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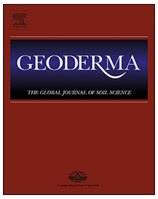

Tensile strength of mollisols of contrasting texture under influence of plant growth and crop residues addition

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ABSTRACT

Tensile strength (TS) of soil aggregates is considered a sensitive and important indicator of the effects of the management practices on soil structure quality, which affects the seed germination and the initial crop growth. However, the influence of plant growth, crop residues addition and the produced aggregating agents on TS has not been widely studied. The objectives of this study were: i) to determine the specific effects of plant growth and different types, rates and location of crop residues in the aggregates tensile strength, and ii) to assess the relationship between the aggregating agents produced by plant growth and crop residues addition and the aggregate tensile strength of soils of contrasting texture. A greenhouse experiment was carried out in pots with a loamy soil (Typic Hapludoll, Santa Isabel series) and a silty-loamy soil (Typic Argiudoll, Esperanza series) under controlled conditions for 112 days. For each soil the following treatments were set up in triplicate: (i) soil type, (ii) with or without plant growth of wheat (*Triticum aestivum* L.), (iii) with or without residues addition, (iv) location of residues (surface *vs.* incorporated), (v) wheat *vs.* soybean (*Glycine* max L.) residues, and (vi) residue rates (6.3 and 15.7 g of dry matter per pot for wheat, and 6.3 and 18.8 g of dry matter per pot for soybean). Pots were exposed to wetting and drying (W/D) cycles. TS values and aggregating agent's content, *i.e.*, total organic carbon (TOC), particulate organic carbon (POC), hot water extractable carbohydrates (HWEC), dilute acid extractable carbohydrates (DAC), total carbohydrates (TC), total glomalin-related soil protein (T-GRSP), and easily extractable glomalin-related soil protein (EE-GRSP) were measured. TS were significantly lower in the Typic Hapludoll (TS = 39.9 kPa) than in the Typic Argiudoll (TS = 61.6 kPa). TS values were significantly higher in the treatments with plants of wheat than in treatments without plants (49.5 *vs.* 30.3 kPa in the Hapludoll and 71.2 *vs.* 50.9 kPa in the Argiudoll). Plant growth increased TS through physical mechanisms, *i.e.* a greater number of drying-wetting cycles. Also, plant growth increased TS by producing aggregating agents. TS values were not directly affected by the addition of different types, rates and locations of crop residues. However, they increased the content of aggregating agents. Multiple regression analysis showed that TS was significantly related to soil type, TC and T-GRSP. TS increased with increasing TC and T-GRSP. These two variables explained 87% of the model variation. The obtained model provides a basis for understanding which are the most important aggregating agents and, consequently, which are the better management systems to improve o recover the structure quality of soils with different textures.

1. Introduction

The intensification of the production systems in the Argentinean Pampas had decreased organic carbon and essential nutrients contents as well as the microbiological activity of the soils. Also the intensification had contributed to soil structure degradation (Ferreras et al., 2009). Soil structure degradation changes soil porosity, which controls water and air transmission and the space in which roots can grow (Oades, 1984). Thus, it causes crop production to be affected (Bronick and Lal, 2005; Whalley et al., 2006; Alvarez and Steinbach, 2009). Soil structure is dependent on the size, stability, distribution and strength of the aggregates as well as on the pore space between and within aggregates (Maa et al., 2015). The study of individual aggregates characteristics, such as water-stable aggregates, mean weight diameter and tensile strength were long used to assess the structural quality of the soils (Kay et al., 1994; Kay and Angers, 1999; Dexter and Watts,

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2000; Imhoff et al., 2002; Blanco-Canqui et al., 2005; Zhang et al., 2012). Kay et al. (1994) mentioned that tensile strength is related to the aggregate size distribution after a given energy is applied. Thus, tensile strength yields information on the condition of the quality of a seedbed that is created by tillage (Kay et al., 1994). Also, they indicated that tensile strength is related to the mean weight diameter because both measurements are indicators of the resistance to aggregate fragmentation. According to this author and Dexter (1988a) aggregates tensile strength also affects indirectly the activity of soil organisms and organic matter decomposition because it depends on the microcracks existent inside the aggregates.

Tensile strength of the aggregates is defined as the force per unit of area that is required to cause the disruption of aggregates (Dexter and Kroesbergen, 1985; Dexter and Watts, 2000), and can be determined by a simple test on aggregates of different size (Dexter and Kroesbergen, 1985; Watts and Dexter, 1998). This indicator is manly influenced by intrinsic soil properties, such as soil water content, soil organic carbon, texture and clay mineralogy (Barzegar et al., 1994; Imhoff et al., 2002; Reis et al., 2014). Also, it is influenced by soil management practices, which determine the degree of disturbance caused on the aggregates (Macks et al., 1996; Munkholm et al., 2001; Blanco-Canqui et al., 2005; Blanco-Canqui and Lal, 2008; Tormena et al., 2008). According to Blanco-Canqui and Lal (2006) any mechanical disturbance of the soil is portrayed in the tensile strength of individual aggregates. Thus, this property is considered a sensitive indicator of the management practices effects on soil structure quality (Dexter and Watts, 2000).

The changes with time of soil strength of individual aggregates are mainly caused by external factors, such as climate conditions, or by internal factors, such as the activity of microorganisms and plant roots. Czarnes et al. (2000) demonstrated that plant growth increased the strength of the soil bonded to the roots compared to the strength of the bulk soil counterpart.

