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Effect of land use change on Andosol's pore functions and their functional resilience after mechanical and hydraulic stresses

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ABSTRACT

The effect of land use change on soil physical resilience of an Andosol was quantified for a native forest (NF), 30 year old pasture (P) and 1 year old crop (C). In order to define soil deformation and resilience, we calculated the coefficient of linear extensibility (COLE) during consolidation/shrinkage and after the recuperation of the soil, i.e. when the applied stress was released. Additionally, on the same soil samples the bulk density, water retention curve and air permeability were measured. Our results show that an intensification of land use induced greater mechanical and hydraulic stresses in the soil leading to higher structure stability (e.g. the pre-compression stress increased from 34 to 61 kPa between the native forest and pasture), but lower pore resilience capacity (e.g. COLEr decreased from −0.13 to −0.10). Both kinds of stresses increased the bulk density of the soil (mechanical > hydraulic). However, while the loading cycle reduced the air permeability as a consequence of a reduction of macro pores, shrinkage created more continuous macro pores between aggregates which resulted in more pronounced gas fluxes. Finally, we concluded that a detailed analysis of shrinkage and consolidation curves along with air permeability measurements can be used to evaluate the physical resilience of the soil.

1. Introduction

Soils are constantly under the impact of mechanical and hydraulic stresses. While the first is responsible for soil deformation, the second allows the soil to improve its structure (Horn et al., 2002). The same authors mentioned that structural changes take place when the applied load or hydraulic stress exceeds the pre-compression and pre-shrinkage stress, respectively. Therefore, soil structural properties (e.g. air capacity and conductivity) may continuously change depending on the relationship between mechanical and hydraulic stresses and the soil's internal strength. The latter is relevant since the land use change exposed the soil to larger mechanical and hydraulic stresses altering the soil structure and related pore functions (Bormann and Klaassen, 2008; Dorel et al., 2000; Dörner et al., 2009a,b; Horn and Peth, in press). In these terms, to maintain soil structure-dependent pore functions such as air and water conductivity, it is essential that land management allows the soil to recover from human and natural induced stresses. The latter is normally called soil resilience.

In general resilience means the tolerance to stress or the proportion of deformation that a body can elastically withstand following the removal of deforming forces. Consequently, soil resilience includes all the processes that enable the soil to counteract stresses (Szalbolcs, 1994; Lal, 1994). According to Lal (1994) the factors affecting soil resilience can be grouped into two categories: endogenous and exogenous. While the first is related to soil's inherent properties (e.g. amount of organic matter, soil texture and structure) and climate (wetting and drying cycles), the second has to do with land use, soil, crops and livestock management.

Soil resilience investigations normally follow the behavior of a defined soil property before, during and after the imposition of a defined stress. Soil physical resilience has been quantified by characterizing the changes in soil porosity and mechanical stress during and after compaction (Ellies, 1988; Gregory et al., 2009; O'Sullivan et al., 1999; Zhang et al., 2005). Gregory et al. (2009) also mentioned that soil physical resilience has been expressed by measuring the stability (Denef et al., 2001) and size distribution (Grant et al., 1995) of aggregates exposed to wet–dry cycles, and by monitoring vertical soil movements after compaction (Tobias et al., 2001). These findings, however, considered only changes in soil volume but did not register the ability of the soil to recover pore-geometry related properties such as air permeability. The latter is relevant if we consider that soil functions are not only related to holding available water for plants, but also to transporting air and water in order to satisfy plant and crop requirements.

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Andosols are described as highly productive soils covering less than 1% of the soils in the world (Lal, 1994; Takahashi and Shoji, 2002; WRB, 2006). These soils exhibit very specific properties like variable charge, high phosphate retention (Shoji et al., 1993), low bulk density, a well-defined inter- and intraaggregate 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) and great shrinkage capacity (Dorel et al., 2000; Dörner et al., 2009a,b). Volcanic ash soils dominate southern Chile covering about 60% of the arable land in the country and a wide range of land uses (e.g. native forest, grasslands, croplands). The latter exposed the soil to different levels of mechanical and hydraulic stresses affecting its structure and related functions.

Until now the investigations of Chilean volcanic ash soils have concentrated on evaluating the effect of an intensification of land use on structure-dependent properties (Ellies, 1988; Ellies et al., 1997, 2000; Dörner et al., 2009a,b, 2010). However, no major study has characterized the impact of land use change and/or soil management on soil physical resilience. In order to fully describe the interactions between physical processes and the consequences of soil resilience, not only the mechanical but also the hydraulic stress release effects must be defined as they both create volume changes. Dorel et al. (2000) and Dörner et al. (2009a, 2010) have already mentioned that desiccation and soil compaction are the two main processes affecting volcanic soils' structure. In these terms, Dörner et al. (2009a) evaluated the impact of hydraulic stress on the pore system by determining the shrinkage curve in two wetting and drying cycles. They found that when the soil was exposed to extremely dry conditions, greater than its preshrinkage stresses, an irreversible soil deformation occurred leading to an increase in the amount of coarse pores but to a decrease in the middle and fine pores as a result of crack formation. How far the response of the soil to a stress applied and then released results in the identical pattern is at present unknown and will be investigated in the following. We hypothesize that by using the information gained during the determination of the shrinkage and consolidation curves the soil pore physical resilience can be evaluated by relating soil deformation to pore functions (air permeability). Therefore, the aim of this work is to characterize the effect of land use change on the physical resilience of an Andosol (according to WRB, 2006) exposed to mechanical (consolidation) and hydraulic (shrinkage) stresses.

