence of iron and aluminum oxides, which are considered major soil aggregating agents (Tisdall and Oades, 1982). However, when native vegetation is converted to agricultural systems, changes occur in the soil

Abbreviations: BS, base saturation; HWEOC, hot water extractable organic carbon; IL, incorporated lime; MAOC, mineral associated organic carbon; POC, particulate organic carbon; POXC, permanganate oxidizable organic carbon; SL, surface lime; SOC, soil organic carbon; TOC, total organic carbon.

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organic carbon (SOC) dynamics, since tillage causes aggregate disruption and exposes organic compounds to microbial degradation, both which result in reduced stocks of SOC *via* mineralization (Sá et al., 2014; Tivet et al., 2013b).

Calcium ions also play an important role as soil aggregation agents, owing to the formation of cation bridges between clay and soil organic matter particles (Tisdall and Oades, 1982), and lime and gypsum are the two main sources of Ca^{+2} and Mg^{+2} ions used to meet the nutritional demands of crop plants in tropical agricultural systems (Pavan et al., 1984). In addition, the application of lime and gypsum is also widely accepted as an effective strategy for reducing soil acidity and for improving soil fertility, root penetration, and crop productivity (Caires et al., 2005; Caires et al., 2006a; Caires et al., 2011). Thus, the benefits of lime and gypsum on soil fertility are well documented; however, an understanding of their influence on SOC pools is lacking. For example, Paradelo et al. (2015) recently reviewed the net effect of lime application on SOC in different land use scenarios and postulated that lime application could either increase or decrease SOC contents, based on three main pathways: (1) increased SOC, in response to improved soil structure; (2) increased SOC, in response to higher biomass-C input *via* enhanced crop yields from improve soil fertility; or (3) decreased SOC, owing to elevated mineralization rates when the biomass-C input is lower than the C oxidized by microbes.

In agricultural fields, lime is either applied by incorporation, in which the lime is mixed into the soil *via* tillage, or by surface application, and many studies have demonstrated that, since surface application does not involve soil disturbance, it is the most appropriate method of lime application under no-till management (Caires et al., 2005; Caires et al., 2006a; Caires et al., 2006b; Yagi et al., 2014). For example, Yagi et al. (2014) reported a 20% reduction in macroaggregate C stocks between 12 and 20 months after lime incorporation in a consolidated no-till field, whereas no reduction was observed in response to surface application. Similarly, Caires et al. (2006a) also observed reductions in soil organic matter (SOM) at 35 months after lime incorporation, but not after surface application. In fact, the deleterious effects of lime on SOC stocks are typically associated with soil incorporation and are typically reported in the first months after application, whereas studies of long-term conservation practices (Tivet et al., 2013b), such as no-till management, have demonstrated that lime amendment might actually increase SOC contents and stocks (Briedis et al., 2012a,b,c).

We hypothesized that lime and gypsum application would directly increase SOC stocks by increasing Ca^{2+} ions, which function as soil aggregation agents, and would indirectly affect SOC by improving biomass-C input rates *via* improved soil fertility. Therefore, to elucidate the impacts of lime and gypsum application on SOC stocks, we examined the long-term effects of incorporated and surface-applied lime and gypsum application on biological activity, SOC stocks, and agronomic productivity in a no-till system with highly weathered soil.

2. Materials and methods

2.1. Experimental site and soil

The lime and gypsum experiment was established in 1998 at a site in located at city of Ponta Grossa, Paraná, in southern Brazil (25°10′S, 50°05′W; Fig. 1), that was previously used as pastureland and had no history of soil acidity correction. According to the Köppen–Geiger System (Peel et al., 2007), the climate is categorized as Cfb type (mesothermal, humid, subtropical), with a mild summer and frequent frosts during the winter. In addition, the annual precipitation is ~1550 mm, the average maximum and

