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Seasonal dynamics of the physical quality of volcanic ash soils under different land uses in southern Chile

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ABSTRACT

In Chile, volcanic soils were developed under almost all of the diverse rain and temperature regimes, from the Arid Mediterranean to the Wet Zone of the South. Due to their andic properties, volcanic soils exhibit characteristics that are entirely different from other soil types around the world. The soil physical quality (SPQ) is strongly related to the functions of the soil pore system. Thus, soils characterized by a good SPQ have the ability to store and conduct water, air and nutrients promoting both: maximum crop yield and minimum environmental degradation. Many studies and much scientific progress have been made concerning the storing and conducting of water and air functions in volcanic soils. However, soil physical quality indicators and their temporal changes have been less studied. Thus, the objectives of this study were: i) to assess the impact of land use changes on the physical quality of three main volcanic soil groups in Chile, ii) to quantify the magnitude of their temporal changes and iii) to compare these results with threshold values found in the literature. Three soils derived from volcanic materials formed under different conditions and with different degrees of development were sampled (with different intrinsic properties), on five sampling dates, under three land uses (intensities): native forest (NF), prairie (P) and crops (C). Undisturbed samples were taken at two soil depths: 0–15 cm and 15–30 cm, in 230 cm^3 metallic cylinders, and then covered with caps and plastic film to prevent mechanical disturbance and evaporation. We measured and /or calculated from these samples: air capacity (AC), plant available water capacity (PAWC), relative field capacity (RFC), bulk density (dB), air conductivity (kl), pore connectivity indexes (C2 and C3), the coefficient of linear extensibility (COLE) and saturated hydraulic conductivity (Ks). Undisturbed soil blocks were collected to evaluate aggregate stability. To assess differences among land uses and seasons in the SPQ indicators, analyses of variance (ANOVA) were used and an LSD test ($p \le 0.05$) was conducted to separate the means. A principal component analysis (PCA) was performed to associate the SPQ indicators. The results of this study allow us to conclude that the impact on SPQ indicators depended on the soil type, considering their degrees of development, clay content and type, as well as the organic carbon content and the season in which the soil functions were determined. When values of the SPQ indicators were compared with critical and/or threshold values of the mineral soils found in the literature, the indicators of dB and RFC fell completely out of the range considered typical for mineral soils. Thus, several questions remain regarding the real critical values of these soil properties in volcanic soils. More work is necessary to establish the critical value of volcanic soil's bulk density, since this is a widely used soil property that serves as an estimator of other functional soil quality indicators.

1. Introduction

During the past 200 years the landscape of southern Chile has changed dramatically, mainly due to processes involving the replacement of native forests for the expansion of agriculture and livestock, especially in the Intermediate Depression (Lara et al., 2012). The destruction of native forests was marked by large fires, which eventually enabled the establishment of agricultural lands as well as urban zones. A high percentage of this area is dominated by soils derived from volcanic materials. In Chile, volcanic soils include different taxonomic orders, such as Inceptisols, Andisols and Ultisols (Luzio, 2010), accounting for 50–60% of the arable land in Chile, where an important part of the production is made up of cereal crops, livestock and forestry (Tosso, 1985). Although most soils in southern Chile are volcanic, they

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have very different properties, according to soil formation conditions. Volcanic soils developed under almost all of the diverse rain and temperature regimes, from the arid Mediterranean area in central Chile to the Wet southern zone (Luzio, 2010). Due to their andic properties (Shoji et al., 1993; Soil Survey Staff, 2010) these soils exhibit characteristics entirely different from other soil types around the world. Andisols have been described as soils with variable charge (Shoji et al., 1993), high air and water holding capacity (Armas-Espinel et al., 2003), high hydraulic conductivity (Ellies et al., 1997) and a great shrinkage capacity (Dörner et al., 2009a, 2012).

Soils, as a system, have several functions and their sustainability is associated with the harmonization of these functions, excluding or minimizing irreversible uses (Blum, 2005). This ability to function was included in the definition of soil quality proposed by Karlen et al. (1997) as: *"the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation"*. Soil quality is determined by both inherent and dynamic properties and processes (Carter, 2002), so that the nature and genesis of different types of soils define their functionality. In these terms, the functioning of volcanic soils, which account for less than 1% of soils worldwide (Soil Survey Staff, 2010), has been less studied than other soils. Ecosystem services provided by the soil (Adhikari and Hartemink, 2016) and their functions, such as: i) biodiversity and production, ii) water and solute flow and iii) structural support (Seybold et al., 1996), are related to structural properties and their dynamics. These can be evaluated through indicators of soil physical quality (SPQ), such as: soil structure, aggregate stability, porosity, available soil water, bulk density and saturated hydraulic conductivity (Rahman et al. 2008; Reynolds et al., 2008, 2009; Dörner et al., 2013). Thus, SPQ is strongly related to the functions of a soil pore system (Dörner et al., 2013). These physical indicators can be associated with capacity parameters that define a general status or the composition of a given volume (such as a pore system), while the intensity parameter includes dynamic aspects over time and space that describe the functionality of that volume (Horn and Kutilek, 2009).

