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Dynamics of soil structure and pore functions of a volcanic ash soil under tillage

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ABSTRACT

Soil structure dependent properties are subject to temporal changes as a consequence of tillage and environmental factors. These changes are well documented in soils with bulk densities >1 Mg m^{-3}; however, no major studies have been carried out in soils with extremely low densities, such as those normally presented by Andosols. Thus, in order to study the temporal dynamics of a volcanic ash soil's physical properties, this study aimed to assess the impact of tillage on soil structure-dependent properties and their development throughout the year. The soil water and temperature dynamics, as well as rainfalls and the penetration resistance, were registered in the field. In order to characterize the effect of mechanical and hydraulic stresses, 10 soil samplings (5–10 cm depths) were conducted before/after tillage, during crop development (*Tritricum aestivum*) and after grazing. The water retention and shrinkage curves, air and saturated hydraulic conductivity, precompression stress, aggregate strength and cohesion between particles were measured. Our results show that the soil structure behaves dynamically at different scales due to mechanical and hydraulic stresses which impact the soil mechanical stability, porosity and related soil-pore functions. In spite of the low bulk density of the Andosol, the mechanical disturbance did not affect the soil structure and related pore functions significantly throughout the year, demonstrating the ability of the soil to recuperate its functions. As observed for the precompression stress (Pc < 90 kPa), bulk density (<1.7 Mg m^{-3}), air capacity (>8%) and hydraulic conductivity (>20 cm d^{-1}), the physical properties of the Andosol did not reach critical values in terms of subsoil compaction. The well-known high resilience capacity of volcanic ash soils allowed the integral functionality of these soils' pores to recover, presenting the same or even greater values as compared to their initial condition; i.e. both hydraulic (k_s) and air (k_l) conductivity clearly decreased after the roller compacted the soil due to a decrease in the amount and continuity of macropores; however, as soon as wetting and drying cycles occurred and the biological activity started (root development during the growing season), k_s and k_l tended to increase as a consequence of a more continuous pore system, thus soil pores were able to reach the initial values previous to soil tillage. Finally, the shrinkage curves show the soil pores' instability after tillage. At the same time, they illustrate the dynamic behavior of the soil structure, highlighting the fact that soils do not behave as a rigid body and temporal variability of hydraulic properties (macropores, hydraulic conductivity) must be expected. Therefore, better hydrological models which consider this dynamic behavior are needed.

1. Introduction

Soil tillage affects soil structure and, consequently, its mechanical stability (e.g. Horn and Baumgartl, 2002) and hydraulic properties (e.g. Strudley et al., 2008). Therefore, we must consider that tilled soils are constantly under the impact of mechanical (e.g. tillage) and hydraulic stresses (wetting and drying cycles) as well as biological activity (e.g. root development and earthworm activity), all of which alter the soil structure and pore related functions. While mechanical stresses are responsible for soil deformation, when an applied stress exceeds the soil precompression stress (e.g. inducing an increase in bulk density and mechanical strength, as well as a decrease in hydraulic conductivity as observed by Liebig et al., 1993; Logsdon and Jaynes, 1996; Green et al., 2003; Zink et al., 2010), the hydraulic stress allows the soil to improve its structure through the formation of continuous pores (Dörner et al., 2011). Therefore, soils behave as dynamic bodies presenting not only spatial (e.g. Zhao et al., 2007; Dec et al., 2011), but also temporal variability (e.g. Fuentes et al., 2004; Osunbitan et al., 2005; Dec et al., 2011; Schwen et al., 2011).

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Temporal changes in soil structure-dependent properties have been observed by many authors, such as Mellis et al. (1996), Green et al. (2003), Fuentes et al. (2004), Osunbitan et al. (2005) and Moret and Arrúe (2007), among others. For example, Fuentes et al. (2004) showed that hydraulic properties (pore-size distribution, hydraulic conductivity) of different managed (natural prairie, conventional till and no till) Ultic Haploxerolls varied throughout time; Osunbitan et al. (2005) assessed an Oxic Tropudalf and determined that, regardless of the tillage system, the bulk density increased and the saturated hydraulic conductivity decreased weeks after tillage; Moret and Arrúe (2007) found that in a Xerollic Calciorthid the saturated hydraulic conductivity decreased due to rain-induced natural soil reconsolidation after tillage. This shows us that soil properties, such as pore-size distribution and hydraulic conductivity, which govern transport processes in soils, are not constant throughout the year, and, consequently, must be considered in hydraulic modeling. In this context, Jury et al. (2011) defined some future directions in soil physics for "Relating Structure and Function Structure at Different Scales". They mentioned that we need to know much more about dynamic changes in void space in various structural units in order to interpolate and extrapolate structure–function relationships in soil hydrology throughout time. This was also discussed by Bormann and Klaassen (2008), Dörner et al. (2010) and Schwen et al. (2011), and is particularly relevant to properly estimate temporal changes in the soil water storing capacity in the context of climate change, which will induce more extreme rainfalls and periods of drought.

