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Air permeability and diffusivity of an Andisol subsoil as influenced by pasture improvement strategies

Permeabilidad y difusión de aire en el subsuelo de un Andisol sujeto a distintas estrategias de mejoramiento de praderas

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ABSTRACT

In southern Chile, grazing systems over volcanic ash soils play an important role for the development of the region. The productivity of these grazing systems should be improved by Pasture Improvement Strategies (PIMs), which in the case of the present study were established 5 years before this analysis. Often topsoil properties were measured while those for describing the functioning of the pore system (e.g., air permeability) in the subsoil (> 0.45 m) are missing. For subsoil samples, these parameters were determined to compare the long-term effect of three PIMs (i.e., NFNP: not-fertilized and not-ploughed, FNP: fertilized but not-ploughed or fertilized and CP: ploughed). Two depth intervals (D1: 0.45 - 0.55 m, D2: 0.55 - 0.65 m) within the same subsoil horizon of a Duric Hapludand were considered. Results show that the subsoil was influenced by tillage. The transformation to an improved pore system was e.g. indicated by increased means of pore indices (C_3) for FNP (123.5%) and CP (46%) as compared to NFNP for D1 (Ψ_m = -6 kPa). The soil air diffusivity values in these subsoil samples were in a range comparable to those reported for non-volcanic but sandy soils in Europe and were generally larger in D2 than in D1. We concluded that soil properties were still in transition to a new equilibrium. Thus, measurements of subsoil properties should be repeated in time intervals to better understand gas transport processes in cultivated Chilean soils that origin from volcanic ash.

RESUMEN

En el Sur de Chile, los sistemas pastoriles sobre suelos volcánicos juegan un rol importante para el desarrollo de la región. La productividad de praderas puede ser mejorada a partir de estrategias de mejoramiento (PIMs), las cuales, en el caso de este estudio, fueron establecidas cinco años atrás. Las propiedades superficiales de los suelos son determinadas para describir la funcionalidad del sistema poroso (p.ej. permeabilidad de aire) pero generalmente no son determinadas en el subsuelo (> 0,45 m). Se determinaron estos parámetros en muestras del subsuelo para comparar el efecto a largo plazo de tres PIMs (NFNP: pradera natural sin fertilización, FNP: pradera natural con fertilización y CP: pradera sembrada). Se consideraron dos profundidades (D1: 0,45 – 0,55 m, D2: 0,55 – 0,65 m) dentro del subsuelo de un Duric Hapludand. El subsuelo fue influenciado por la labranza. El mejoramiento del sistema poroso se reflejó en un aumento de los índices de poros (C_3) para FNP (123,5%) y CP (46%) al compararse con NFNP para D1 (Ψ_m = -6 kPa). Los valores de difusión de aire en las muestras del subsuelo estuvieron en un rango comparable a los valores reportados para suelos arenosos en Europa y fueron mayores en D2 que en D1. Concluimos que las propiedades del suelo aún están en transición a un nuevo equilibrio. Se requieren nuevas mediciones en intervalos de tiempo para comprender mejor los procesos de transporte de gas en los suelos volcánicos chilenos cultivados.

Palabras clave: Difusión de oxígeno, permeabilidad de aire, interacción suelo-planta, funciones de poros del subsuelo, sistemas pastoriles.

INTRODUCTION

Grazing systems constitute an important part of the landscape and play a relevant role for dairy and meat production in southern Chile (1,340,400 ha). Over 44% of these pastures are degraded and relatively low in productivity (4,000 kg dry matter ha^{-1} year^{-1}) if compared to pastures with e.g., moderate nitrogen fertilization (Lobos *et al.*, 2016). Various strategies have been implemented to improve these grasslands (Zúñiga *et al.*, 2015) which result in alterations within the plant-soil-atmosphere-continuum (Ordóñez *et al.*, 2018). The soil structure can be negatively modified (Krümmelbein *et al.*, 2006) depending on the pasture improvement management (PIMs) affecting the soil capacity to store and to conduct water and air (Zúñiga *et al.*, 2015; Ordóñez *et al.*, 2018). In these terms, both Dörner *et al.* (2013) and Ordóñez *et al.* (2018), assessed that pasture grasses on less mechanically disturbed volcanic ash soils are more efficient to uptake water from the soil during drought periods, highlighting the relevance of soil structure conservation for pasture management.

The soil flora and fauna play a major role for gas, water, and heat transport processes in soils. Biopores created by earthworms and plant roots can act as preferential flow paths (Jarvis, 2007), preferential elongation paths for plant roots (Passioura, 2002; McKenzie *et al.*, 2009), and are important for exchange processes within the plant-soil-atmosphere continuum. The air-filled porosity, the continuity, connectivity, and tortuosity of the soil porous system are parameters influencing pore functions like the transport of gas, water, and heat. The gas diffusivity in soil is especially influenced by air-filled and continuous pores. This becomes obvious if diffusion coefficients for air in different materials are compared (Table 1). The diffusion coefficient for oxygen in water is 10,000-times lower compared to that in air (Gliński and Stępniewski, 1985; Himmelblau, 1964). Numerous approaches have been used during the last decades to determine the parameters continuity, connectivity, and tortuosity of soil pores (Dörner *et al.*, 2012; Uteau *et al.*, 2013; Mordhorst *et al.*, 2017) based on, for example, the interpretation of observations on gaseous tracer diffusion experiments. These parameters have been rarely determined for Andisols (Zúñiga *et al.*, 2015) although they can deliver information about changes in pore functioning induced by management (Groenevelt *et al.*, 1984).

