



Soil changes associated with land use in volcanic soils of Patagonia developed on dynamic landscapes

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ABSTRACT

This paper aimed to identify indicators of soil degradation in volcanic soils developed in the ecotone between the Andean Forests and the Patagonian steppe. The study area is located in the Percy River Basin, Argentine, on alluvial fans with volcanic soils. Sampling was conducted in two adjacent hillslopes where native forest was replaced by a rangeland with grass-shrub vegetation and a 32-years old *Pinus radiata* plantation. Sectioned and bulk soil samples were collected along three transects in each land cover up to 40 cm depth. Two forest patches of *Maytenus boaria* were selected as controls. Physical, chemical and magnetic properties were analyzed. Native forest soils were rich in silt fraction, organic matter and non-crystalline minerals, and presented the lowest values of magnetic susceptibility. Rangeland and plantation soils differed from forest soils in these properties. Soil changes were mainly associated to changes in mineralogy resulting from soil desiccation and to the selective removal of fine particles by erosion, together with differences in the effects of recent volcanic events on the soils. Changes in soils associated with land use affected key properties related to pedogenetic processes. Magnetic susceptibility, organic matter content, texture, and pH NaF were key for understanding soil degradation processes in this dynamic environment.

1. Introduction

Worldwide, land use change, driven by the need to provide goods and services to human populations, have deeply affected land health by accelerating the soil degradation processes (Gaspar et al., 2013). In different forest ecosystems, the change of land use was proved to diminish soil quality (Cerrí et al., 1991; Navas et al., 2008). While chemical soil properties changes, driven by the transition from forest to rangeland, can be highly variable and even positive (Guo and Gifford, 2002; Murty et al., 2002), different authors agree that overgrazing causes physical soil degradation (Belsky and Blumenthal, 1997; Mekuria et al., 2007). Changes occurring in the soil depend, among other factors, on intrinsic soil properties, initial fertility and also domestic animals stocking rates (Binkley et al., 2003; Álvarez-Yépez et al., 2008).

Nowadays there is a tendency to increase forest cover in some countries, and forest plantations are being established across the globe

for commercial and restoration purposes (Chazdon, 2008). However, the effects of afforestation in ecosystem and soil are under discussion. Changes in biodiversity, hydrological cycle and soil properties are the most challenged when natural vegetation is replaced by exotic conifers. Changes in soil properties may include chemical, biological, physical and morphological modifications in the soil profile (Amiotti et al., 2000; Broquen et al., 2000; Guo and Gifford, 2002).

The Patagonian Andean Region, despite being seen as a conserved and natural area, is subjected to intense land use changes. Deforestation, livestock grazing, agriculture and urbanization have triggered several land degradation processes (Carabelli and Scoz, 2016). The subhumid sector, corresponding to the transition (ecotone) between the Andean Forests and the Patagonian steppe, is a fragile ecosystem with the highest anthropic pressure and high losses of native forests (Veblen et al., 1999). Livestock grazing has accelerated the soil degradation processes in different environments of Patagonia (Ares et al., 1990; Chartier et al., 2013), and the most drastic changes were found in the sub-humid sector (Bertiller and

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Bisigato, 1998), where rangeland soils are supposed to have a very slow recovery, with no change in organic carbon 15 years after grazing exclusion (Nosetto et al., 2006).

Nowadays, plantations with exotic conifers are also concentrated in the sub-humid sector, being promoted as an economic activity while a palliative to erosion (Irisarri and Mendía, 1997). Although there is little local available information, it was shown that soil fertility is depleted where exotic conifers are planted in very fertile soils, both, replacing native forests (Gobbi et al., 2002) or even degraded rangelands (La Manna et al., 2016a).

The landscape of the Patagonian Andean Region is dominated by glacial geomorphs covered by volcanic ash deposits. In the subhumid sector, with precipitations around 600–800 mm per year, the volcanic ash weathered to imogolite, a non-crystalline aluminosilicate with strong affinity for water, metal cations and organic molecules (Besoin, 1985; McDaniel et al., 2012). In this xeric environment, imogolite may dehydrate to crystalline clays such as halloysite, which is a 1:1 layer silicate (Besoin, 1985; Parfitt and Wilson, 1985). The presence of non-crystalline aluminosilicates is key not only for determining land productivity but also resistance to erosion (McDaniel et al., 2012). Overgrazing, mainly if soil loses its cover, might result in desiccation of soil, allowing non-crystalline materials to evolve to halloysite (Parfitt and Wilson, 1985). On the other hand, in a landscape with a rugged topography, the slope position might modify the soil water regime, altering the degree of weathering processes and, thus, the formation of non-crystalline minerals. The influence of land use and slope position on volcanic soils has been poorly addressed in Patagonia.

Several studies around the world have considered physical and chemical soil properties to assess soil quality in response to degradation processes (Bastida et al., 2008; Zucca et al., 2010; Moebius-Clune et al., 2011). Soil organic carbon content has been considered to be a good indicator of environmental quality for mineral soils because of the influence that organic matter has on key functional properties, such as fertility, soil structure and water relations (Ogle and Paustian, 2005). Soil organic carbon resulted a key variable for evaluating soil changes associated with different land use (Quijano et al., 2017) and slope positions (Powers and Schlesinger, 2002).

Magnetic susceptibility is also a soil property often considered in studies about soil degradation and erosion (De Jong et al., 1998; Royall, 2007; Quijano et al., 2014). Mass magnetic susceptibility (χ) is a fast and non-destructive technique to quantify the degree of induced magnetization of a soil sample in response to an applied magnetic field. Soil magnetic susceptibility depends on the concentration of the ferrimagnetic minerals and is sensitive to the magnetic mineralogy, grain size, shape and orientation of the mineral grains (Dearing, 1999; Magiera et al., 2006). Iron oxides and hydroxides in soils unaffected by anthropogenic pollution are valuable pedo-environmental indicators due to its sensitivity to physico-chemical conditions in sedimentary environments, including soil forming processes (Torrent et al., 2010), degree of pedogenesis (Geiss and Zanner, 2006), weathering processes and biological activities (Dearing et al., 1996; Singer et al., 1996). Enhancement of magnetic susceptibility due to the secondary formation of iron compounds (i.e. magnetite and maghemite) through pedogenic processes (Mullins, 1977; Maher, 1986; Van Dam et al., 2004) is used to identify differences between topsoil and subsoil. Several soil studies have used magnetic susceptibility as a tracer of the topsoil movement to evaluate soil erosion and soil degradation (Gennadiev et al., 2002; Royall, 2007; Sadiki et al., 2009; Jordanova et al., 2014), however, magnetic susceptibility studies were never carried out in Holocene volcanic soils of Patagonia Argentina.

1.1. Objectives

The aim of this study was to identify indicators of soil degradation in volcanic soils developed on dynamic landscapes of the forest-steppe ecotone in the Patagonian Andean region. Two specific objectives were considered: i) to evaluate some physical, chemical and magnetic soil properties under different land use (native forest, forestation and rangeland); ii) to assess the effect of slope position on soil properties under different land uses (forestation vs. rangelands).

2. Materials and methods

The study was carried out in the Percy River Basin (42°54'00" S; 71°22'12" W), a rugged topography near to Esquel Town, in the forest-steppe ecotone of the Patagonian Andean Region. The Percy River Basin is one of the most fragile areas of the Chubut province in Argentina, with one of the oldest European settlements in Patagonia. This basin is characterized by large eroded areas, the degradation of riparian systems and high losses of native forests (Kutschker et al., 2009; Miserendino et al., 2016). Soils were developed from holocenic volcanic ashes and ecosystem degradation is worsened because of the high erodibility of volcanic soils in this area (La Manna et al., 2016a).