2. Materials and methods

2.1. Soil and land uses

An Andosol (Typic Durudand according to CIREN, 2003 or Petroduri-Silandic Andosol after Salazar et al., 2005; WRB, 2006) located in southern Chile was used to quantify the effect of land use change on soil physical resilience. The sites are located 330 m above sea level; the topography is complex with slopes between 4 and 15% and in some cases >30%. The climate is temperate rainy with Mediterranean influences and a mean annual temperature of around 11 °C. The yearly rainfall is 2000 mm. The soil was formed from deposition of volcanic ashes over moraines. According to IREN (1978), the soil profile presents variable depths (from 65 to 80 cm) with a well-developed first horizon (0–14 cm depth, granular until subangular blocky structure), two horizons with a subangular blocky structure (14–50 cm depth), and a less-developed horizon without structure formation (55–80 cm, silty). Many stones can be found up to a depth of 80 cm.

The soil was under the following land uses: native forest (NF), 30 year old pasture (P) and crop (C). All sites were first checked by soil mapping and described according to CIREN (2003). The secondary native forest (NF) was dominated by *Nothofagus obliqua*, *Aextoxicon punctatum*, *Nothofagus dombeyi*, *Amomyrtus luma*, *Luma apiculata* and *Lapageria rosea*. The 30 years old pasture (P), dominated by *Ballica perenne*, *Dactylis glomerata*, *Trifoliums repens* among others, was used for livestock feed during the year. Both sites (NF and P) had a residence time of at least 30 years. The soil under crop, which was previously used as a pasture, was cultivated with a chisel plough in April 2008. Thereafter, *Tritricum aestivum* was seeded.

2.2. Soil sampling

Disturbed and undisturbed soil samples were collected in October, 2008 at depths of 5, 20 and 50 cm from 3 land uses: NF, P and C. Undisturbed soil samples were collected in metallic cylinders for both hydraulic (220 cm^3; h: 5.6 cm, and d: 7.2 cm) and mechanical (112 cm^3; h: 3 cm and d: 3.5 cm) properties. The samples were covered with plastic caps to prevent additional mechanical disturbance and evaporation.

2.3. Laboratory analysis

Soil texture was determined with the hydrometer method (Day, 1965). The Bouyoucos method was used after dispersion of clay and organic matter destruction. The particle density was measured with the Pycnometer method using vacuum (Klute, 1986), the organic carbon was determined according to Sadzawka et al. (2004) and the amount of allophane was calculated following the equation proposed by Parfitt and Wilson (1985).

The water retention curve and soil shrinkage were measured in undisturbed samples (*n*: 7 for each depth and land use), simultaneously. In order to describe the effect of the hydraulic stress on pore functions, all samples were dried twice: the first one (w/d1) till 25 °C (nearly the highest temperature registered in the top 5 cm of the soil) and the second one (w/d2) at 60 °C, 90 °C till 105 °C. The samples were first carefully saturated from beneath and then drained at water potential values of −1, −2, −3, −6, −15, −33, −50 kPa. The water content was registered at each water potential with an electronic balance. To characterize the shrinkage behavior at water potentials lower than −50 kPa, samples were shifted to dry air conditions (25 ± 2 °C) for 2 days and then rewetted again for 5 days. Thereafter, the samples were drained at the same matric potentials as in w/d1 followed by air dryness (25 °C) and defined oven dryness (60, 90 and 105 °C). From saturation and through the different water tensions and dehydration temperatures, the water content and vertical deformation (measured at 7 fixed points for each soil sample) were recorded with an electronic balance and caliper gauge (0.05 mm accuracy), respectively. The volume deformation of the soil was used to calculate and to relate the corresponding pores to the actual soil volume. Thus, the shrinkage intensity was used to correct the measured changes in water content by using the corresponding height differences. Each sample was used to measure the water retention and shrinkage curves from saturation to different dehydration temperatures.

The consolidation curve was measured using an oedometer (*n*: 3 for each land use but only at depths of 5 and 20 cm). The water saturated samples were drained at −6 kPa and then weighed. The samples were first stressed by static loading for 6 min with 6, 12, 25, 50, 100, 200 and 400 kPa and thereafter, the stresses (σ_n) were removed until 200, 100, 50, 6, 1 kPa were reached. Each stress during the loading and unloading cycle was applied for 6 min. The soil deformation was measured during the experiment (0.05 mm accuracy) and the bearing capacity was defined in accordance with Casagrande (1936).

In order to define the effect of hydraulic and mechanical stresses on pore functions, the air conductivity (k_l) was measured