Table 1. Diffusion coefficients of oxygen in selected materials, representing the three soil-phases (gaseous, liquid, and solid), at 20 °C and 101.3 kPa.

Tabla 1. Coeficientes de difusión de oxígeno en materiales seleccionados que representan las tres fases del suelo (gaseosa, líquida y sólida), a 20 °C y 101,3 kPa.

Material	Diffusion coefficient (m^2 s^{-1})
Air	2.01 * 10^{-5} (Gliński and Stępniewski, 1985; Ball *et al.*, 1981)
Water	2.01 * 10^{-9}(Himmelblau, 1964)
Solid mineral	10^{-11}(Jost, 1960)

Crops raised on agricultural soils influence the pore size distribution, directly due to the specific root architectures (i.e., distribution and root length according to Pagenkemper *et al.* (2013), and indirectly, by the amount of carbon fixed by plants and supplied for soil flora and fauna, which also influences pore functions (e.g., earthworms as described in Pagenkemper *et al.* (2015)).

Pastures can have a large botanical diversity, which typically decreases with increasing management intensities (e.g., amount of applied fertilizer). For example, with addition of nitrogen fertilizers (20 to 50 kg N ha^{-1} year^{-1}) a reduction on half of the total number in plant species can be observed (Plantureux *et al.*, 2005). The same is valid for cutting or grazing at high intensity (Olff and Ritchie, 1998), while at low intensity mowing; grasslands show a high degree in biodiversity (see Plantureux *et al.* (2005) for a review about management effects). Most pasture species show shallow roots (e.g., *Lolium perenne* L.) while tap roots are found for herbaceous like *Plantago lanceolata* L. and *Hypochaeris radicata* L. (Perkons *et al.*, 2014; Moreno *et al.*, 2005). As a consequence of plant-induced changes in soil structure (Angers and Caron, 1998), diversity in botanical composition is accompanied by diversity in soil properties like pore size distribution, organic carbon, and water content caused by specific root architectures. In turn, root size, length, and distribution are influenced by soil properties. Regional plants like *Bromus valdivianus* Phil. increase the biological diversity. It is a fast-growing perennial grass, which is tolerant to water stress, with annual yield and herbage quality like *L. perenne* and *B. valdivianus* can be distinguished from commonly used *L. perenne* by its deeper root system (López *et al.*, 2013), among other properties.

The distribution of plant roots is influenced by the intensity of the management, such as repeated wheeling (Horn *et al.*, 2001), trampling (Peth, 2004), and tillage (Dörner and Horn, 2006) and can result in the formation of platy structures, which can act as a rooting barrier (Dörner and Horn, 2009). Crop yield is directly increased by applying fertilizers for plant nutrition (e.g., mainly phosphate in volcanic ash soils) or indirectly if fertilizers like $CaCO_3$ are used as ameliorant. With increasing yields, the amount of roots and carbon available for soil flora and fauna increases as well. The root distribution influences the pore size distribution, and thus, the pore functions (Uteau *et al.*, 2013). Natural processes like evaporation and plant water uptake lead to the formation of shrinkage-induced relatively rigid cracks (Horn *et al.*, 1994). For volcanic ash soil, this can be very relevant due to their shrinkage behavior (Dörner *et al.*, 2010). The penetration of finer root hairs results in the creation of new and highly connected, lateral side pores, increasing the relative diffusion coefficient of the biopore-wall (Haas and Horn, 2018), and consequently, the exchange between biopores and the soil matrix. Furthermore, whenever a new surface is created, swelling pressures occur, leading to the formation of new cracks after the pressure is dissipated (Jayawardane and Greacen, 1987). Another plant-induced process on pore functions is the hydraulic lift (Vetterlein and Marschner, 1993). This is a redistribution of water, potentially causing small-scaled increases in the water content. While the water content is reduced by plant water uptake the air-filled porosity is increasing. Thus plant-soil-atmosphere interactions result in crack forming processes, thereby creating a highly connected porosity with relatively low tortuosity and altered pore geometry and pore size distribution (Jayawardane *et al.*, 1995; Blackwell *et al.*, 1989; Peng *et al.*, 2005). This overview suggests that the pore functions are strongly affected by soil management. Most studies are related to topsoil properties. For example, Dec *et al.* (2012), found a management-dependent impact on pore functions due to wetting and drying cycles some months after animal trampling in a grazing system in southern Chile. In this study we assume that these effects of management can be found as well in subsoils. Therefore, undisturbed soil cores were excavated from subsoil influenced by volcanic ashes. In the laboratory experiments parameters related to aeration and physical functionality were determined at field water content and after drainage to defined matric potential.

We hypothesized that pore functions were altered depending on management practices, e.g. caused by differences in root architecture (i.e., distribution and root length densities) or mechanical disturbance of the soil structure.

The objective of this paper is to determine parameters related to the aeration and physical functionality of the subsoil of an Andisol, namely the relative oxygen diffusion coefficient, air permeability, air-filled porosity, and specific pore indices. The aim is to evaluate the impact of PIMs on pore functions of the subsoil samples from two depth intervals.

MATERIAL AND METHODS

Soil Material

The experiment was established in April 2013 in an experimental field at Universidad Austral de Chile (Estación Experimental Agropecuaria Austral -EEAA-, 39°46′ S, 73°13′ W, 12 m a.s.l.) in Valdivia, Chile. The average annual air temperature is 12 °C and annual mean precipitation is 2,440 mm. In the last 100 years, a well-defined decrease of precipitation was observed (González-Reyes and Muñoz, 2013). The soil corresponds to a Duric Hapludand, Valdivia Series according to CIREN (2003), influenced by volcanic ashes and rich in mica throughout the soil profile. The slope of the soil surface at the study site was less than 2%.