The geomorphology of the study area corresponds to alluvial fans (Andrada de Palomera, 2002), and soils have been mapped in a unique unit characterized as dissected phase of Entic Haploxerolls (Phaeozem vitric, according to the World reference base (WRB) of the International soil classification system) and Typic Vitrixerands (Andosol vitric) (Irisarri et al., 2000).

The original vegetation of the study area is composed of a forest dominated by *Maytenus boaria* Mol with a shrub stratum, which is still preserved as isolated patches in certain sectors. Throughout the last century, the forest matrix has been degraded and was mostly replaced by grass-shrub vegetation, as a result of overgrazing and fires. Two representative situations of forest replacement were considered: a) by rangeland; b) by afforestation with exotic conifers.

Sampling was conducted in two adjacent hillslopes with 10° mean slope and south-east aspect (155°) (Fig. 1). One of the hillslopes, present grass-shrub vegetation (80% covered), dominated by *Rumex acetosella* L., a perennial and invasive exotic herbaceous plant (Franzese and Ghermandi, 2012) accompanied by species indicative of degradation as *Acaena splendens* Hook. & Arn and *Mulinum spinosum* (Cav.) Pers. and grasses of low palatability as *Pappostipa speciosa* Trin. et Rupr. This rangeland has been used for grazing for the last 100 years. On the other hand, the adjacent hillslope corresponds to a 32 years *Pinus radiata* D. Don plantation from 1985. Two patches of native forests of *M. boaria* were also sampled. They are located near the rangeland and the plantation, in sites with moderate slope (8°) and south-east aspect (Fig. 1).

Three soil pits up to 150 cm depth were excavated to examine the soil profiles in each land use (Fig. 2) that were described according to USDA (Schoeneberger et al., 1998). Furthermore, in control forests and in the high, medium and lower parts of hillslopes of rangeland and plantation soil profiles were established to assess the vertical variation of soil properties as well as along the slope.

In the patches of the native forests, a total of 11 points were sampled up to a depth of 40 cm. Of these, five were sectioned at 5 cm depth increments and the other six were 0–40 cm depth bulk samples. Along the hillslopes, of forestation and rangeland, three transects placed 35 m apart and parallel to the main slope, were established for each land use. The lower part of the slope corresponded to the lowest portion of the plantation, which is not exactly the end of the topographic slope. Along the transects soil samples were taken to a depth of 40 cm in 10 points that were placed 25 m apart from each other. In the sample points, 0–40 cm depth bulk samples were collected. In each transect at three slope positions (the upper, middle and lower slope) soil samples were sectioned at 5 cm depth increments. Although this sampling was possible in most of the points, some soils were too loose in depth preventing an accurate fractioning. Where the samples could not be correctly sectioned up to 40 cm, 0–40 cm depth bulk samples were also taken. Where the samples could be appropriately sectioned up to 40 cm, the average of soil variables of the sectioned samples was considered for bulk sample data analysis. Thus, 11, 30 and 30 sampling points 0–40 cm depth were included for native forests, plantation and rangeland, respectively. A total of 39, 68 and 47 sectioned samples were obtained for native forests, plantation and rangeland, respectively. In all cases, metal tools were avoided in order to not contaminate samples with metals.

Soil samples were air-dried and passed through a 2 mm sieve. Total dry weight and percentage of coarse fragments were determined. Texture was

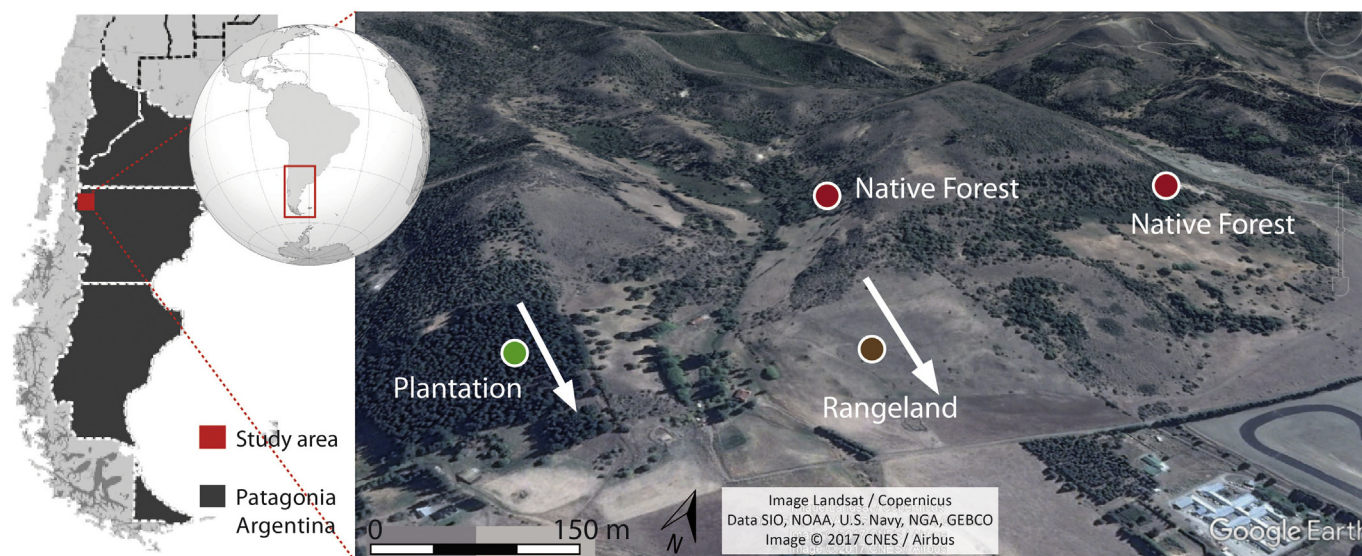


Fig. 1. Location of the study area in Patagonia and study sites. White arrows show the direction of sampling. Image from Google Earth (2017).

analyzed by Coulter laser granulometer after destruction of organic matter with 10% H_2O_2 at 80 °C. Organic matter (SOM) was analyzed by loss on ignition (Davies, 1974). The pH (soil–water ratio 1:1) and pH in NaF 1 N (1:50) were measured using pH-meter. pH NaF measured at 2 and 60 min is considered an indicator of non-crystalline aluminosilicates in soils (Fiedes and Perrot, 1966). Calcium carbonate content was also analyzed in selected samples with a pressure calcimeter.

Mass magnetic susceptibility (χ , $10^{-8} \text{ m}^3 \text{ kg}^{-1}$) was measured at low (χ_{lf} , 0.47 kHz) and high (χ_{hf} , 4.7 kHz) frequency fields on the soil fine fraction (< 2 mm). Soil samples were prepared in standard non-magnetic 10 cm^3 cylindrical pots and measured with a Bartington MS2 magnetic susceptibility meter linked to a MS2B dual frequency sensor via a simple coaxial cable (Bartington Instruments Ltd., Oxford, UK).

Percent frequency-dependent magnetic susceptibility (χ_{fd} %) was calculated using the following equation: $\chi_{\text{fd}} \% = [(\chi_{\text{lf}} - \chi_{\text{hf}}) / \chi_{\text{lf}}] \times 100$ (Mullins and Tite, 1973). The difference between low and high frequency magnetic susceptibility values is used for qualitative studies to indicate the contribution of pedogenic fine-grained ferromagnetic particles close to the boundary between the superparamagnetic (SP < 0.02 μm) and the stable single domain grains (SSD 0.02–0.04 μm) (Liu et al., 2005), whereas the low frequency magnetic susceptibility measurements are proportional to the concentration of ferrimagnetic minerals in soils (Dearing, 1999).

