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Soil fertility, plant nutrition, and grain yield of upland rice affected by surface application of lime, silicate, and phosphogypsum in a tropical no-till system

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ABSTRACT

The development of technologies that provide rapid acidity amelioration of the soil profile through the surface application of amendments and phosphogypsum, such as no-till (NT) systems, is extremely important to provide adequate chemical conditions in tropical soils with low natural fertility, which limits the grain yield of upland rice (*Oryza sativa* L.). Thus, this study aimed to evaluate the effects of surface applications of lime, silicate, and phosphogypsum, applied individually or in mixtures, on the chemical properties of the soil profile in an NT system and to determine their effects on the nutrition, yield components, and grain yield of upland rice. The experiment was designed as a completely randomized block with eight treatments replicated four times. The combination of phosphogypsum with lime and/or silicate improved the surface and subsurface soil chemical properties 12 months following application. The mixtures increased the concentrations of K, Ca, Mg, N–NO_3^-, and S–SO_4^{2-} in the subsurface layers. The sulphur concentration in the flag leaves of upland rice was higher with phosphogypsum application. The number of panicles per m^2 and grain yield of upland rice were positively influenced by the surface application of soil acidity amendments and phosphogypsum mixtures.

1. Introduction

Rice (*Oryza sativa* L.) is an important component of the diets of approximately half of the world's population (Kumar and Ladha, 2011). This cereal is cultivated primarily in Asia under controlled flood irrigation (Farooq et al., 2009; Prasad, 2011); however, a reduction in hydric resource availability for crop irrigation, resulting from increased industrial and human consumption, has led to the search for alternative methods of rice cultivation with lower water demand (Feng et al., 2007; Qu et al., 2008). The use of soil conservation management systems for the cultivation of upland rice has been suggested as an excellent alternative to increase global rice production and to reduce water use in agriculture, especially for soils with low available water capacity (Bouman and Tuong, 2001; Nascente et al., 2013).

The benefits of no-till (NT) systems for improving soil water retention and crop yields have led to worldwide adoption (Gozubuyuk et al., 2014); NT systems are currently used over an area of approximately 157 million ha, distributed primarily in Latin America (66 million ha), the USA and Canada (36 million ha), and Australia (18 million ha) (FAO, 2015).

The continued success of NT systems has been achieved through soil fertility management (Soratto and Crusciol, 2008a). However, in several tropical regions, the benefits of these agricultural production systems are limited by soil acidity, which reduces the availability of macronutrients and results in problems associated with manganese and aluminium toxicity (Oliveira and Pavan, 1996; Caires et al., 2008b; Churka Blum et al., 2013). Limestone is a common material that is used to ameliorate soil acidity; however, due to the low solubility and mobility of carbonate in the soil profile, surface liming effects are usually limited to lime application/incorporation sites (Caires et al., 2005, 2006; Soratto and Crusciol, 2008b). Under these conditions, the development of the root system is limited to a small volume of soil in the superficial layers, which in turn negatively influences crop grain yield, mainly in regions with frequent dry spells (Caires et al., 2008a).

Among certain strategies used to ameliorate subsurface soil acidity is the replacement of lime by the surface application of more soluble

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materials (Castro and Crusciol, 2013). However, to be considered effective, these materials must contain oxides, hydroxides, or silicates as neutralizing constituents (Alcarde and Rodella, 2003). By-products such as steel industry slags (basically composed of Ca and Mg silicate) can be a good alternative to replace or increase the surface liming effect due to their higher solubility and alkalinity compared with lime, which can reduce the time associated with the liming reactions in the soil profile (Peregrina et al., 2008; Yi et al., 2012). In addition, Ca, Mg, and Si sources may be useful for crops, reducing lime consumption (Castro and Crusciol, 2013) and improving the performance of Si-accumulating crops (Liang et al., 1994; Korndörfer and Lepsch, 2001; Guntzer et al., 2011).

The surface application of soil acidity amendments (lime and silicate) with low solubility has restricted the yield potential of several crops as a result of high Al^{3+} levels and low availability of basic ions in the subsurface soil (Reeve and Sumner, 1972; Smith et al., 1994; Caires et al., 2011), which can reduce the downward movement of alkaline substances. The occurrence and reaction of free Al^{3+} species in water generates hydrogen ions in the soil solution (Lindsay, 1979), which results in high potential acidity (H + Al) levels. This effect supposedly increases the neutralizing constituents required to reduce the generated acidity.

By-products such as phosphogypsum reduce the concentration of free Al^{3+} in the soil solution (Sumner et al., 1986; Shainberg et al., 1989), especially in the subsurface soil layers (Sumner, 1993), which is favourable for the amelioration of soil profile acidity in a shorter time period. Supposedly, the phosphogypsum reaction can improve the time effects of soil acidity amendments (lime and silicate), which is related to the high solubility and mobility of Ca sulphate throughout the soil profile (Farina et al., 2000; Alcarde and Rodella, 2003). Each type of gypsum has specific chemical characteristics, but most of them are considered excellent sources of Ca^{2+} and SO_4^{2-} for subsurface soil layers, which allows greater development of deep roots in acidic soils, reducing water stress caused by drought periods (Sumner et al., 1986; Alva and Gascho, 1991; Rutherford et al., 1994; Soratto and Crusciol, 2008a; Soratto et al., 2010; Caires et al., 2011).