Three management practices were considered. The first site referred to as 'initial situation' (Ordóñez *et al.*, 2018; as 'NsF' in Salas *et al.*, 2016; or as T3 in Zúñiga *et al.*, 2015) corresponds with a 'non-fertilized naturalized pasture (NFNP)' was neither fertilized nor limed. The vegetation was not sown but spontaneously grown. Two sites were managed in correspondence to typical pasture improvement managements (PIMs) used in southern Chile: 1) a fertilized naturalized pasture (FNP, as 'NcF' in Salas *et al.*, 2016 or as T4 in Zúñiga *et al.*, 2015) without tillage treatment. Here, the initial naturalized pasture was improved through fertilizer addition and liming to improve soil pH conditions; 2) a cultivated pasture (CP) was applied. Here, the initial pasture was eliminated through two consecutive applications of glyphosate (2.2 kg ha^{-1} equivalent acid), after which the soil was ploughed, harrowed, vibro-cultivated and rolled. Thereafter, the *L. perenne* cv. Rohan (25 kg ha^{-1}) and *T. repens* cv. Weka (4 kg ha^{-1}) were sown. For FNP and CP, fertilizer and lime were applied annually as follows: 200 kg N ha^{-1} year^{-1} (Nitromag, 21% N); 120 kg P ha^{-1} year^{-1} (triple superphosphate, 46% P), 120 kg K ha^{-1} year^{-1} (potassium chloride, 60% K) and 2,000 kg $CaCO_3$ ha^{-1} year^{-1} (as lime). PIMs were established in April 2013, when the soil water content was close to field capacity (soil water content ≤40%). 25 sheep (Finnish Landrace x Romney Marsh) grazed on each plot (equivalent to 625 sheep ha^{-1}). For more details about grazing criteria, earlier botanical composition and detailed soil parameter see Parga *et al.* (2007), Flores *et al.* (2017), Descalzi (2017) and Ordóñez *et al.* (2018).

Undisturbed soil samples (7.1 cm in diameter, 5.7 cm in height) were collected in September 2017. Two depths were sampled (namely, 0.45 - 0.55 m or 0.55 - 0.65 m); both located within the B_3 layer (for more details about the sampling site see Zúñiga *et al.*, 2015). To determine the effect of PIMs' on specific root water uptake, the samples were measured at field moisture and after saturation and drainage at defined matric potential. To achieve this, firstly, gaze was placed at the bottom of each sample and hold by an elastic strap. Secondly, samples were saturated form the bottom with distilled water and afterwards drained at sand beds to equilibrate to a matric potential (Ψ_m) of -6 kPa. Thus, coarser pores with pore diameters >50 µm remained air-filled. The elastic strap and the gaze were removed prior to the determination of air permeability and oxygen diffusivity.

The botanical composition of sampling sites was photographed, and species were identified immediately in the field and partly in the laboratory using the photos. To verify if soil cores were influenced or not-influenced by roots, a visual qualification was carried out by carefully removing soil in the sampled depths, by looking for the occurrence of roots. The root intensity was qualified, analogously.

Air permeability

The procedure for determining the air permeability (k_a) was applied as described in Peth (2004). Air conductivity (k_l) was determined to derive k_a. In the laboratory, k_l was measured for each sample under steady-state flow conditions with a self-constructed air permeameter consisting of a set of floatblock flow meters (Key Instruments, now Brooks Instrument GmbH, Dresden, Germany). The gradient in air pressure used for this measurement was equal to 0.1 kPa. The value of ka (μm^2) was calculated as:

$$k_a = \frac{k_l\,\eta_a}{\rho_a\,g} \qquad (1)$$

where η_a denotes the viscosity (Pa s) and ρ_a the density (kg m^{-3}) of air, and g is the gravitational acceleration (m s^{-2}). Values of k_a were classified according to Reszkowska *et al.* (2011) from ''very low'' (<8.5 μm^2) to ''very high'' (>85 μm^2). The values were calculated from k_l classes according to a German classification system (Horn and Fleige, 2003) assuming a standard temperature of 20 °C and an atmospheric pressure of 101.3 kPa.

Oxygen diffusivity

The effective gas diffusion coefficient (D_s) was parameterized using a double chamber system (Rolston and Moldrup, 2002). The gas exchange through a soil core that was placed between two gas-tight chambers was monitored using oxygen microsensors (OX-100, UNISENSE A/S, Aarhus, Denmark) connected to a 16-bit AD-converter (4 channel Multimeter, UNISENSE A/S, Aarhus, Denmark). Values of D_s were calculated from changes in O_2 concentrations and the length of the soil core (7.1 cm) according to Uteau *et al.* (2013):

$$D_S = \frac{-\ln\left(\frac{\Delta C}{2} * C_{eq}\right) * V * L}{\mathrm{A} * \mathrm{t} * 2} \qquad (2)$$

where D_s is the effective gas diffusion in soil (m^2 s^{-1}), ΔC the difference in oxygen concentration between both chambers (g m^{-3}), C_{eq} the final oxygen concentration at equilibrium (g m^{-3}). V is the chamber volume (m^3), L the core length (m), A the soil core surface area (m^2), and t is the time from the start of the experiment (s). Oxygen diffusivity is expressed as relative oxygen diffusion coefficient (D_s/D_0), defined as the ratio of the oxygen diffusion coefficient in the soil (D_s) to that one of oxygen in free air (D_0 = 2.01 * 10^{-5} m^2 s^{-1}) at a given temperature and atmospheric pressure conditions (Gliński and Stępniewski, 1985). Prior to measurements, a two-point calibration was applied for oxygen electrodes. The zero point (0 kPa) was obtained by using an anoxic solution (2 g sodium ascorbate diluted in 100 mL of 0.1 M NaOH), while a value of pO_2 = 20.95 kPa was assumed for a well-aerated aqueous calibration solution.