Geochemical analysis was performed for some selected soil samples, including five sampling points in control forest and one of the three transects (i.e., 10 sampling points) for the rangeland and the plantation soils. A total of 17, 32 and 21 samples (sectioned + bulk) were considered for native forests, plantation and rangeland, respectively. The analyses of the following elements: Ca, Mg, K, Na, Al and Fe were performed by atomic emission spectrometry using inductively coupled plasma ICP (OES) after total acid digestion with HF (48%) in a microwave oven (Navas and Machín, 2002). Concentrations, obtained after three measurements per element, were expressed in mg kg^{-1} .

The eruption of Chaitén volcano (Chile) affected the study area in 2008. In order to analyze the possible influence of recent ash in magnetic susceptibility of soils, this variable was analyzed on 20 samples that had been taken near to Esquel town six months after the eruption. Deposited ash had been collected from flat sites with prairie vegetation during September 2008. Samples had been air dried and conserved in capped containers.

In order to analyze soil parameters in relation to land use and slope position, different approaches were boarded. To evaluate soil differences associated with land use, isolating the effect of the granulometry, a cluster analysis was carried out, considering the 0–40 cm bulk samples. The

percentages of sand and clay were included in the cluster, and non-hierarchical method, considering K-means algorithm and Euclidean distance was used to group the study samples into homogeneous groups, following the methodology proposed by Di Rienzo et al. (2013). Differences in soil properties between native forests, plantation and rangeland were analyzed for each cluster, by two-way analysis of variance (ANOVA), considering land use (3 levels) as factor. Tukey's HSD (Honestly Significant Difference) was applied as post hoc analysis when ANOVA test showed a p-value < 0,05. ANOVA assumptions (normality and homogeneity of variances) were checked by Q-Q plots, Shapiro-Wilk's W test modified and Levene's test, following Di Rienzo et al. (2013). Those variables that do not meet assumptions, were analyzed by Kruskal–Wallis test and pairwise comparisons.

Grain size fractions, magnetic susceptibility and geochemical parameters were evaluated according to land uses and sample depth, separately for each slope position (upper, middle, bottom), considering the sectioned samples. Data were analyzed by ANOVA, considering Land use and sample depth as factors, and also their interaction (Land use \times Depth). Separate tests for each sample depth were performed when the interaction Land use \times Depth was statistically significant. ANOVA assumptions were checked.

Correlation between magnetic susceptibility, grain size fractions and geochemical variables were analyzed by Pearson test. Analyses were carried out with the Infostat software (Di Rienzo et al., 2013).

3. Results

3.1. Soil profiles

Soils under forests, both in the native forest and in the plantation, presented a continuous fresh litter layer. In the native forest, Oi and Oe horizons were differentiated, with an average thickness of 2 cm. In the plantation, fresh litter and the duff layers formed a continuum with an average thickness of 4 cm.

Sequence of mineral horizons were similar in the different profiles, regardless the vegetation type and the landscape position. Soils developed from volcanic ash, deposited on glaci-fluvial materials, were deep and with little differentiation of horizons. Although the depth of the lithological discontinuity varied between the profiles, the ash deposit was deeper than 90 cm for all cases (Fig. 2).

Despite the proximity of the study sites, large textural differences were found between the profiles (Fig. 2). The grain size distribution differed

between the ash and the glaciﬂuvial material (2C2 and 2C3 horizons found in the native forest and 2C2 in rangeland proﬁles). However, the greatest textural differences were found among soil layers developed from volcanic materials. Proﬁles described in native forests showed dominance of silt fraction, presence of non-crystalline aluminosilicates (according to pH NaF values), and high contents of organic matter (Fig. 2a). These ﬁne-textured soils seem well-developed andic soils, which could be classiﬁed as Haploxerands (Andosol humic, according to the WRB). On the other hand, soils in the plantation and rangeland hillslopes varied according to slope position. Proﬁles at the middle slope, showed in Fig. 2b and c, were sandy-textured, without non-crystalline aluminosilicates, and with low contents of organic matter. These sandy-textured soils seem poorly-developed volcanic soils, which could be classiﬁed as Vitrixerands (Andosol vitric, according to the WRB).

All the volcanic proﬁles showed a negative reaction to HCl and carbonate contents were lower than 0,20%.

3.2. Soil properties in the uppermost 40 cm

As it was shown in Fig. 2, grain size greatly varied in the study proﬁles. The samples granulometry varied not only according to land use, but also within each type of vegetation. Thus, the sand fraction in the 0–40 cm bulk samples varied between 31.3 and 74.0% in the native forest, 46.5 and 92.8% in the plantation and between 43.8 and 84.8% in the rangeland. In turn, silt fraction varied between 24.1 and 64.4 in the native forest soils, 6.4 and 45.1 in the plantation and between 12.8 and 48.8 in the rangeland. This variation was related to the rugged topography and the position on the slope, as will be discussed below.

Cluster analysis allowed distinguishing two groups of samples, one where sand fraction dominates, and most of textural classes resulted loamy sand, sand and sandy loam (cluster I) and the other one which grouped samples with higher content of the silt fraction, with silt loam, loam and also sandy loam textural classes (cluster II). Most of the plantation soil samples were grouped in cluster I. On the contrary,

