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Soil physical quality on tillage and cropping systems after two decades in the subtropical region of Brazil

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ABSTRACT

Sustainability of crop production systems depends on the preservation of soil physical quality over time. This study aimed to determine long-term effects of soil tillage and cropping systems on physical attributes and hydraulic properties of an Oxisol in Southern Brazil, emphasising management practices to preserve or improve the soil structure quality under no-tillage system. The experiment was conducted in randomized block design, using a 5 × 2 factorial arrangement (tillage × cropping systems), with four replications. The five tillage systems consisted of conventional tillage (CT); minimum tillage, chiselled soil every year (MTC1); minimum tillage, chiselled soil every three years (MTC3); continuous no-tillage for 11 years (NT11); and continuous no-tillage for 24 years (NT24). The two cropping systems consisted of annual crop sequence with wheat in the winter and soybean in the summer, designated as crop succession (CS); and a 4-year crop rotation (CR) with white lupine-maize—black oat-soybean—wheat-soybean—wheat-soybean in winter–summer, respectively. Undisturbed soil cores were collected from 0–0.10; 0.10–0.20 and 0.20–0.30 m of soil depth, to determine the soil bulk density (BD), total porosity, macroporosity, microporosity, pore size distribution and classes, soil water retention curve, infiltration rate and field-saturated hydraulic conductivity. There was no interaction between tillage and cropping systems, and no effects of cropping systems on soil physical and hydraulic properties. Regardless the cropping system, chiselling effects on soil physical properties persisted for less than 22 months, and were restricted to below 0.20 m soil depth. The CT resulted in soil pulverization at 0–0.10 m depth, leading to lower BD and higher macroporosity compared to the other soil tillage systems. At layers below 0.10 m, CT increased the BD and reduced the macroporosity to critical levels for crop growth. Continuous use of no-tillage improved soil physical quality mainly at deeper layers, and provided higher plant available water retention in the soil at matric potentials ranging from −10 to −200 kPa in relation to CT and MTC1. The adoption of NT improves soil physical quality and plant available water over time, and periodic soil chiselling aiming to disrupt compacted layers should be avoided because of its effects on reducing soil compaction level are short-lived.

1. Introduction

Soil conservation has been pointed out as one of the major challenges for ecosystem sustainability. In the last decade, population growth in association to changes in dietary behaviour has sharply increased the global demand for food, thus promoting a widespread process of land use intensification. This fact has augmented the environmental pressures on the soil system, leading to increasing risks for its capacity to continue to perform functions such as providing food security, water security, energy security, biodiversity, and other ecosystem services (Brevik et al., 2015). Thus, scientists must focus on developing and implementing solutions concerning soil management and conservation to match high crop productivity to maintenance and improvement of soil quality (Banwart, 2011).

Several measures have been indicated to enable high crop productivity and soil quality conservation in agricultural areas, such as: organic farming (van Leeuwen et al., 2015); terracing

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(Zhao et al., 2013); use of soil amendments, e.g., plant-based biochars (Weyers and Spokas, 2014); crop residue retention (Pittelkow et al., 2014); increased plant straw additions (García-Orenes et al., 2012; Kahlon et al., 2013; Tejada and Benítez, 2014; Sadeghi et al., 2015); diversified crop rotations (Bhattacharyya et al., 2006; Ba et al., 2014; Pittelkow et al., 2014; Abdollahi et al., 2015), and conservation tillage systems, such as no-tillage (NT) (Kahlon et al., 2013). In this context, NT has long been regarded as one of the most important management practices to enable sustainable cropping intensification to meet future agricultural demands (Derpsch et al., 2014) and, at same time, preserve the soil quality by reducing soil erosion (Lal, 2007), and increasing the soil organic carbon content (Zotarelli et al., 2012), aggregate stability (Alvarez and Steinbach, 2009), biodiversity (Adl et al., 2005), and biological activity (Anken et al., 2004; Babujia et al., 2010).

The agricultural areas managed under NT have been continuously increasing in the last decade. In 1999, NT was used on about 45 million ha worldwide, increasing to 111 million ha in 2009 (Derpsch et al., 2010). In Brazil, the area under NT grew from 1.3 million ha in 1991/92 to 31.8 million ha in 2011/12 (FEBRAPDP, 2015). The rapid worldwide adoption of NT by farmers can be ascribed to some key advantages, such as reduction in fuel and labour consumption, time saving, and erosion control (Lal, 2007). However, concerns about excessive soil compaction in untilled areas have still been present in different agricultural regions, such as South America (Alvarez and Steinbach, 2009; Botta et al., 2012; Moraes et al., 2014), North America (McVay et al., 2006; Kahlon et al., 2013; Munkholm et al., 2013), Asia (Chen et al., 2014; Singh et al., 2014), Australia (D'emden et al., 2010) and Europe (Anken et al., 2004; Soane et al., 2012; Dal Ferro et al., 2014; López-Garrido et al., 2014). Soil compaction has been long known to reduce the total porosity, macroporosity, aeration, water infiltration capacity and hydraulic conductivity (Silva et al., 2009), increasing soil bulk density and resistance to penetration (Moraes et al., 2014), which limits the soil depth and volume explored by roots to take up water and nutrients (Chen et al., 2014). These changes may reduce crop yields, especially in dry years (Franchini et al., 2012); impair agricultural machinery performance (Botta et al., 2012); and increase soil, water and nutrient losses, greenhouse gas emissions, and pollution of water resources (Lipiec et al., 2003).

