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Soil fertility and nutrient budget after 23-years of different soil tillage systems and winter cover crops in a subtropical Oxisol

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ABSTRACT

Growing cover crops to recycle soil nutrients in no-tillage systems provide nutrients accumulation in more labile forms in the soil surface reducing the demand for fertilizers. This study aimed to evaluate the long-term (23-yrs) effect of soil tillage systems and winter cover crops on (*i*) soil acidity, (*ii*) nutrient availability, and (*iii*) P and K budget in a subtropical Oxisol from Southern Brazil. The experiment was established in 1986 with six winter treatments (blue lupine, hairy vetch, oat, radish, wheat, and fallow) and two tillage systems (conventional tillage - CT and no-tillage - NT) in a very clayey Rhodic Hapludox in Southern Brazil. Nutrient availability (P, K, Ca, and Mg) and soil acidity (pH, potential acidity, base and Al saturation) were evaluated in five soil depths (0–5, 5–10, 10–20, 20–30, and 30–40 cm). Nutrient budget was calculated considering the inputs (amount of P and K applied via fertilizer) and outputs of P and K from the system (exported by the grains), and the soil available P and K before and after 23-years of experiment. Continuous NT system for 23-years resulted in higher soil fertility in the topsoil (0–10 cm) compared to CT, but with some limitations of nutrient availability and soil acidity below 10 cm depth. Long-term NT builds up a strong gradient of nutrient availability, with higher concentration of nutrients on the soil surface layers that abruptly decrease with soil depth, unlike CT. Surface application of lime in NT reduced soil acidity up to 20 cm compared to CT. The budget of P was negative for all treatments, highlighting the P-sink behavior of this strongly weathered subtropical Oxisol. However, NT system resulted in less negative budget compared to CT and, therefore, higher efficiency of use of P. Growing cover crops in the winter is effective to increase P and K availability through plant cycling, but the plants grown in winter did not affect soil acidity. Nutrient cycling by winter cover crops reduced P and K losses, especially when the soil is not plowed. Fallow in the winter decreases the use efficiency of P and K. Among the cover crops tested, black oat stood out by its greater production of biomass, resulting in higher P and K availability in the soil surface. Lupine resulted in a greater cycling of P possibly due to its ability to absorb P from less labile forms in the soil.

1. Introduction

Strongly weathered subtropical soils, such as those found in Southern Brazil, naturally have high acidity and low fertility (Bortoluzzi et al., 2015). Native plants from these regions developed mechanisms to grow under these adverse soil conditions. These plants can alter soil pH in the rhizosphere, uptake Al with posterior complexation into plants tissues, complex Al and Fe in the rhizosphere due to organic acids released by roots, increase P affinity, and form mycorrhiza associations (Vitorello et al., 2005). However, cash crops grown in this region, such as soybeans (*Glycine max* (L.) Merr.), maize (*Zea mays* L.), and wheat (*Triticum aestivum* L.), have low tolerance to Al^{3+} toxicity and require high availability of nutrients, such as P and K (Arunakumara et al., 2013).

After burning of forests to clear land for cultivation during the 1950s and 1960s in Southern Brazil, farmers obtained reasonable crop yields in the first 2–3 years (Casão Junior et al., 2012). After that, nutrients depletion associated with plowing and heavy harrowing following residue burning to reduce biomass volume to facilitate mechanical operations, resulted in rapid lowering of the grain yields that motivated the first farmer's migratory cycle in Southern Brazil towards the Northeastern and West-Central Brazil (Batistella and Valladares, 2009). With the advancement of research after the green revolution, these areas were chemically recovered by the addition of limestone and

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fertilizers, becoming productive again (Roy et al., 2016). Later, with the adoption of no-tillage (NT) system, which exponentially increased in Brazil from 1 million hectares in the early 1990s to 31.8 million hectares in 2011/2012, representing approximately 25% of the area under NT in the world (FEBRAPDP, 2016), the production costs markedly decreased due to lower energy consumption, lower nutrient losses, and higher nutrient cycling.

The beneficial effects of soil management under NT are undeniable. Typically, soils cultivated in NT system exhibit high chemical fertility in the topsoil (0 to 7–10 cm depth) compatible with plant uptake, while deeper soil layers have high Al content and low availability of essential nutrients such as P and K (Calegari et al., 2013; Martínez et al., 2016; Rheinheimer et al., 2008; Tiecher et al., 2012, 2012). In such conditions, NT limits root growth to superficial layers due to the higher concentration of nutrients in the topsoil and due to subsoil compaction (Franchini et al., 2017; Hamza and Anderson, 2005), which in turns decreases the plant access to water and nutrients reserves from deeper soil layers (Nunes et al., 2015). In this scenario, cover crops play an important role, especially when soil is not disturbed as in NT system, because they (*i*) stimulate soil microbiological activity (Mbuthia et al., 2015), (*ii*) increase nutrient cycling and soil organic matter content (Conceição et al., 2013), (*iii*) improve nutrient acquisition from the soil in situ, or from added fertilizers (Teles et al., 2017), and (*iv*) improve soil physical properties and alleviate soil compaction stress (Calonego et al., 2017).

Growing different plant species successively in the same area can alter the dynamics of soil acidity. The reasons for such are numerous, including the imbalance in the cation-anion absorption, particularly affected by nitrogen sources, and increased efflux of protons because of P deficiency (Singh Gahoonia and Nielsen, 2004). Changes in soil rhizosphere pH often has been shown to have variations of up to 1.7 units (Li et al. 2009). Soil acidification is intensified by growing legumes because they generally have a higher uptake and exportation of basic cations (Ca, Mg, and K) (Li et al., 2013). Moreover, the biological N fixation in legumes reduces nitrate uptake increasing nitrate leaching along with basic cations (Frageria and Nascente, 2014).