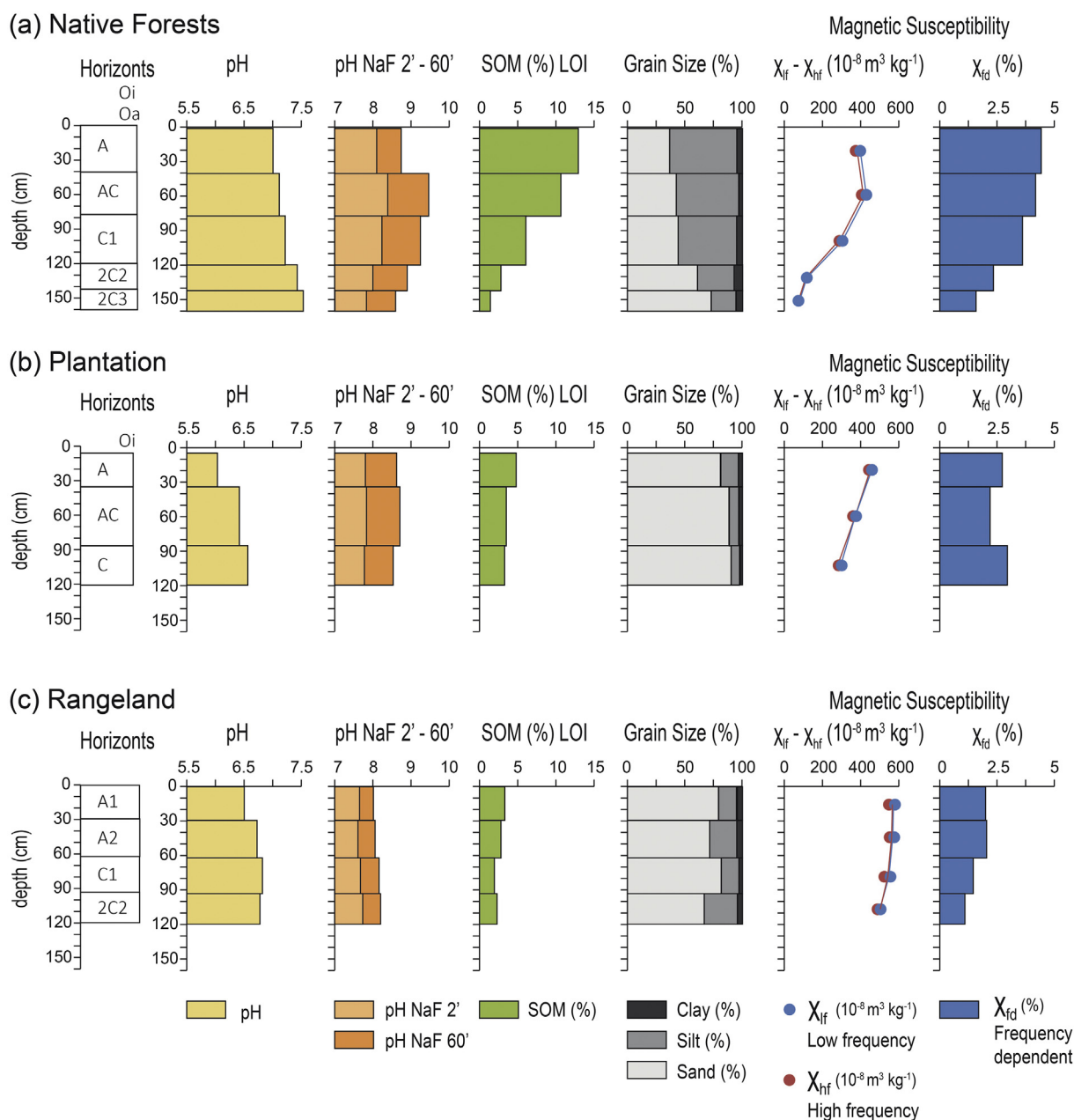


Fig. 2. Soil profiles described in native forest (a) and in middle slope of plantation (b) and rangeland (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

Soil properties according to land use. Samples (0–40 cm depth) were classified in two clusters according to texture. Different letters indicate significant differences between land uses. Those parameters statistically significant were written in bold.

Variable	Cluster I (N=34)				Cluster II (N=37)			
	Native Forest (n=3)	Plantation (n=20)	Rangeland (n=11)	p	Native Forest (n=8)	Plantation (n=10)	Rangeland (n=19)	p
pH water	6.83 ± 0.27	6.44 ± 0.10	6.57 ± 0.13	=0.366	6.77 ± 0.19	6.42 ± 0.23	6.32 ± 0.11	=0.141
pH NaF 2'	8.51 ± 0.13 b	7.92 ± 0.05 a	7.89 ± 0.07 a	= 0.030 ^Z	8.57 ± 0.08 a	7.95 ± 0.07 b	7.99 ± 0.05 b	< 0.001
pH NaF 60'	9.06 ± 0.08 b	8.51 ± 0.05 a	8.45 ± 0.07 a	< 0.001	9.06 ± 0.08 a	8.65 ± 0.07 ab	8.49 ± 0.05 b	= 0.001 ^Z
OM (%)	9.45 ± 0.58 b	3.95 ± 0.22 a	4.27 ± 0.30 a	< 0.001	12.05 ± 0.73 b	5.62 ± 0.65 a	6.17 ± 0.47 a	< 0.001
Coarse frag (%)	1.5 ± 1.4	2.4 ± 0.5	2.5 ± 0.7	=0.080 ^Z	3.4 ± 0.6 a	1.4 ± 0.5 b	2.3 ± 0.4 ab	= 0.048
χ_{if} (10 ⁻⁸ m ³ kg ⁻¹)	377.9 ± 26.8 c	433.4 ± 10.4 b	527.9 ± 14.0 a	< 0.001	384.5 ± 13.6 b	508.9 ± 12.2 a	511.6 ± 8.8 a	< 0.001
χ_{fd} %	3.4 ± 0.2 a	2.5 ± 0.1 b	2.6 ± 0.1 b	= 0.007	3.8 ± 0.1 a	3.2 ± 0.1 b	3.1 ± 0.1 b	= 0.004
Ca (mg kg ⁻¹)	17800.3 ± 1572.4	15850.0 ± 1283.8	14983.8 ± 1572.4	=0.491	23533.4 ± 1426.2	17708.6 ± 1746.7	18268.1 ± 1746.7	=0.099
Mg (mg kg ⁻¹)	3823.0 ± 451.9 ab	4612.9 ± 368.9 a	3940.3 ± 451.9 b	=0.406	4970.5 ± 456.6	4613.4 ± 559.2	3486.9 ± 559.2	=0.229
K (mg kg⁻¹)	10161.4 ± 1041.1	12557.5 ± 850.1	12293.8 ± 1041.1	=0.285	9100.6 ± 465.4 b	12738.9 ± 570.0 a	10741.6 ± 570.0 ab	= 0.020
Na (mg kg ⁻¹)	15438.4 ± 1215.4	20160.9 ± 992.4	18788.8 ± 1215.4	=0.092	14940.9 ± 912.5 b	20747.1 ± 1117.6 a	15264.1 ± 1117.6 b	= 0.032
Fe (mg kg ⁻¹)	24609.1 ± 2465.7	28350.5 ± 2013.2	24779.8 ± 2465.7	=0.462	27990.6 ± 1998.9	29972.2 ± 2446.9	29223.0 ± 2446.9	=0.820
Al (mg kg ⁻¹)	36875.6 ± 2488.4	44603.5 ± 2031.8	39142.9 ± 2488.4	=0.147	43012.0 ± 2826.0	47290.7 ± 3461.2	39788.0 ± 3461.2	=0.394

Z = indicates that the analysis performed was Kruskal Wallis test (non-parametric).

native forest and rangeland samples were grouped in cluster II. Mean comparison results for each cluster are shown in Table 1. Results showed that, even reducing the granulometry effect, great changes in soil properties were found associated with the vegetation type.

Although the maximum value of pH in water (7.7) was recorded in the native forest, and the minimum (5.0) in the plantation, no significant differences were found for this property. For both sandy and silty-textured clusters, pH NaF and soil organic matter were significantly lower where native forest was replaced. The lowest contents of organic matter were found in sandy samples of both the plantation and rangeland. According to NaF pH test, many samples showed absence of non-crystalline aluminosilicates. However, pH NaF registered in both, the native forest and silty samples of the plantation, suggests the presence of imogolite and imogolite-halloysite transition in some profiles (Irisarri, 2000). By contrast, in none of the rangeland samples, non-crystalline aluminosilicates were present.

Native forest showed significantly lower values of magnetic susceptibility, for both sandy and silty-textured soil clusters. Differences in frequency dependent magnetic susceptibility were also found, with native forest showing the highest values, but all the samples had values lower than 5%.

Magnetic susceptibility for native forest and plantation soils was higher in samples rich on fine fractions (cluster II) than in the sandy ones (cluster I). Thus, in native forest soil, χ_{if} tended to be positively correlated with clay fraction, and in the plantation, χ_{if} was positively

Table 2

Correlation between magnetic susceptibility and the different granulometric fractions for different land use. 0–40 bulk samples were considered for the analysis. Pearson correlation coefficient and p value are shown. The correlations statistically significant were written in bold.