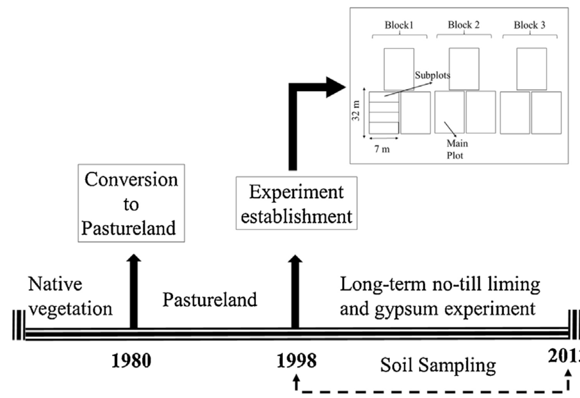

Fig. 1. Chronology of the experimental site from 1980 to 2013.

minimum temperatures are 22 and 13 °C, respectively, and the average altitude is 970 m above sea level. Furthermore, the soil is classified as a clay red Latosol (Brazilian classification; Embrapa, 2013), which is equivalent to a clayey, kaolinitic, thermic Oxisol (Rhodic Hapludox; USDA, Soil Taxonomy classification, 2010) with 610 g kg^{-1} of clay. In addition, the soil samples (0–20 cm topsoil) collected before the start of the experiment indicated that soil had the following soil fertility: pH 4.6 ($CaCl_2$); 77.6 $mmol_c\ dm^{-3}$ H + Al; 3.0 $mmol_c\ dm^{-3}$ Al^{3+}, 25 $mmol_c\ dm^{-3}$ Ca^{2+}, 20 $mmol_c\ dm^{-3}$ Mg^{2+}, 3.6 $mmol_c\ dm^{-3}$ K^+, and 0.3 mg dm^{-3} P.

2.2. Experimental design

The experiment followed a completely randomized block design in a split plot arrangement, with three replicates for each treatment. The plot size was 224 m^2 (32 × 7 m) and the subplot size was 56 m^2 (8 × 7 m). The main plot factor was lime application treatment: 1) control, *i.e.*, no lime application; 2) incorporated lime (IL), *i.e.*, 4.5 Mg lime ha^{-1}, in a single application at the beginning of the experiment; or 3) surface lime (SL), *i.e.*, 4.5 Mg lime ha^{-1}, applied as three annual applications of 1.5 Mg lime ha^{-1} $year^{-1}$ for the first three years of the experiment. The lime used in the experiment contained 224 g Ca kg^{-1}, 140 g Mg kg^{-1}, and 89% effective calcium carbonate equivalent, and its rate was calculated to raise the base saturation (BS) of the topsoil (0–20 cm) to 70%. In the subplots, four rates of gypsum were surface-applied: 0, 3, 6, or 9 Mg ha^{-1}. The gypsum, a by-product of a Brazilian phosphate fertilizer industry, contained 235 g Ca kg^{-1}, 153 g S kg^{-1}, 3 g P kg^{-1}, and 156 g H_2O kg^{-1}. Plowing and harrowing were only conducted at the beginning of the experiment and only in the IL plots. During the experimental period (1998–2013), the area was managed as a no-till system (Fig. 1) and was cultivated with either maize (three times in: 2002, 2005, and 2008) or soybean (12 times in: 1999, 2000, 2001, 2003, 2004, 2006, 2007, and between 2009 and 2013), during the summer, and with barley (1999), wheat (2001), or fallow (other years), during the winter. Fertilizers used for crops were as follow: i) maize: applied 185 kg ha^{-1} N (*i.e.*, 35 kg N ha^{-1} ha at sowing in band application and 150 kg ha^{-1} in broadcast application at the fourth leaf emergence) plus 53 kg ha^{-1} P, and 72 kg ha^{-1} K in band application; ii) soybean: applied 4.5, 20 and 37 kg ha^{-1} of NPK at sowing in band application; iii) barley: applied 28 and 92 kg ha^{-1} of N and P_2O_5 using di-ammonium phosphate (DAP) in band application. Also was applied 45 kg ha^{-1} of N as urea in broadcast application; iv) wheat: were applied 130 kg ha^{-1} N (30 kg ha^{-1} at sowing, and 100 kg ha^{-1} as urea applied on broadcast application), 29 kg ha^{-1} P, and 55 kg ha^{-1} K.