Soil pore characteristics and pore functions

Soil cores were dried at 105 °C for 24 h to determine bulk density (ρ_b). Total porosity (Θ_t) was determined from Θ_b under the assumption of a specific particle density of 2.38 Mg m^{-3} (Zúñiga *et al.*, 2015). For each soil core, the difference between Θ_t and volumetric water contents (Θ_t) was defined as air filled porosity (Θ_a).

Pore functions were described as relations between air-filled porosity and air permeability or gas diffusivity. Buckingham (1904) assumed the diffusion being proportional to the square of Θ_a in variably textured and structured soils. Marshall (1959) used empirical fitting parameters α and β with 1 indicating a maximum in pore continuity:

$$D_S D_O^{-1} = \alpha \Theta_a^{\beta} \qquad (3)$$

As described by Mordhorst *et al.* (2017), continuity and, therefore, diffusivity decrease in the presence of tortuous and/or constricted air-filled pores. If the actual flow path for gas transport is extended compared to the shortest distance, then α <1, whereas, β ranges between 1 and 2 (Buckingham, 1904; Marshall, 1959; Ball *et al.*, 1988).

The continuity indices (C_1, C_2 and C_3) defined by Ball *et al.* (1988), were also determined in this study as:

$$C_1 = D_S\, D_O^{-1}\, \Theta_a^{-1} \qquad (4)$$

$$C_2 = k_a\, \Theta_a^{-1} \qquad (5)$$

$$C_3 = k_a\, \Theta_a^{-2} \qquad (6)$$

These indices are based on equations of Groenevelt *et al.* (1984) and were tested by Dörner *et al.* (2012), Uteau *et al.* (2013), and Mordhorst *et al.* (2017) for the characterization of the pore functioning. Indices emphasize the functional fraction of Θ_a contributing to the diffusive (C_1) or convective gas transport (C_2 and C_3) (Mordhorst *et al.*, 2017). Soils with similar pore-size distribution and pore continuities are indicated by analogous C_2 values, while C_3 is supposed to provide information about changes in pore functioning induced by management (Groenevelt *et al.*, 1984).

The diffusion-based index for the tortuosity (τ) (Moldrup *et al.*, 2001) was used here as well:

$$\tau = (D_O\, \Theta_a\, D_S^{-1})^{0.5} \qquad (7)$$

Statistical analyses

The statistical software R (R Development Core Team, 2018) was used to evaluate the data. The statistical evaluation of parameters (i.e., air-filled porosity, air permeability, oxygen diffusivity, and continuity indices) started with the definition of an appropriate linear statistical mixed model (Verbeke and Molenberghs, 2000) This model included the PIMs (NFNP, FNP and CP), the depths (0.45 - 0.55m and 0.55 - 0.65 m) and the water regime (i.e., field conditions or drained to defined matric potential (i.e., Ψ_m = -6 kPa)) as well as all their interaction terms (two-fold, three-fold and four-fold) as fixed factors. The sampling cylinder was regarded as random factor. The data was assumed to be normally-distributed and to be heteroscedastic. These assumptions are based on a graphical residual analysis. Multiple contrast tests (e.g., see Bretz *et al.,* 2011, Schaarschmidt and Vaas, 2009) were used in order to compare the several levels of the influence factors.

RESULTS AND DISCUSSION

The impact of management practices on botanical composition was remarkable (Figure 1), where the non-fertilized naturalized pasture (NFNP) showed an intense moss cover (Figure 1a), which was not observed in FNP (Figure 1b) and CP (Figure 1c). In NFNP, acidification led to an increase in mosses, dead grass and low forage value as *Anthoxanthum odoratum* L., was frequently observed on acidified agriculturally used land or, for example, between two lime applications (Yu *et al.*, 2010). FNP and CP showed a more intense growth (Figure 1b and 1c), which was previously described in Ordóñez *et al.* (2018). For FNP and CP, the application of lime reduced the exchangeable aluminum (Al^{3+}) in the soil solution, changing the ecological condition and preventing the growth of mosses, while the addition of fertilizers further strengthened the growth of grasses with high forage value (as *L. perenne*), furthermore, increasing the leaf-area-ratio and, consequently, the yield of the pasture (CP = 714 kg ha^{-1} and FNP = 2,306 kg ha^{-1} as presented in Ordóñez *et al.* (2018)). Besides these commonalities in botanical composition of the pasture improvement strategies slight differences were visible for FNP and CP: the amount in weeds (i.e., herbaceous plants like *P. lanceolata* and *H. radicata*) increased in FNP compared with CP where the initial botanical composition was eli-

Figure 1. Botanical composition of investigated plots in the experimental field at Universidad Austral de Chile (EEAA) in Valdivia, Chile as influenced by pasture improvement managements (PIMs): A) NFNP – non-fertilized naturalized pasture, B) FNP – fertilized naturalized pasture, C) CP – cultivated pasture. For more details about PIMs see 'Soil material' section (2.1) or Zúñiga *et al.* (2015); Salas *et al.* (2016), and Ordóñez *et al.* (2018). The area of the image sections shown are approximately 0.5 m^2 in size.