	χ_{if}		
	Native forest	Plantation	Rangeland
Sand	0.20 (p = 0.57)	-0.72 (p < 0.001)	0.38 (p = 0.04)
Silt	-0.27 (p = 0.43)	0.70 (p < 0.001)	-0.40 (p = 0.03)
Clay	0.52 (p = 0.09)	0.78 (p < 0.001)	-0.18 (p = 0.34)

correlated with clay and silt fractions (Table 2). On the contrary, in the rangeland soils, samples grouped in cluster I tended to have higher values of χ_{if} . In rangeland samples χ_{if} was positively related to sand fraction and negatively related to silt fraction (Table 2).

Samples grouped in cluster II showed significant differences in geochemistry, with higher contents of K and Na in plantation soils (Table 1).

3.3. Soil properties along the slopes in rangeland and plantation

Fig. 3 shows how some soil properties of 0–40 cm bulk samples in rangeland and plantation vary along the slope. In rangeland and plantation, the organic matter tended to increase at the lower slope, similarly to pH NaF values. A general pattern of loss of sand fraction and enrichment in silt and clay fractions was also observed along the slope in the plantation. Thus, soils at the bottom slope were more similar to native forest soils. In the rangeland, soils at the top of the slope (Position 1) could be influenced by nearby forest patches, which would protect the soil from erosion process (see Fig. 1). For this case, soils at the upper slope showed sand and silt values similar to the found in native forests, and organic matter contents greater than those found at middle slope. From position 2 to downslope, the pattern of loss of sand fraction and enrichment in silt and clay fractions was also found in the rangeland.

Magnetic susceptibility varied along the slope and presented a different behavior regarding the granulometric fractions depending on the type of vegetation. In the rangeland, there was a general parallelism between χ_{if} and the sand fraction that were directly related along the slope, whereas the relationship between χ_{if} and the silt fraction was inverted (Fig. 3b; Table 2).

In the plantation, data dispersion was greater and the relationship between χ_{if} and particle sizes was opposite to that in rangeland. χ_{if} varied along the slope associated with fine particles. χ_{if} was directly related to clay and silt fractions but it was negatively associated with sand (Fig. 3a; Table 2).

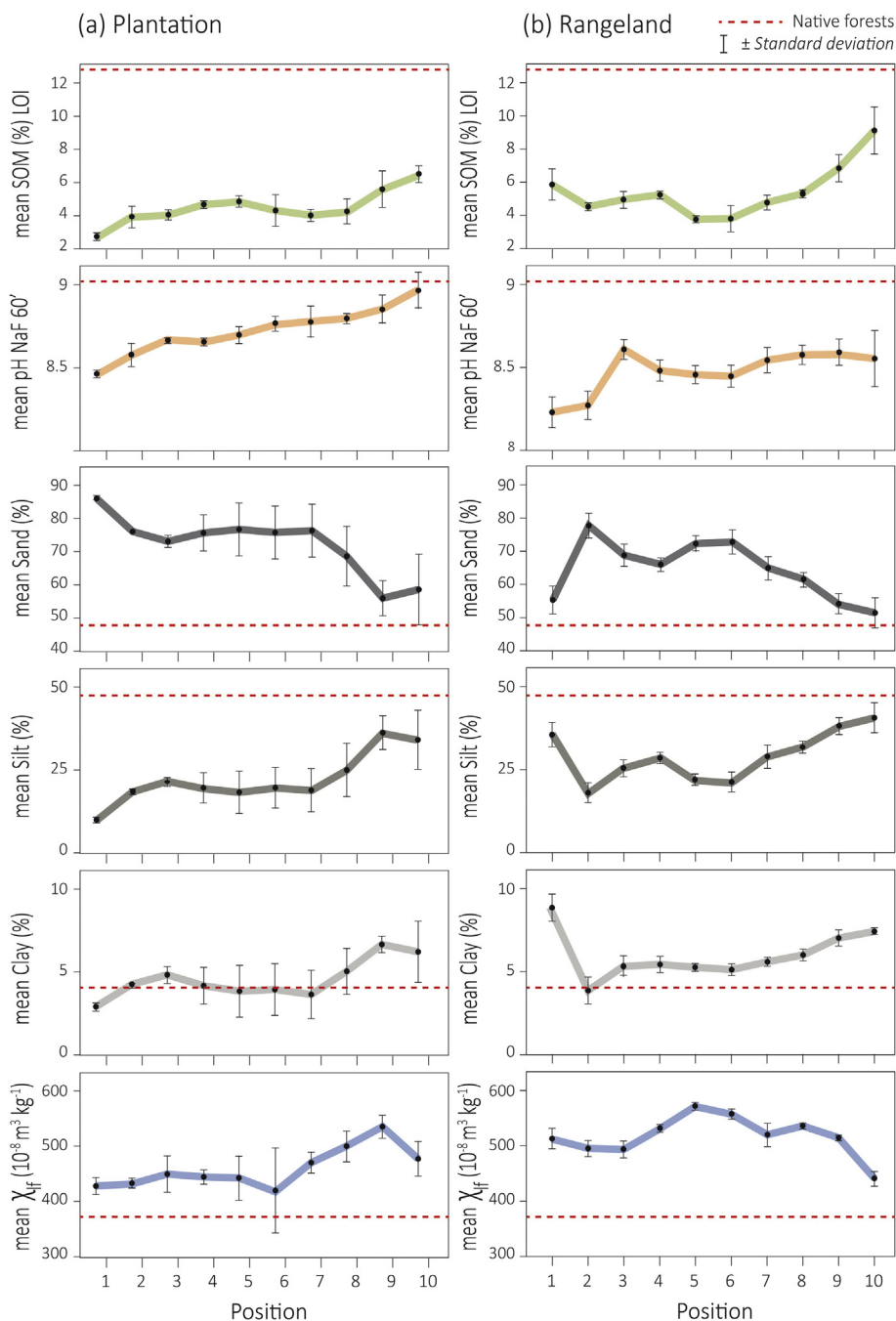


Fig. 3. Soil properties in plant plantation (a) and rangeland (b) along the slope, from Position = 1 (upper slope) to Position = 10 (bottom). Dotted line shows the mean value for native forest soils.

3.4. Soil sectioned samples - variations according to sample depth

ANOVA run with sectioned samples showed that grain size fractions, magnetic susceptibility and geochemistry varied according to the Land use factor. On the contrary, the depth factor was not significant for most of the cases, and the interaction factor (Depth × Land use) was significant just for some variables at the bottom slope (Table 3). Texture greatly varied between native forest and plantation soils all along the slope. On the contrary, rangeland soils at upper slope and at bottom had similar texture than native forest soils, with significant differences at middle slope.

Native forest presented lower values of magnetic susceptibility than rangeland and plantation, all along the soil profiles (Fig. 4; Table 3). Plantation and rangeland differed among them at the upper and middle

slope positions, and were similar at the bottom slope (Table 3), where textures tended to resemble (Fig. 3). Although the Depth factor was non-significant (p > 0.05), some tendencies were found which are shown in Fig. 4. Magnetic susceptibility showed a tendency to increase in the 5–15 cm depth interval for the different vegetation types and positions on the slope. The general shape of the curves was associated with variation in Fe content (Fig. 5), and a positive correlation between magnetic susceptibility and Fe was found (r = 0.54; p < 0.001). At the bottom slope, curves intersected in depth (Fig. 4c). The lowest values of magnetic susceptibility were recorded in the soil surface (0–5 cm). Recent volcanic ashes from Chaitén volcano, which left a minimal imprint on some soils of the area (ca. 1 mm; Tarabini, 2017) had very low values of magnetic susceptibility ($\chi_{f,r}$: $42,8 \pm 2,2 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$).