In order to describe how tillage management affects the soil and its functions (water and air holding capacity and conductivity), temporal changes of structure-dependent properties were investigated using less- and very-sensitive soil parameters. The bulk density (e.g. Mellis et al., 1996; Moret and Arrúe, 2007) and the penetration resistance (e.g. Osunbitan et al., 2005) have been used in many studies despite their low sensitivity (as discussed in Horn and Fleige, 2009 and Dec et al., 2011). On the other hand, Moret and Arrúe (2007), Osunbitan et al. (2005) and Schwen et al. (2011) studied temporal changes in very sensitive soil hydraulic properties, which allows us to understand the dynamics of pore geometry factors such as pore-size distribution, continuity, tortuosity and interconnection between pores (Bear, 1972). These pore geometry factors, which has been studied by Schjønning et al. (2002), Dörner and Horn (2006) and Reszkowska et al. (2010), among others, are relevant since allows to understand water and air transport processes in soils. In addition, characterizing temporal changes in these structure-dependent properties gives us the opportunity to study the soil resilience capacity, understood as the ability of the soil to counteract stresses (Lal, 1994) and recuperate soil pore functions (Dörner et al., 2011) throughout a defined period of time.

Most studies conducted to understand the dynamic processes in soils have been carried out in soils with bulk densities >1.0 Mg m^{-3}; less work has been focused on soils with extreme physical properties, such as those properties normally presented by Andosols. These highly productive soils present very particular properties, such as a bulk density of < 0.9 Mg m^{-3}, a well-defined inter- and intra-aggregate pore system (Armas-Espinel et al., 2003; Dörner et al., 2010), high hydraulic conductivity (Ellies et al., 1997; Regalado and Muñoz-Carpena, 2004), stable soil aggregates (Hoyos and Comerford, 2005), great shrinkage capacity (Dorel et al., 2000; Dörner et al., 2009a) and a large resilience capacity (Dörner et al., 2011); their temporal variability has not yet been the subject of major investigations. Volcanic ash soils dominate southern Chile, covering about 60% of the country's arable land, with a wide range of land uses (e.g. native forest, grasslands and croplands). Until now, investigations in Chilean volcanic ash soils have been focused on evaluating the effect of the land use change (e.g. native forest to grassland) on structure-dependent properties (Ellies, 1988; Ellies et al., 1997, 2000; Dörner et al., 2009a,b, 2010; Dec et al., 2011), and have later been concerned with characterizing the impact of soil management on soil physical resilience (Dörner et al., 2011). However, no major work has been done i) to understand the dynamic processes that occur after tillage and their relationship with mechanical and hydraulic stresses and ii) to evaluate the temporal dynamics of soil pore functions and their resilience capacity. Therefore, we hypothesized that the physical properties of the studied Andosol present a dynamic behavior as a result of tillage (mechanical stresses) and wetting and drying cycles (hydraulic stresses). Due to the well-known high resilience capacity of Andosols, the soil is able to recuperate its initial soil-pore functions. Consequently, our objective was to assess the impact of tillage on soil structure-dependent properties and their development and recuperation throughout the year.

2. Materials and methods

2.1. Soil and management

An Andosol (Typic Hapludand, according to CIREN, 2003; or Vitric-Silandic Andosol as mentioned by Salazar et al., 2005; WRB, 2006) located in southern Chile was used to quantify the effect of soil tillage and wetting and drying cycles on the dynamic behavior of soil structure and pore related functions. The site is located 150 m above sea level; the topography presents slopes between 4 and 15%. The climate is temperate rainy with Mediterranean influences and a mean annual temperature of around 11.4 °C. The yearly precipitation is between 1300 and 1500 mm. The soil was formed from the deposition of volcanic ashes over moraines. According to IREN-UACH (1978), the soil profile presents variable depths (from 65 to 120 cm) with a defined low permeable soil layer. The soil texture ranges from silty loam to silty clay loam.

Before tillage, the soil had been under pasture for 15 years. During this time the prairies were used as the main source of livestock feeding during the year. In May, 2009 the soil was tilled 5 times with an off-set disc harrow (22 discs, approximately 2000 kg and 20 cm of working depth, respectively) and once with a field cultivator. Wheat (*Tritricum aestivum*) was seeded three days after tilling the soil with the field cultivator. Thereafter, the soil was compacted with a roller (weight = 1500 kg and working width = 300 cm), which was the last mechanical disturbance applied to the soil. During soil tillage and seeding a Tractor John Deere 6425 was used. A detailed description of soil management is presented in Table 1.

2.2. Field measurements and soil sampling

In order to characterize the dynamics of rainfall, soil temperature and water content, a rain gauge, thermistors (Pt100 soil temperature sensors) and TDRs (SM200 soil moisture sensors) were used. Both thermistors (n = 3) and TDRs (n = 3) were installed in June, 2009 at 5, 20 and 50 cm depths. The measurements took place every 10 min. TDRs were calibrated following the technique proposed in the SM200 User Manual 1.1 (Delta-T Devices Ltda, 2006). For this purpose, disturbed material (<2 μm) was used to prepare soil cores with defined bulk densities similar to those observed in the field at each depth and volumetric water contents of 10, 20, 30, 40 and 50%, approximately.

In order to characterize some soil physical properties before tillage, disturbed and undisturbed soil samples (in metallic cylinders of 220 cm^3; h = 5.6 cm, and d = 7.2 cm and 112 cm^3; h = 3 cm and d = 3.5 cm for hydraulic and mechanical properties, respectively), and soil aggregate samples were collected in March, 2009 from depths between 5 and 10 cm. Thereafter, undisturbed soil samples and soil aggregates were repeatedly collected at