Figura 1. Composición botánica de las parcelas investigadas en el campo experimental de la Universidad Austral de Chile (EEAA) en Valdivia, Chile de acuerdo con las estrategias de mejoramiento de praderas (PIMs): A) NFNP – pradera natural sin fertilización, FNP – pradera natural con fertilización, CP – pradera sembrada. Para obtener más detalles sobre PIMs, consulte la sección "Material del suelo" (2.1) en Zúñiga *et al.* (2015); Salas *et al.* (2016), y Ordóñez *et al.* (2018). El área de las secciones de imagen mostradas es de aproximadamente 0,5 m^2.

minated chemically (by applying Glyphosate) and physically (due to ploughing and harrowing). The rooting intensity increased in the order: NFNP < CP < FNP (data not shown). For NFNP the rooting intensity was reduced due to decreased plant growth, while in CP, tillage destroyed the pore continuity (e.g. created by biopores), or even may have caused the occurrence of platy structures (rooting barriers, Dörner and Horn, 2006). In NFNP conservation of soil structure in the soil profile was observed as discussed in Ordóñez *et al.* (2018). For grasses, most of the roots (i.e., >50%) are found within 0-20 cm soil depths while herbaceous plants are known for their ability to grow into larger depths (Perkons *et al.*, 2014; Moreno *et al.*, 2005). The results presented in this study underline the interaction of management practices, botanical composition and soil properties of pastures as also discussed in Ordóñez *et al.* (2018). Differences in botanical composition result in specific rooting intensities and root distribution (Głąb and Kacorzyk, 2011). Since continuous and less tortuous pores are formed with the decay of the roots (Pagenkemper *et al.*, 2013) an impact on pore capacities and functions was found, which in the case of FNP implied the possibility to obtain water from deeper soil horizons in one of the driest summers in the last 50 years in southern Chile as presented in Ordóñez *et al.* (2018).

Although, PIMs and consequently botanical compositions did not significantly ($p > 0.05$) impact on pore capacities (total porosity (Figure 2), general trends in the change in volumetric water contents and air-filled pore volumes (Figure 3)) or pore functions in terms of air permeability (Figure 4a), D_s/D_0 (Figure 4b) or pore indices (τ, C_1, C_2, C_3 (Figure 5 and Figure 6)) can be observed (Table 2). Median values of total porosity (Figure 2) reflect the andic properties of the studied site as also stated in the same soil for Zúñiga *et al.* (2015) and Ordóñez *et al.* (2018). Total porosity decreased with depth for NFNP and FNP and was higher for NFNP than for FNP (Figure 2). CP showed no depth-dependent trend. Air-filled porosity (Figure 3a) decreased with increasing depth (NFNP and NFP) or increased with increasing depth while volumetric water content behaved oppositely (Figure 3b). The values underline the relatively high pore volumes and air-capacities of volcanic ash soils, which is in line with results presented by Dörner *et al.* (2010, 2011, and 2015). However, air capacities presented in this study are higher, possibly caused by an over-estimated specific particle density which according to Zúñiga *et al.* (2015), is 2.38 Mg m^{-3} in the sampled depths. However, specific particle densities in soils influenced by volcanic ashes can be as low as 1.76 Mg m^{-3} (Zúñiga *et al.*, 2015).

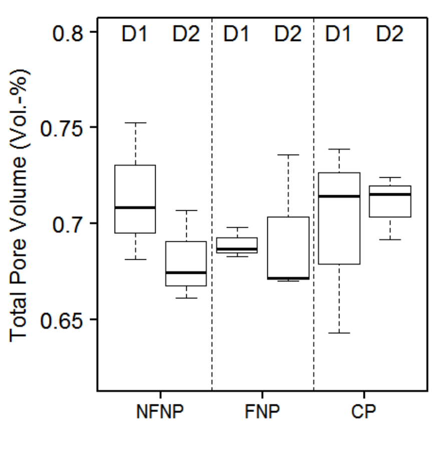

Figure 2. Boxplots for total pore volume at two soil depths (D1: 0.45-0.55 m; D2: 0.55-0.65 m) for three pasture improvement managements NFNP (non-fertilized naturalized pasture), FNP (fertilized naturalized pasture), and CP (cultivated pasture).

Figura 2. Gráficos de cajas para volumen total de poros a dos profundidades (D1: 0,45-0,55 m; D2: 0,55-0,65 m) para tres estrategias de mejoramiento de praderas NFNP (pradera natural sin fertilización), FNP (pradera natural con fertilización), y CP (pradera sembrada).

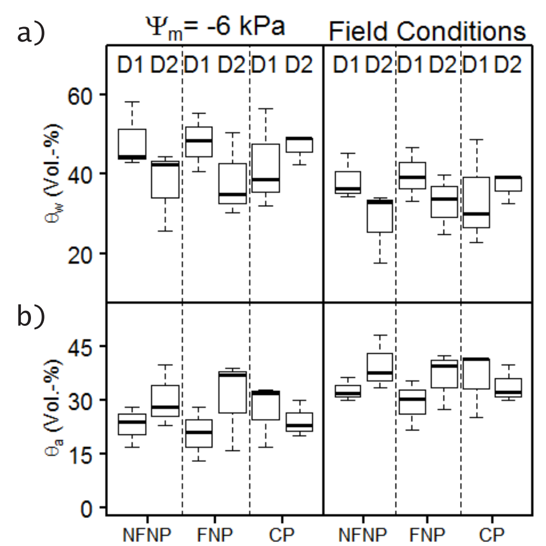

Figure 3. Boxplots for: a) air-filled porosity (θ_a), and b) volumetric water content (θ_w) versus soil depth (D1: 0.45-0.55 m; D2: 0.55-0.65 m) for water contents at ψ_m of -6 kPa (left) and at field conditions (right columns) and for the pasture improvement managements NFNP (non-fertilized naturalized pasture), FNP (fertilized naturalized pasture) and CP (cultivated pasture).