At the upper slope, the plantation soil had greater values of K, Na

Table 3

Properties of sectioned samples soils according to land use and slope position. Significant results for Land use factor of ANOVA test are shown with bold letter and asterisks.

Variable	Native Forest	Upper slope		Middle slope		Bottom Slope	
		Plantation	Rangeland	Plantation	Rangeland	Plantation	Rangeland
Sand (%)	50.3 ± 2.2	86.6 ± 0.4 *	52.2 ± 2.3 *	73.1 ± 0.6	69.1 ± 1.3	60.4 ± 3.9	52.1 ± 3.1
Silt (%)	44.5 ± 2.1	10.5 ± 0.4 *	38.1 ± 1.9 *	22.1 ± 0.5	25.6 ± 1.1	33.7 ± 3.2	40.8 ± 2.8
Clay (%)	5.3 ± 0.4	2.9 ± 0.1 *	9.8 ± 0.6 *	4.8 ± 0.1	5.3 ± 0.2	6.0 ± 0.7	7.1 ± 0.4
X _{tr} (10 ⁻⁸ m ³ kg ⁻¹)	390.2 ± 8.8	429.0 ± 10.3 *	523.2 ± 23.0 *	452.2 ± 9.9 *	492.1 ± 6.1 *	476.5 ± 17.1	450.4 ± 8.5
Ca (mg kg ⁻¹)	19752.4 ± 666.3	13868.2 ± 657.5	15721.5 ± 929.8	18678.8 ± 473.6	17540.8 ± 914.7	16799.5 ± 945.1	20814.8 ± 378.3
Mg (mg kg ⁻¹)	4073.5 ± 182.8	4612.9 ± 368.9 *	3940.3 ± 451.9 *	5225.7 ± 126.0 *	3820.3 ± 151.5 *	4000.6 ± 339.7	3312.6 ± 162.5
K (mg kg ⁻¹)	10264.8 ± 416.9	12708.2 ± 526.6	11480.4 ± 744.8	11953.1 ± 232.1	10714.6 ± 329.0	13500.4 ± 408.4 *	10002.8 ± 292.8 *
Na (mg kg ⁻¹)	15387.8 ± 369.5	19198.1 ± 602.3	17074.7 ± 851.7	19659.4 ± 156.3 *	16962.8 ± 511.2 *	21737.9 ± 353.1 *	13453.5 ± 246.3 *
Fe (mg kg ⁻¹)	25550.7 ± 460.2	27746.9 ± 539.6 *	31775.7 ± 763.1 *	33902.6 ± 467.8 *	28976.4 ± 827.3 *	26082.2 ± 1170.9	26670.3 ± 537.1
Al (mg kg ⁻¹)	38899.1 ± 641.4	41364.4 ± 958.0	43680.2 ± 1354.9	50247.8 ± 1143.8 *	39145.3 ± 1792.1 *	44246.2 ± 1153.1	35895.8 ± 619.2

Parameters written in bold indicate significant differences respect to native forest soil.

*Indicates significant differences between plantation and rangeland.

Shaded text indicates that Interaction Factor (Land use × Depth) was significant. For these cases, comparisons were done for each depth, separately. Results were detailed in the text.

and Fe and lower values of Ca than native forest soils (Table 3). Rangeland presented intermediate values of Ca and the maximum values of Fe and Al. At the middle slope the greatest values of Mg, Na, Al and Fe were found in the plantation. Rangeland differed from native forest soils just in the content of Fe. At the bottom slope, the plantation soils have still greater values of K and Na than native forests. For this slope position, some properties showed significant interaction between ANOVA factors. The plantation soil showed the greatest values of Al for the most superficial samples (0–5; 5–10 cm). The Fe content was significantly greater in rangeland for most depths. Ca and Mg resulted greater in native forest for the superficial samples (0–5 cm), but at depth, increments in Ca and Mg were found in rangeland soils.

Most of the differences found in the geochemistry according to the land use (Table 3) were lost when the texture clusters were considered (Table 1). Thus, geochemistry seemed to have a great relationship with the different grain size fractions. The geochemical analysis of the

sectioned samples showed that K and Na were positively associated with the sand fraction, Ca with silt fraction and Fe tended to be associated with the clay fraction (Table 4).

4. Discussion

The study area presents volcanic soils with little differentiation of horizons. In spite of the proximity between the study sites, the correspondence to the same landforms (Andrada de Palomera, 2002) and the same soil unit (Irisarri et al., 2000), soils greatly differed in physical, chemical and magnetic properties. The soils of the area consist of a mosaic of sandy-textured, poorly-developed volcanic soils (Vitrixerands/Andosol vitric, according to WRB) and fine-textured, well-developed andic soils (Haploxerands/Andosol humic, according to WRB). Soils seem to be the result of natural processes in an area affected by volcanic ashes and a rugged topography, but also of middle term

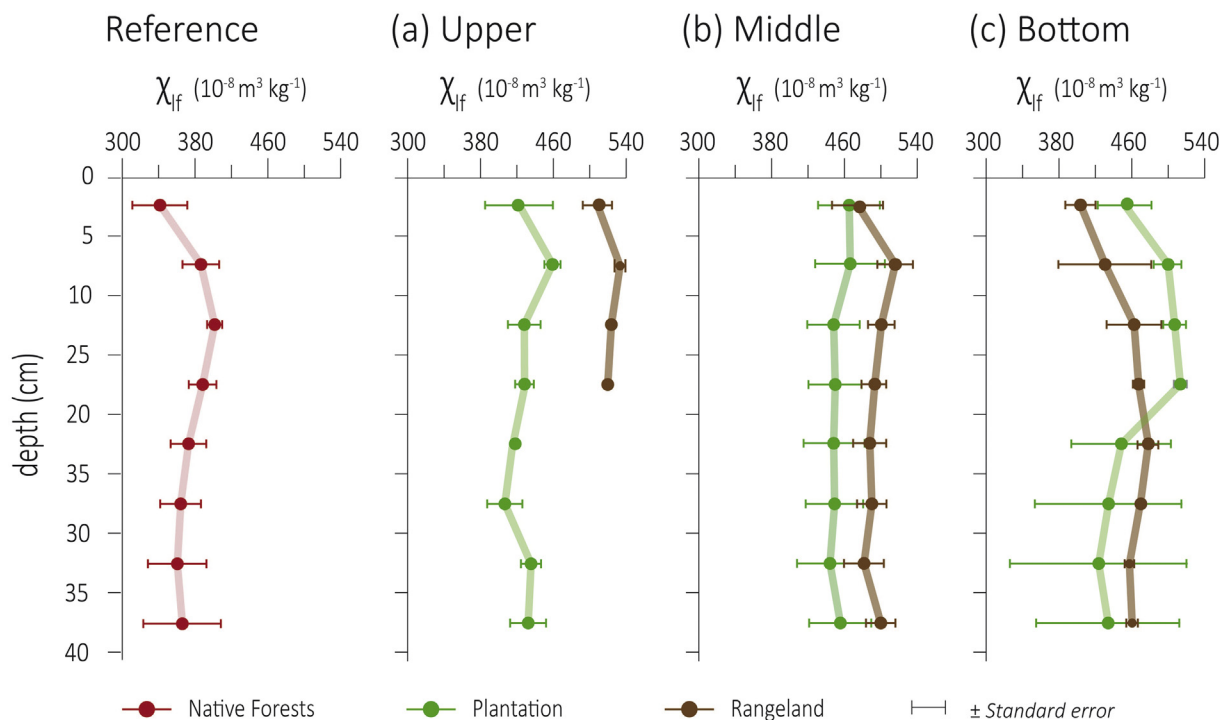


Fig. 4. Magnetic susceptibility profiles for sectioned soil samples. Mean values for native forests (reference), and for rangeland and plantation in the high (a), medium (b) and lower (c) parts of hillslopes are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