The impacts of NT and other tillage systems on soil physical quality have been widely investigated, but contradictory results have been found (Alvarez and Steinbach, 2009). Tillage effects on soil physical properties are known to be time-, space-, and management-dependent (Tangyuan et al., 2009; Wang and Shao, 2013; Munkholm et al., 2013; Derpsch et al., 2014), resulting in highly variable results. Additionally, few studies have focused on integrated effects of tillage and cropping systems on soil structure (Munkholm et al., 2013). Accordingly, long-term soil management experiments conducted in different regions are of great importance to clarify the tillage effects on soil physical quality (Ba et al., 2014). It is important to consider that the magnitude of tillage effects on soil structure quality is highly dependent on the variability and sensitivity of the physical attributes used. Particle size distribution, bulk density, pore size distribution, available water, and aggregate stability have been the most widely used parameters to assess the impact of agricultural management and changes in land use on soil physical quality (Zornoza et al., 2015).

Periodic soil chiselling has been considered a feasible practice to improve soil physical conditions in areas under NT (Munkholm et al., 2003; Botta et al., 2006; López-Garrido et al., 2014; Klein and Camara, 2007). If well performed, soil chiselling may immediately disrupt compacted layers, but the effects are short-lived, not exceeding a year (Veiga et al., 2007), since this operation does not exclude the major cause of soil compaction (Botta et al., 2006). In this context, the use of crop rotations including plants with high potential for shoot and root biomass production has been recommended to prevent the formation of compacted layers and improve soil physical quality (Calonego and Rosolem, 2010; Munkholm et al., 2013; Silva et al., 2014). This recommendation is based on the increase in plant available water content, soil organic matter content, soil aggregate stability, and biopores formed by the root system of the plants included in the crop rotation (Silva et al., 2009; Ba et al., 2014).

Unlike the pores produced by tillage, biopores produced by plant roots are long and continuous, with high effectiveness for water and air flow (Dörner et al., 2010). According to Dexter (1991), biopores do not modify the soil bulk density, because the root growth reduces the porous space in the surrounding region. However, biopores can decrease the soil resistance to penetration, increase the soil friability, and saturated hydraulic conductivity. Furthermore, continuous pores or biopores attenuate the soil compaction effects on plant growth, since they become pathways for the root growth of subsequent crops through compacted layers (Calonego and Rosolem, 2010).

The following hypotheses were tested: (i) crop rotation under NT enables the long-term preservation of the soil physical quality, preveting the formation of compacted layers; (ii) periodic soil chiselling in NT is not necessary when cropping systems are based on rotation; and (iii) soil physical quality is improved with time after the adoption of NT.

Therefore, this study aimed to determine the long-term effects of soil tillage and cropping systems on physical attributes and hydraulic properties of an Oxisol in Southern Brazil, emphasising management practices to preserve or improve the soil physical quality under NT.

2. Materials and methods

2.1. Study site

The experiment was established in 1988 at the Experimental Station of Embrapa Soybean, in Londrina (latitude 23°11′S; longitude 51°11′W; and 620 m altitude), State of Paraná, southern Brazil. According to the Köppen classification, the climate of the region is humid subtropical (Cfa), with annual average temperature of 21 °C and mean maximum and minimum temperatures, respectively, of 28.5 °C in February and 13.3 °C in July. The average annual precipitation is 1651 mm, with January being the wettest month (217 mm), and August the driest (60 mm). The trial was established on an Oxisol (Latossolo Vermelho Distroférrico, Brazilian classification; Rhodic Eutrudox, USA classification) with 755 g clay kg^{-1} soil, 178 g silt kg^{-1} soil and 67 g sand kg^{-1} soil. The soil particle density at 0–0.3 m depth is 2.90 Mg m^{-3}, and the mean slope of the experimental area is 0.03 m m^{-1}. Before the establishment of the experiment, the area had been cropped with coffee (*Coffea arabica* L.) for approximately 40 years, with the entire area receiving similar management and inputs.

2.2. Experimental design and treatments

The experiment was laid out in a randomized block design, with a 5 × 2 factorial arrangement (tillage × cropping systems), and four replications. The five tillage systems consisted of: (1) NT24: continuous no-tillage for 24 years, sowing directly through the residue of the previous crop with the opening of only a narrow furrow in the sowing row; (2) NT11: continuous no-tillage for 11 years; (3) CT: continuous conventional tillage for 24 years, performed by means of a heavy disk harrow at an average depth of 0.15 m followed by disking with a light disk harrow at 0.08 m depth, preceding the summer and winter crops; (4) MTC1: minimum tillage, with annual chiselling before the winter crop,