Figura 3. Gráficos de cajas para: a) poros saturados de aire (θ_a), y b) contenido volumétrico de agua (θ_w) versus profundidad de suelo (D1: 0,45-0,55 m; D2: 0,55-0,65 m) para contenidos de agua a -6kPa de ψ_m (izquierda) y a condiciones de campo (columnas derechas) para tres estrategias de mejoramiento de praderas NFNP (pradera natural sin fertilización), FNP (pradera natural con fertilización), y CP (pradera sembrada).

The water contents under field conditions (Figure 3a) range between field capacity at Ψ_m = -6 kPa (Figure 3b) and the permanent wilting point (Ψ_m = -1500 kPa) according to Ordóñez *et al.* (2018). The statistical analysis showed significant impacts of the water content (i.e., measured under field conditions or under defined matric potential (Ψ_m = -6kPa)) on air-capacities (see supplementary data for t-values; dF = 12; $p \leq 0.05$). Such equilibration to defined matric potential also impacted the volumetric water content (see supplementary data for t-values; dF = 12; $P \leq 0.01$).

The impact of PIMs on pore functions is elucidated in Figures 4a and 4b and Tables 2 and 3. The air permeability (k_a) ranged from mean to very high (Table 3). Both, the air permeability (k_a, Figure 4a) and the relative oxygen diffusion coefficient (D_s/D_0, Figure 4b) increased with soil depth for each PIMs. This depth-dependency within each PIM was especially distinct for FNP that could be related to high diversity species and the effect of roots in depth. While drainage seemed to impact values of k_a only weakly, values of D_s/D_0 were markedly increased due to drainage. These increased values for k_a and D_s/D_0 are in line with expectations based on data in Table 1 for the air-filled porosity (Figure 3a) and water content (Figure 3b). The statistical analysis showed a significant impact of water content on air permeability within the upper depth of FNP and the lower depth of CP (t = 4.041; dF = 12; $p < 0.01$ and; t = 4.086; dF = 12; $p < 0.01$, respectively). The values of D_s/D_0 are remarkably high, especially under field conditions with values that are comparable to sandy soils with high air-filled porosity (Moldrup *et al.*, 2000); or with a well-structured, more silty soil (Mordhorst *et al.*, 2017). Much lower values were found for European soils rich in clay (Uteau *et al.*, 2013) or for biopore walls of these soils (Haas and Horn, 2018). The ratio D_s/D_0 (Figure 4b) was significantly influenced by drainage to -6 kPa in the upper subsoil (FNP, t = 3.82; dF = 12; $p \leq 0.05$) and in the lower part (NFNP and CP with t = 3.22; dF = 12; $p \leq 0.05$ and t = 4.565; dF = 12; $p \leq 0.01$; respectively). The tortuosity index τ (Figure 5a) increased (NFNP) or decreased, indicating a better pore functioning, with depth (FNP and CP) for Ψ_m = -6 kPa. Here, values scattered more intensively compared to field conditions, where τ decreased with increasing depth (NFNP and CP) or increased with depth (FNP).

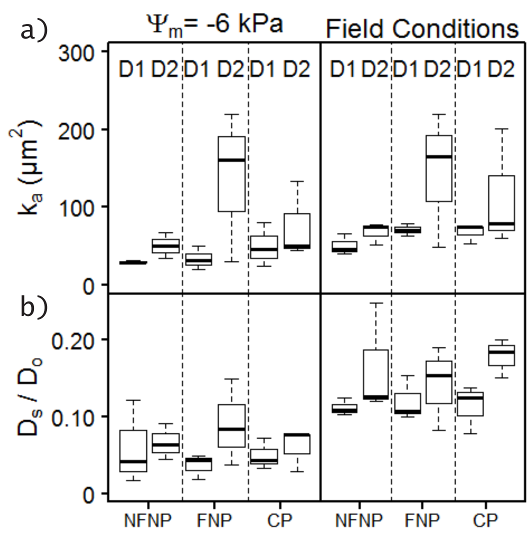

Figure 4. Boxplots for: a) air permeability (k_a) and b) relative oxygen diffusion coefficient (D_s/D_0) versus soil depth (D1: 0.45-0.55 m; D2: 0.55-0.65 m) for water contents at ψ_m of -6 kPa (left) and at field conditions (right columns) and for the pasture improvement managements NFNP (non-fertilized naturalized pasture), FNP (fertilized naturalized pasture) and CP (cultivated pasture).

Figura 4. Gráficos de cajas para: a) permeabilidad de aire (k_a), y b) coeficiente de difusión relativa de oxígeno (D_s/D_0) versus profundidad de suelo (D1: 0,45-0,55 m; D2: 0,55-0,65 m) para contenidos de agua a -6kPa de ψ_m (izquierda) y en condiciones de campo (columnas derechas) para tres estrategias de mejoramiento de praderas NFNP (pradera natural sin fertilización), FNP (pradera natural con fertilización), y CP (pradera sembrada).