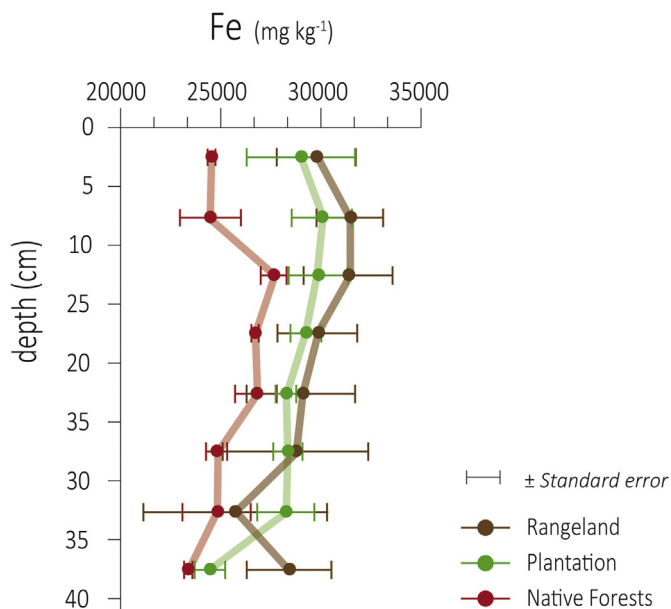


Fig. 5. Ferrum contents profile for sectioned soil samples of native forest, plantation and rangeland. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

erosion and degradation processes associated to land use.

The soils of the study area have been poorly studied, and there are no previous studies at a detail scale as the addressed in this work. In turn, it is a dynamic environment, where alluvial processes and volcanic events modify and renew the soils. Soils are only slightly weathered and have been continually modified by the contributions of fresh volcanic ashes (Valenzuela et al., 2002).

4.1. Soil textural differences

The native forest soils were rich in silt fraction all along the profiles, even in the C horizon (Fig. 2a), and most of the 0–40 cm bulk samples were silty loam-textured (see Table 1; cluster II). On the other hand, the sand fraction dominated in the middle slope position for rangeland and plantation (Fig. 2), but texture varied along the hillslope (Fig. 3). Most of soil samples were sandy-textured in the plantation (cluster I; Table 1) and loam-textured in the rangeland (cluster II; Table 1). These results suggest that some differences between soils already existed before the land use change.

The native forest soils were more similar to rangeland soils, both in texture and geochemistry (Table 3), than to plantation soils. In the rangeland both at upper slope (Position 1; Fig. 3), where soils were protected by a nearby forest patch (see Fig. 1), and bottom slope, the soils presented textures quite similar to those found in native forest. On the contrary, intermediate points along the slope, showed an increment in sand fraction and a decrease in fine grain fractions (Fig. 3b).

Table 4

Correlation between the different granulometric fractions and the geochemical properties. Sectioned samples were considered for the analysis. Pearson correlation coefficient and p value are shown. The correlations statistically significant were written in bold.

	Sand	Silt	Clay
Ca	-0.32 (p = 0.01)	0.35 (p < 0.001)	0.12 (p = 0.33)
Mg	0.12 (p = 0.36)	-0.12 (p = 0.35)	-0.07 (p = 0.56)
K	0.25 (p = 0.04)	-0.27 (p = 0.03)	-0.09 (p = 0.47)
Na	0.25 (p = 0.04)	-0.27 (p = 0.03)	-0.07 (p = 0.58)
Fe	0.07 (p = 0.60)	-0.12 (p = 0.36)	0.23 (p = 0.07)
Al	0.10 (p = 0.45)	-0.13 (p = 0.31)	-0.13 (p = 0.44)

Although plantation soils seem a priori different to native forest soils, both in texture and geochemistry, enrichment in silt and clay fractions along the slope were also evidenced (Fig. 3a). These textural changes found along the slopes suggest a selective removal by erosion (Kwaad, 1977; Navas et al., 2017). In volcanic soils it was proved that erosion processes affect mainly microaggregates, which are mobilized with no previous dispersion (Poulenard et al., 2001). Although this process may seem a low-selective process in relation to granulometry, these microaggregates can be enriched in fine fractions. Rodríguez Rodríguez et al. (2002) showed a selective removal of clay fraction in volcanic soils, although not in a disperse state, but rather as highly stable granular aggregates. Studies about volcanic soils texture in Patagonian Andean Region showed that microaggregates, hard to be dispersed even under laboratory conditions, are formed by silt and clay size particles and organic colloids (La Manna et al., 2016b).

Once canopy is closed and the soil is completely covered by litter in plantations, as occurred in the study site, erosion was proved to be minimal, as low as the found in native forests (La Manna et al., 2016a). The enrichment in clay and silt fractions at bottom in the plantation would reflect an active slope processes when the soil was unprotected (i.e., degraded and open native forests and the first years of the plantation).

On the contrary, in native forests patches, a dense vegetation cover, should have always protected the soil, minimizing the loss of soil, and, furthermore, facilitating the entrapment of fine particles transported by wind over the time (Broquen et al., 2003; Tarabini, 2017).

The textural differences may also involve mineralogical differences. Mineralogical studies conducted on soils located near to Esquel town, showed that sand fraction is dominated by volcanic glass, hyalopilitic groundmass and feldspars (Valenzuela et al., 2002). In the plantation, for example, where sand fraction dominates, soils were rich in Na and K (Table 3), and a positive relationship between sand fraction and Na and K was found (Table 4). These results may suggest that certain minerals rich in Na and K, for example feldspars, would predominate in sandy soils. On the other hand, the native forest and rangeland soils were rich in Ca (Tables 1 and 3), positively correlated with silt fraction (Table 4) and calcium silicates would prevail in these soils.

4.2. Changes in soil organic matter and non-crystalline minerals

The textural differences partly explain the variation in organic matter content (Feller and Beare, 1997). Thus, in both, the plantation and the rangeland, and even in native forests, the samples richest in fine fractions had higher contents of organic matter (Table 1, Fig. 3). Differences found along the slope, with higher values of organic matter and pH NaF at the bottom slope, also may reflect a natural process, associated with differences in the soil water regime as water preferentially accumulates at the lower parts of slopes.

Even minimizing the effect of texture, the loss of native forest implied a drastic decrease in organic matter contents (Table 1). Studies about soil organic carbon under different land uses showed that changes in organic carbon related to the transition from forest to pasture are highly variable (Guo and Gifford, 2002). Reported changes in soil carbon ranged from -50% to +160% (Murty et al., 2002). Our results showed that the magnitude of the change respect to native forest varied according to soil texture (Table 1).

A meta-analysis study showed that C stocks decline after land use changes from native forest to plantation (Guo and Gifford, 2002). Others studies, developed on volcanic soils, also documented that pine plantations involved a decrease in organic matter (Laclau, 2003). In Patagonia, different studies suggest that the soil fertility prior to planting would determine the effect of the pines on soil organic matter (Gobbi et al., 2002; Nosetto et al., 2006; La Manna et al., 2016a).