Soils characterized by a good physical quality have the ability to store and conduct water, air and nutrients promoting both: maximum crop yield and minimum environmental degradation (Topp et al., 1997). A good SPQ is strongly related to a stable and resilient pore system (e.g. Dörner et al., 2011), as well as soil characteristics related to pore geometry, such as pore size distribution, pore continuity and connectivity (Dörner et al., 2012; Zúñiga et al., 2015). Although this has been studied by many scientists in mineral soils with crystalline clays (e.g. Reynolds et al., 2009; Horn and Fleige, 2009), it requires more attention in volcanic ash soils, especially due to their extreme physical properties (e.g. bulk density $< 0.9\,\mathrm{Mg\,m^{-3}}$), which normally fall off the current scale of critical values. Therefore, it is important to evaluate the impact of land use changes in different types of volcanic soils regarding their SPQ, in order to define the applicability of the critical values defined for non-volcanic soils (Dörner et al., 2013). Scientists have recently made significant progress in understanding the impact of land use changes on soil properties; the transition from native forests (or less intensive managements) to pastures, crops or exotic plantations results in a strong decline in some soil quality indicators. This is reflected as increases in: i) soil bulk density (Rahman et al., 2008; Dörner et al., 2009b; Dörner et al., 2013), ii) soil compaction (Dörner et al., 2012), iii) penetration resistance (Ellies et al., 1993), iv) subsidence or decrease of the soil depth (Ellies et al., 1993; Dörner et al., 2016), and decreases in: v) soil structural stability (Ashagrie et al., 2005; Candan and Broquen, 2009), and vi) losses of total soil porosity and coarse pores (Rahman et al., 2008; Dörner et al., 2009b, 2012).

As a consequence of land use changes and wetting–drying cycles, soil physical properties change in space and time, respectively. This statement highlights the fact that soils are not rigid bodies (Horn et al., 2014), and changes occur due to external and internal stresses. While the first has been relatively well-documented for volcanic ash soils (Cuevas et al., 2004; Dörner et al., 2011), temporal changes, relevant for volcanic ash soils due to inherent properties (e.g. shrinkage processes, Dörner et al., 2010) have been less studied (Dec et al., 2011.). Soil physical quality indicators have still scarcely been studied in soils derived from volcanic materials (Dec et al., 2011; Dörner et al., 2012). The latter is relevant since critical values for these properties have been defined for soils with different origins (Reynolds et al., 2009; Horn and Fleige, 2009) and their applicability to soils with extreme soil physical properties is uncertain. Additionally, the response of volcanic ash soils to the effect of land use changes is different due to their variable origin and further pedological development (e.g. Goebel et al., 2017). Therefore, the objectives of this study were: i) to assess the impact of land use changes on the physical quality of three main volcanic soil groups in Chile, ii) to quantify the magnitude of their temporal changes and iii) to compare these results with the threshold values found in the literature.

2. Materials and methods

2.1. Experimental conditions

Three soils derived from volcanic materials were sampled in the "Los Ríos" and "Los Lagos" Regions of Chile. Chosen soil series were classified by CIREN (2003) as: i) Huiti (HUI) Acrudoxic Duraquand; ii) Osorno (OSR) Typic Hapludand; and iii) Cudico (CUD) Typic Hapludult. These soils were selected due their different development degrees, which are representative of the main groups of volcanic soils in Chile, these soils cover large areas under agriculture use. Soils evaluated range values of soil organic carbon (SOC) between 1.2–16.8%, allophane contents of 0.2-12.1%, extractable Al with ammonium acetate ($\mathrm{Al_a}$) of $86–2143\,\mathrm{mg\,kg^{-1}}$ and particle density $1.75–2.47\,\mathrm{g\,cm^{-3}}$ (more details are shown in Table 1 of Valle and Carrasco, 2018).

The selected land uses in this study were: i) a secondary native forest (NF); ii) a prairie used as permanent pasture for the last 10 years (P); and iii) crops (C), which were different for each soil. In HUI, the soil was under supplementary forage crops (*Brassica rapa* L.); in CUD the sequence was: wheat-rape-wheat (*Triticum aestivum* L. - *Brassica napus* L. - *T. aestivum*), whereas in OSR it was: wheat-oat-wheat (*T. aestivum* - *Avena sativa* L.-*T. aestivum* L.). The land use intensity can be ordered as follows: NF $<$ P $<$ C.

2.2. Soil sampling

In order to register the temporal variability of the studied soil physical properties, 5 sampling dates (SD) were used: i) January 2012 (summer, SD1); ii) July 2012 (winter, SD2); iii) October 2012 (spring, SD3); iv) January 2013 (summer, SD4); and, v) May 2013 (autumn, SD5). Samples were taken at two soil depths: 0–15 cm and 15–30 cm, in metallic cylinders with $230\,\mathrm{cm^3}$ of volume ($h = 5.6$ cm, $d = 7.2$ cm), and then covered with caps and plastic film to prevent mechanical disturbance and evaporation. Undisturbed soil blocks were collected to evaluate aggregate stability. Disturbed soil samples were taken for chemical characterization and to determine the particle size distribution from each soil series, land use and soil depth.

2.3. Soil physical quality indicators

To assess changes in SPQ, the following indicators were used: air capacity (AC), plant available water capacity (PAWC), relative field capacity (RFC), bulk density (dB), air conductivity (kl), pore connectivity indexes (C2 and C3), coefficient of linear extensibility (COLE), aggregate stability (mean weight diameter, MWD) and saturated hydraulic conductivity (Ks) To determine AC and PAWC indicators the water retention curve (WRC) was measured. Undisturbed soil samples