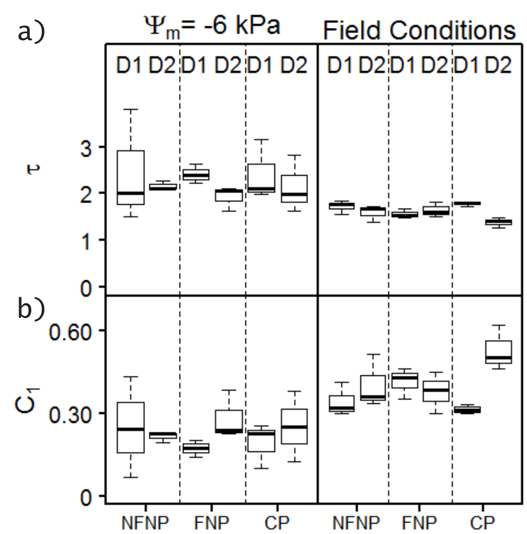

Figure 5. Boxplots for a) tortuosity (τ) and b) continuity index (C_1) versus soil depth (D1: 0.45-0.55 m; D2: 0.55-0.65 m) for water contents at ψ_m of -6 kPa (left) and at field conditions (right columns) and for the pasture improvement managements NFNP (non-fertilized naturalized pasture), FNP (fertilized naturalized pasture) and CP (cultivated pasture).

Figura 5. Gráficos de cajas para: a) tortuosidad (τ), y b) índice de continuidad (C_1) versus profundidad de suelo (D1: 0,45-0,55 m; D2: 0,55-0,65 m) para contenidos de agua a -6kPa de ψ_m (izquierda) y en condiciones de campo (columnas derechas) para tres estrategias de mejoramiento de praderas NFNP (pradera natural sin fertilización), FNP (pradera natural con fertilización), y CP (pradera sembrada).

Table 2. Mean values and standard deviations in parenthesis of pore capacities parameters (Θ_t – total pore volume; Θ_w – water content and Θ_a – air-filled porosity in Vol.-%) and of pore functions (k_a – air permeability (μm^2); D_s/D_0 – relative oxygen diffusion coefficient; τ – tortuosity and pore indices (C_1, C_2 and C_3) for measurements conducted: a) under field conditions and b) at defined matric potential (Ψ_m = -6kPa). The treatment considered different pasture improvement managements (PIMs): NFNP – non-fertilized naturalize pasture, FNP – fertilized naturalized pasture, CP – cultivated pasture and soil depths (D1: 0.45-0.55 m; D2: 0.55-0.65 m).

Tabla 2. Valores promedio y desviaciones estándar en paréntesis de parámetros de capacidad de poros (Θ_t – volumen total de poros; Θ_w – contenido de agua y Θ_a – poros llenos de aire en Vol.-%) y de funciones de poros (k_a – permeabilidad de aire (μm^2); D_s/D_0 – coeficiente de difusión relativa de oxígeno; τ – tortuosidad y índices de poros (C_1, C_2 y C_3) para mediciones llevadas a cabo: a) en condiciones de campo y b) a un potencial mátrico definido (Ψ_m = -6kPa). Los tratamientos consideran distintas estrategias de mejoramiento de pradera (PIMs): NFNP – pradera natural sin fertilización, FNP – pradera natural con fertilización, CP – pradera sembrada y por la profundidad de suelo (D1: 0,45-0,55 m; D2: 0,55-0,65 m).

	Θ_t	Θ_w	Θ_a	k_a	D_s/D_0	τ	C_1	C_2	C_3
		Vol.-%		μm^2	%			-	
a) Field conditions									
NFNP – D1	71.4 (3.6)	38.6 (5.8)	32.8 (3.3)	50.1 (13.8)	11.2 (1.1)	1.72 (0.14)	0.34 (0.06)	151.3 (27.9)	460.2 (60.7)
NFNP – D2	68.1 (2.4)	28.3 (9.1)	39.8 (7.7)	67.7 (14.8)	16.5 (7.2)	1.59 (0.18)	0.40 (0.10)	170.6 (30.1)	439.4 (112.5)
FNP – D1	68.9 (0.7)	39.8 (6.8)	29.2 (7.1)	70.8 (8.1)	12 (2.9)	1.56 (0.11)	0.42 (0.06)	250.1 (47.7)	922.2 (403.3)
FNP – D2	69.3 (3.7)	32.8 (7.6)	36.5 (8.1)	144.7 (87.9)	14.2 (5.5)	1.64 (0.17)	0.38 (0.08)	374.2 (189.8)	989.2 (380.9)
CP – D1	68.9 (5.0)	33.9 (13.4)	36.0 (9.4)	67.5 (12.7)	11.4 (3.2)	1.78 (0.05)	0.32 (0.02)	202.2 (88.0)	644.3 (477.8)
CP – D2	71.1 (1.6)	37.1 (3.9)	34.0 (5.2)	113.5 (76.9)	17.9 (2.5)	1.38 (0.11)	0.53 (0.08)	318.4 (166.7)	908.8 (346.2)
b) Defined matric potential									
NFNP – D1		48.6 (8.5)	23.0 (5.6)	29.0 (2.0)	6.0 (5.5)	2.45 (1.21)	0.25 (0.18)	130.2 (25.4)	611.3 (285.6)
NFNP – D2		37.4 (10.3)	30.3 (8.7)	49.9 (16.3)	6.7 (2.4)	2.15 (0.11)	0.22 (0.02)	163.2 (14.5)	561.6 (126.2)
FNP – D1		48.1 (7.4)	20.1 (7.5)	33.5 (14.9)	3.7 (1.6)	2.42 (.21)	0.17 (0.03)	167.1 (63.6)	903.5 (442.1)
FNP – D2		38.7 (10.6)	30.7 (12.7)	136.8 (97.8)	9.1 (5.6)	1.92 (0.27)	0.28 (0.09)	394.2 (194.4)	1255.2 (168.3)
CP – D1		42.4 (12.7)	27.3 (9.0)	49.9 (28.5)	5.0 (2.0)	2.42 (0.65)	0.19 (0.08)	196.5 (106.4)	854.3 (666.5)
CP – D2		46.9 (3.8)	24.3 (5.1)	75.8 (50.5)	6.0 (2.7)	2.14 (0.61)	0.25 (0.13)	294.9 (134.5)	1184.4 (330.8)