The use of cover crops with high soil–root contact are particularly important for P and K uptake because they have low mobility in Oxisols (Kaminski et al., 2010; Tiecher et al., 2012) due to large amounts of clay minerals and iron oxides. In the long-term, the lack of any recycling of crop residues in mono-cropping systems with low residue production might cause severe K depletion from soil K reserve (non-exchangeable K) (Srinivasarao et al., 2014), or K losses by leaching (Alfaro et al., 2006). Different crop rotation management systems can alter soil P availability in the long-term due to access of soil organic P by increasing exudation of acid enzyme phosphatase (Chavarría et al., 2016; Cui et al., 2015; Kunze et al., 2011), or by the exudation of organic acids with low molecular weight that promotes P mobilization by ligand exchange or by occupying P adsorption sites (Bayon et al., 2006; Neumann and Römheld, 1999). Moreover, the mycorrhizal or non-mycorrhizal character of cover crops have regulatory effect on enzyme activity linked to organic P mineralization in the soil (Kunze et al., 2011). The use of non-mycorrhizal plants as lupin and oilseed radish (*Raphanus sativus* L.) increase the phosphatases enzymes activity in the soil compared to vetch (*Vicia sativa spp.*) and black oat (*Avena strigosa* Schreb) (mycorrhizal plants) (Dalla Costa and Lovato, 2004). Even though, Rosolem and Calonego (2013) found that nutrient losses occurred in all crop rotations systems evaluated in a period of 3-yrs. in NT system in an Alfisol from São Paulo, Brazil, with negative budgets ranging between 15 and 33% for P, and between 7 and 21% for K. However, nutrient losses can be reduced by using cover crops that promotes P and K accumulation, maintaining the nutrient in the soil-plant system, and avoiding K losses by leaching or P losses by soil-fixation.

Therefore, it can be expected that growing cover crops with different strategies to access soil nutrients over time may alter soil nutrients cycling and soil acidity, especially in NT system. As the soil can be considered the memory of an agricultural production system, we can analyze the records of soil management by the changing in its chemical properties over time. In this sense, long-term studies are important to indicate which cover crops and soil tillage systems are the most suitable for a more sustainable agriculture. Particularly in subtropical conditions, long-term experiments with continuous monitoring of soil chemical properties and crop yields are rare. The present study offers a unique opportunity to assess the impacts of several winter cover crops, including legumes (blue lupin - *Lupinus angustifolius* L. and hairy vetch - *Vicia villosa* Roth), grasses (black oat and wheat - *Triticum aestivum* L.), cruciferae (oilseed radish), and winter fallow, associated with different tillage systems on nutrients availability and soil fertility.

This study aimed to evaluate the long-term (23-yrs) effect of soil tillage systems and winter cover crops on (*i*) soil acidity, (*ii*) nutrient availability, and (*iii*) P and K budget in a subtropical Oxisol from Southern Brazil.

2. Material and methods

2.1. Site description

The experiment was established in 1986 at the Agronomic Institute of Paraná, in Pato Branco, Paraná State, Brazil, under a very clayey Rhodic Hapludox. The A horizon (0–1 m depth) has 720 g kg^{-1} clay, 140 g kg^{-1} silt, and 140 g kg^{-1} sand. Clay fraction is composed mainly by kaolinite (60–70%) (silicate type 1:1), with 10–15% of silicate type 2:1 (vermiculite and/or montmorillonite), iron oxides (15%) (of which 51% hematite, 36% goethite and 13% maghemite) and 5% gibbsite (Costa, 1996). Climate is sub-humid tropical or Köeppen's Cfb, meaning climate without dry season, with rainy summer and with the average hottest month lower than 22 °C. The 30-yrs. average of annual rainfall ranges from 1200 to 1500 mm. The 30-yrs. monthly average temperature and monthly average precipitation of the experimental station are presented in Fig. 1.

2.2. History of the experimental area

The experimental area was covered by subtropical forest until 1976, when it was cleared and cultivated with maize, soybean, and beans (*Phaseolus vulgaris* L.) for 10 years in a conventional system with one-disc plow and two-disc harrowing before each crop. During this period, the area experienced high soil losses by erosion. Lime and fertilizers were applied at unknown rates. Selected soil chemical properties at the beginning of the experiment (1986) are presented in the Table 1.

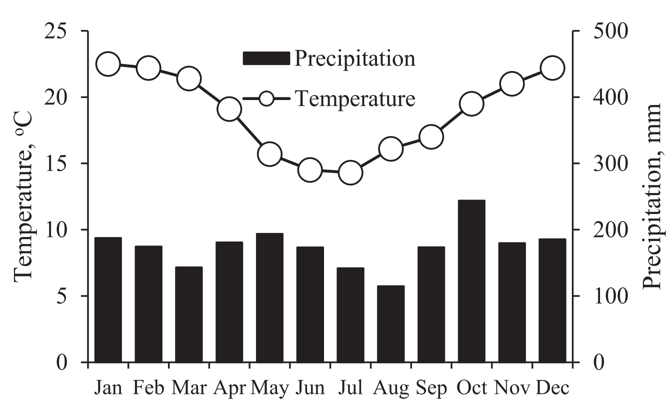

Fig. 1. 30-years average temperature and average precipitation in the experimental area. Source: Meteorological Station of Experimental Station of IAPAR, Pato Branco, State of Paraná.