Although upland rice has been considered acid-tolerant, new cultivars with better genotypic performance are apparently less tolerant to high Al^{3+} toxicity and the poor chemical conditions of tropical soils (Fageria et al., 2015). In addition, some studies suggest that fertilizer application, including Si sources, significantly increases upland rice grain yield, which indicates greater nutrient demand (Seebold et al., 2000; Korndörfer and Lepsch, 2001; Crusciol et al., 2013). Therefore, the adoption of new techniques in acidic soils under NT systems is essential to provide better conditions for plant development, resulting in increases in upland rice production.

The identification of alternatives that enable the amelioration of soil acidity at depth in an NT system through surface application without the incorporation of amendments may facilitate the success and continued use of this type of agricultural system. In addition, there is limited information on the surface application of acidity amendments and phosphogypsum applied as a mixture to tropical soils, which may have potential to improve the reactions of substances with low mobility and solubility.

Thus, this study was based on the following hypotheses: a) the surface application of silicate can neutralize soil acidity and provide Ca at depth in a shorter time period compared with the application of lime only; b) the application of soil acidity amendments (silicate + lime) in a mixture is more efficient than individual applications of each amendment with respect to reducing the acidity of the soil profile; c) due to its high mobility, the addition of phosphogypsum to soil acidity amendments (silicate + lime) promotes the enrichment of bases in the soil profile in a shorter time period compared with individual or mixed applications of lime and silicate; and d) the application of soil acidity amendments mixed with phosphogypsum can increase the grain yield of upland rice.

In summary, the aims of this study were to evaluate the effects of superficially applied silicate, lime, and phosphogypsum mixtures on the amelioration of the soil profile under an NT system, and to determine their effects on the nutrition, yield components, and grain yield of upland rice crop.

2. Materials and methods

2.1. Site description

A field experiment was conducted in the Cerrado region, Selvíria, State of Mato Grosso do Sul, Brazil (51°22′ W, 20°22′ S, 335 m a.s.l.) over two growing seasons. The soil was classified as a clay-textured Typic Acrustox (USDA, 1999). The chemical properties of the soil were determined at multiple depths (0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m) prior to installing the experiment (Table 1), according to the methodologies described by van Raij et al. (1986).

The long-term (1956–2006) mean temperature during the rice growing season was 26.9 °C, with a minimum of 21.4 °C and a maximum of 32.4 °C. The mean rainfall during this period was 749 mm. In addition, during the experimental period, the minimum and maximum air temperatures and rainfall were measured daily (Fig. 1).

2.2. Experimental design and treatment establishment

The experiment was designed as a randomized complete block with eight treatments and four replications. Each plot covered an area of 35 m^2 (5.0 m × 7.0 m). The following treatments were tested: (i) control (no lime, silicate, or phosphogypsum); (ii) phosphogypsum (3.0 Mg ha^{-1}); (iii) lime (2.1 Mg ha^{-1}); (iv) silicate (2.2 Mg ha^{-1}); (v) lime and silicate mix (1.05 Mg ha^{-1} + 1.1 Mg ha^{-1}); (vi) lime and phosphogypsum mix (2.1 Mg ha^{-1} + 3.0 Mg ha^{-1}); (vii) silicate and phosphogypsum mix (2.1 Mg ha^{-1} + 3.0 Mg ha^{-1}); and (viii) lime, silicate, and phosphogypsum mix (1.05 Mg ha^{-1} + 1.1 Mg ha^{-1} + 3.0 Mg ha^{-1}).

The dolomitic limestone and Ca and Mg silicate rate (R) was calculated to increase the base saturation (BS) in the topsoil (0–0.20 m) to 70%, using Eq. (1) as described by Cantarella et al. (1998).

$$R\left(\mathrm{kg\ ha^{-1}}\right) = (BS_2 - BS_1)\ CEC/(ECCE/100) \tag{1}$$

where ECCE is the effective Ca carbonate equivalent of the amendments; BS_2 is the estimated base saturation (70%); and BS_1 is the base saturation measured in the soil, calculated using Eq. (2) as described by Cantarella et al. (1998).

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

where Ca_{ex}, Mg_{ex}, and K_{ex} are basic exchangeable cations, and CEC is the total cation exchange capacity, which was calculated using Eq. (3).

$$\begin{aligned} CEC\left(\mathrm{mmol_c\ dm^{-3}}\right) = {} & Ca_{ex} + Mg_{ex} + K_{ex} \\ & + \text{total acidity at pH 7.0 } (H + Al) \end{aligned} \tag{3}$$

The phosphogypsum rate (GR) was calculated using Eq. (4), as recommended by van Raij et al. (1997).

$$GR\left(\mathrm{kg\ ha^{-1}}\right) = 6CL \tag{4}$$

where CL is the clay content (g kg^{-1}) in the 0.20- to 0.40-m soil layer.

The dolomitic limestone was composed of 30% Ca and 7.2% Mg with an ECCE of 86%. The Ca and Mg silicate, a by-product obtained from the steel manufacturing process, contained 23% SiO_2, 26% Ca, and 7.8% Mg with an ECCE of 82%; minor amounts of heavy metals were detected,