Values of C_1 are shown in Figure 5a. The impact of sampling depth and drainage followed a trend reversed to that of τ since the calculations of both parameters are based on D_s/D_0 and air-filled porosities (Equations 4 and 7). The air-permeability-based indices C_2 and C_3 (Figures 6a and 6b) increased for larger soil depth (exception: C_3 for NFNP under field conditions) and was lower for field conditions than for Ψ_m = -6 kPa. The impact of drainage was more pronounced for C_2 than for C_3. Lowest values were found for NFNP while values scattered more intensively for Ψ_m = -6 kPa compared to field conditions. Larger values of continuity indices (C_1, C_2, C_3), and small values for τ indicate a better pore functioning, as indicated by Equations 4-7. However, the improvement of pore functions in the subsoil by PIMs is most likely caused by more intense rooting and by the resulting formation of highly connected, less tortuous, and thus improved ecologically functioning pores. Besides these trends, no statistically significant differences in pore indices were found, possibly cau-

Table 3. Classification of air permeability (k_a) as described in Horn and Fleige (2003) for measurements conducted: a) under field conditions and b) at defined matric potential (Ψ_m = -6kPa) as influenced by pasture improvement managements (PIMs): NFNP – non-fertilized naturalize pasture, FNP – fertilized naturalized pasture, CP – cultivated pasture and soil depths (D1: 0.45-0.55 m; D2: 0.55-0.65 m). Class values: 3 – *Mean*, 4 – *High*, 5 – *Very high*.

Tabla 3. Clasificación de la permeabilidad de aire (k_a) descrita por Horn y Fleige (2003) para mediciones llevadas a cabo: a) en condiciones de campo y b) a un potencial mátrico definido (Ψ_m = -6kPa). Los tratamientos consideran distintas estrategias de mejoramiento de pradera (PIMs): NFNP – pradera natural sin fertilización, FNP – pradera natural con fertilización, CP – pradera sembrada y por la profundidad de suelo (D1: 0,45-0,55 m; D2: 0,55-0,65 m). Valores de referencia: 3 – *Promedio*, 4 – *Alto*, 5 – *Muy alto*.

	Class value	
	Field conditions	**Ψm = -6kPa**
NFNP – D1	4	3
NFNP – D2	4	4
FNP – D1	4	3
FNP – D2	5	5
CP – D1	4	4
CP – D2	5	4

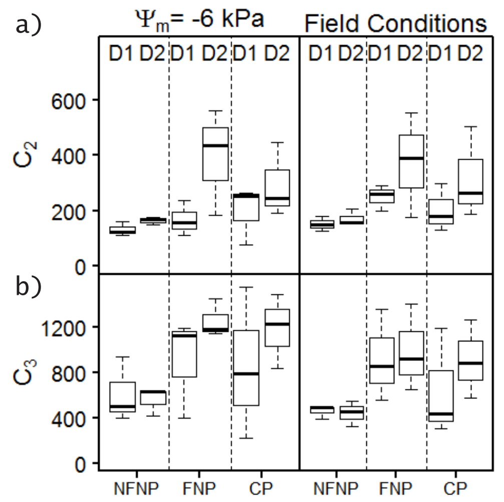

Figure 6. Boxplots for: a) continuity index (C_2) and b) continuity index (C_3) versus depth at two soil depths (D1: 0.45-0.55 m; D2: 0.55-0.65 m) for water contents at ψ_m of -6 kPa (left) and at field conditions (right columns) and for three pasture improvement managements NFNP (non-fertilized naturalized pasture), FNP (fertilized naturalized pasture) and CP (cultivated pasture).

Figura 6. Gráficos de cajas para: a) índice de continuidad (C_2), y b) índice de continuidad (C_3) versus profundidad de suelo (D1: 0,45-0,55 m; D2: 0,55-0,65 m) para contenidos de agua a -6kPa de ψ_m (izquierda) y en condiciones de campo (columnas derechas) para tres estrategias de mejoramiento de praderas NFNP (pradera natural sin fertilización), FNP (pradera natural con fertilización), y CP (pradera sembrada).

sed by the high spatial heterogeneity of the measured values. This heterogeneity effect could be reduced by increasing the number of samples or the size of the samples. However, the results clearly indicate that soils of grassland after application of PIMs underlie a transition to a new stage of equilibrium in pore structure. These changes need time and can take several decades, especially if subsoils are considered (Pagenkemper *et al.*, 2013; Uteau *et al.*, 2013).

CONCLUSIONS

This study aimed at quantifying the impact of pasture improvement strategies (PIMs) of an Andisol in southern Chile on subsoil pore functions and pore capacities.

The application of PIMs resulted in altered soil capacities and pore functions, consequently, PIMs are influencing the amount of plant available water and oxygen available for the respiration of the roots, particularly for the case of fertilized but not-ploughed site (FNP).

The obtained parameters and data give a first data base for subsoils (0.45 - 0.65 m) of pastures with varying management and can be used for dynamic flux simulations and estimation of the ecosystem functioning to better understand interactions of the plant-soil-atmosphere-continuum.

PIMs were established 5 years before sampling. Measurements should be repeated in periodic manner to better understand processes in Chilean ash soils as influenced by differing management practices.

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