Roots affect soil aggregates strength through abiotic and biotic mechanisms. They generate cycles of drying-wetting, create soil pores and channels, and produce physical enmeshment of soil particles (Six et al., 2004). Live roots produce mucilage that acts as agent of soil aggregation. Besides, that substance stimulate the microbial activity because they are essential carbon sources for the microorganisms (Six et al., 2004; Rillig et al., 2015; Erktan et al., 2016). Dead roots and plant residues also stimulate the microbial activity because they are carbon sources as well (Golchin et al., 1994; Rillig et al., 2006; Linsler et al., 2016). Microorganisms produce many extracellular compounds as part of their metabolisms that are considered important agents of soil aggregation (Rillig and Mummey, 2006; Bronick and Lal, 2005). Between them, polysaccharides have long been associated with the stability of soil aggregates (Tisdall and Oades, 1982). More recently, other compounds produced by fungi, such as glomalin, the glomalin-related soil protein (GRSP) and hydrophobins have received attention as agents of soil aggregation (Rillig and Mummey, 2006; Spohn and Giani, 2011). The functions of these binding agents seem to depend on the type of fungi and plant species (Piotrowski et al., 2004). Furthermore, roots residues and microbial debris increase soil total and particulate organic matter that produces binding agents of soil aggregates when decomposed (Six et al., 2004; Bronick and Lal, 2005).

Some researchers have indicated that the production and functions of the total and particulate organic carbon, carbohydrates, and GRSP are strongly conditioned by the interactions between types of soil microorganisms, type, rates and location of added crop residues and the roots activity (Abiven et al., 2007; Guimarães et al., 2009; Reis et al., 2014).

The effect of root activity and crop residue addition on the size aggregate distribution and aggregates stability of silty-loam soils are well studied (Sonnleitner et al., 2003; Denef and Six, 2005; Cosentino et al., 2006; Abiven et al., 2007; Carrizo et al., 2015). Some studies show the individual influence of the aforementioned factors in the aggregates tensile strength. Kay et al. (1994) indicated that soil wetting/drying cycles induced changes in the aggregates tensile strength. Materechera et al. (1992) and Munkholm et al. (2001) found plant growth and the microbial activity increased the aggregates tensile strength. Hadas et al. (1994) and Blanco-Canqui and Lal (2007) reported that crop residue addition increased aggregates tensile strength. Despite these reports, few have gone in to details with specific effect of plant growth, residue addition and the produced aggregating agents in the tensile strength of freshly formed soil aggregates. Thus, understanding these effects on soil tensile strength is still a challenge. We hypothesized that plant growth and crop residues addition increase tensile strength by increasing particulate organic carbon, carbohydrates and GRSP production, and that the magnitude of the increase depends on soil texture. Hence, the objectives of this study were: i) to determine the specific effects of plant growth and different types, rates and location of crop residues in the aggregates tensile strength, and ii) to assess the relationship between the aggregating agents, produced by plant growth and crop residues, and the aggregate tensile strength of soils of contrasting texture.

2. Materials and methods

2.1. Experimental design and treatments

A greenhouse experiment was carried out with soils of contrasting texture and total carbon organic (TOC) under controlled temperature (15–25 °C) and humidity (50–70%) conditions. As described in the research of Carrizo et al. (2015), the soils used in this experiment were collected from two fields that were managed under long-term no-till (last ten years) with agricultural rotations located in Santa Fe province (Argentina). The soil of one field is classified as Typic Hapludoll, Santa Isabel series (33°93′S, 61°57′W) with loamy texture (16% clay, 43% silt, and 41% sand) and SOC content of 21.1 g kg^{-1}. The other is classified as Typic Argiudoll, Esperanza series (31°26′S, 60°56′W) with silty clay loam texture (24% clay, 71% silt, and 5% sand) and SOC content of 15.3 g kg^{-1}. Each field was split in 3 sectors. In each sector soil samples (N = 20) was collected in fall of 2012 at the depth of 0–20 cm. Briefly, soil samples were collected using a shovel and then gently crumbled by the natural planes of weakness. After sampling, crop residues and coarse roots were removed, and the soil was air-dried and sieved through a 2 mm sieve. The material smaller than 2 mm from the 20 samples of each sector was bulked to obtain a composite sample (about 100 kg each) that was used to fill in 5-l pots up to a bulk density of about 1.3 g cm^{-3}. All treatments were applied on each of the 3 replications of each soil type.

For each soil the following treatments were set up in triplicate: (i) soil type, (ii) with or without plant growth of wheat (*Triticum aestivum* L.), (iii) with or without residues addition, (iv) location of residues (surface or incorporated), (v) wheat *vs.* soybean (*Glycine* max L.) residues, (vi) residue rates (6.3 and 15.7 g of dry matter per pot that is equivalent to 0.2 and 0.5 kg of dry matter m^{-2} for wheat, and 6.3 and 18.8 g of dry matter per pot that is equivalent to 0.2 and 0.6 kg of dry matter m^{-2} for soybean; where 0.2 kg was considered low rate and 0.5 kg and 0.6 kg were considered high rate) (Fig. 1). The two location of residue were used to simulate the tillage system used in the region studied; *i.e.* no-till and conventional tillage.

Residues were cut down into 1 cm pieces and applied before seeding. In the incorporated crop residues treatments, residues were hand-mixed within the upper 10 cm of the soil. Immediately, in the treatments with plants, pre-germinated seeds were planted and four plants of wheat were allowed to grow per pot (127 plants m^{-2}). All necessary nutrients were added through Hoagland solution. The salts used to make up the solution were KNO_3, $Ca(NO_3)_2$, $NH_4H_2PO_4$, $MgSO_4$, and micronutrient (H_3BO_3, $MnCl_2$, $ZnSO_4$, $CuSO_4$, H_2MoO_4, iron tartrate) (Hoagland and Arnon, 1950). For each soil, all pots had the same water content at the beginning of the experiment. Then, pots were exposed to wetting and drying (W/D) cycles. Each time that soil