In native forest and in some soil samples of the plantation, non-crystalline minerals were detected. On the contrary, in the rangeland halloysite would be the dominant clay. Differences found in organic

matter and pH NaF under the different land uses (Table 1) are likely due to changes in mineralogy, resulting from soil desiccation. Land use change may expose soil to desiccation, allowing the non-crystalline materials to evolve to halloysite-type crystalline minerals (Parfitt and Wilson, 1985), reducing the potential of soils to stabilize organic matter and increasing soil carbon mineralization (Hernández et al., 2012). Rainfall simulation experiments performed near the study area showed that loamy sand and sandy loam soils, poor in organic matter and without non-crystalline aluminosilicates, are the most erodible soils (La Manna et al., 2016a). Since in the study area these textures prevailed, our results suggest that replacement of native forest, by altering organic matter and mineralogy, also involve an enhancement of soil erodibility. These changes also entangle a decrease in water storage capacity (Dahlgren et al., 2004; McDaniel et al., 2012), which is key for soil fertility in an area where rainfall is out of phase with the growing season.

4.3. Soil magnetic susceptibility

The textural differences, both, inherited from parent materials and enhanced by erosion process, along with the associated mineralogy and pedogenetic process, seem to be related to the differences found in magnetic susceptibility. Magnetic susceptibility was higher in rangeland [χ_{lf} : $(491,0 \pm 6,2) \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$] and plantation [χ_{lf} : $(450,0 \pm 5,4) \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$] than in the native forest [χ_{lf} : $(390,2 \pm 7,5) \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$]. Relationship between grain size, mineralogy and magnetic susceptibility seems complex in the study area. Spatial variability of magnetic susceptibility within the landscapes varies with the slope position and soil factors, such as soil texture, which are affected by soil redistribution (De Jong et al., 1998; Mathé and Lévêque, 2003). Our study along the slope showed that, in the rangeland, the magnetic susceptibility was directly related to the coarse grain fraction (Fig. 3b, Table 2). These results suggest that magnetic properties are from lithogenic origin (i.e., from parent material). Mineralogical studies in volcanic soils of the study area showed that the heavy fraction of sand fraction is dominated by hypersthene and hornblende, silicates and aluminosilicates of iron and magnesium (Valenzuela et al., 2002), which could influence the values of magnetic susceptibility (Hunt et al., 1995). Besides, mineralogical and physicochemical compositions of the parent ashes, and their magnetic susceptibility, differ widely according to the chemical composition of the magmas of the volcanoes that generated them (Auer, 1950).

In the plantation, the magnetic susceptibility was directly related to the fine fraction (Table 2), and magnetic susceptibility was higher in samples rich on fine fractions (cluster II) than in the sandy ones (cluster I) (Table 1). Magnetic susceptibility in native forest soils also tended to be related to clay fraction (Table 2). Since secondary minerals correspond mainly to the fine fraction, these results suggest that enhancement of magnetic susceptibility could be related to soil formation processes. Along the forested slope, the soil was gradually enriched in fine fractions, organic matter and non-crystalline aluminosilicates (according to pH NaF values). In turn, magnetic susceptibility was increasing down slope (Fig. 3a). Recent studies on volcanic soils showed that magnetic susceptibility is positively correlated to andic properties (Grison et al., 2015, 2016; Vingiani et al., 2014). In xeric conditions, as in the eastern part of the study area, non-crystalline minerals formation is restricted (McDaniel et al., 2012), and thus, andic properties and magnetic enhancement are not strong. While our soils with non-crystalline materials showed a magnetic susceptibility value of $365.63 \pm 14.43 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, other andic soils showed values $> 800 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ (Vingiani et al., 2014).

On the other hand, the influence of fire on magnetic susceptibility cannot be ignored. Fire was the main technique for land management for cattle production in the Patagonia Andean Region (Veblen et al., 1999; Carabelli and Scoz, 2016). Under oxidant and oxygen-depleted conditions, such as those caused by fire, the change of magnetite

(Fe_2O_3) and magnetite (Fe_3O_4) - iron minerals type from II to III- is induced, which leads to increased magnetic signal (Oldfield and Crowther, 2007). The greatest magnetic susceptibility found in the rangeland may be attributable to the effect of fire. Ferromagnetic minerals could have percolated in depth, since all along the profiles high values were found (Fig. 4). On the other hand, the plantation was installed 30 years ago, replacing an open native forest, which might have suffered fires (no recorded), with less severity and frequency than rangeland. The patches of native forest considered as controls in this study are forests relicts that have been saved from fire.

Studies in other parts of the world, carried out in remote areas far from industrial or urban sources of pollution, like ours, where the enhancement of magnetic susceptibility was proved to have a lithogenic origin, show that topsoil susceptibility value measured in forest was significantly lower than that measured in arable fields (Magiera et al., 2006). Coincidentally, soils under forest in our study area presented the lowest magnetic susceptibility values.

The magnetic susceptibility slightly varied in the first 40 cm along the soil profiles. Incremental samples showed an increase in the 5–10 cm or 10–15 cm depth intervals for the different land uses and positions on the slope (Fig. 4). Generally, upper soil layers have higher magnetic susceptibility than the subsoils due to in situ neoformation of minerals strongly magnetic (Le Borgne, 1955). On the contrary, in our study, the lowest values of magnetic susceptibility were found in the first portion of the soil (0–5 cm). Possibly, this result is influenced by recent ashes from Chaitén volcano, which presented low magnetic susceptibility [χ_{lf} : $42,8 \pm 2,2 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$]. Chaitén volcano ashes are mainly formed by volcanic glass (SiO_2 fundamentally), quartz crystals, albite, potassium feldspar and dickite (Vargas et al., 2008). At greater depths (> 15 cm), magnetic susceptibility tended to decrease. This is consistent with many other studies done in different environments, land uses and parent materials (Fialová et al., 2006; Pingguo et al., 2016). Fig. 4c shows that, in the lower part of the slope, the rangeland and plantation curves intersect in depth. This result and the positive interaction between Land use and Depth factors found in the ANOVA for the bottom slope (Table 3) could be explained by the occasional plowing practiced in the lower rangeland, which could lead to mixing of horizons.

In depth, the lowest values of magnetic susceptibility in the soil profiles were found in the glacialfluvial material, below the lithological discontinuity (Fig. 2a). This decrease in magnetic susceptibility could be related to mineralogical differences. Szuszkiewicz et al. (2016) also reported the impact of the geological setting on vertical variability of magnetic susceptibility studying soil profiles developed from different sedimentary, igneous and metamorphic bedrocks in Poland. The decrease may also be influenced by an increase in carbonate concentration in depth, which has a diluting effect on magnetic signal (Feng and Johnson, 1995; Quijano et al., 2014), since volcanic ash samples showed a very low carbonate concentration ($< 0.20\%$).

All the samples, regardless depth, vegetation type and land use, showed low values of frequency dependent, always lower than 5%. Values of $\chi_{\text{fd}}\% < 5$ are typical of samples in which non-superparamagnetic grains dominate or where extremely fine grains ($< 0.005 \mu\text{m}$) dominate the superparamagnetic fraction (Dearing, 1999; Quijano et al., 2014). The magnetic properties of the study soils developed on volcanic ash deposits are controlled primarily by non-superparamagnetic larger-sized ferrimagnetic minerals of lithogenic origin (Goebel et al., 2017). Magnetic susceptibility could be markedly affected by the mineralogical and physicochemical compositions of the parent ash, which in turn differ widely according to magmas of the volcanoes that generated them (Auer, 1950). Although all the samples showed low values of $\chi_{\text{fd}}\%$, the native forest showed the maximum records that can be related to an enhancement of secondary ferrimagnetic minerals result from pedogenesis. This study is the first approach to the subject of magnetic susceptibility in soils of the Argentinean Patagonia Andean Region, suggesting new topics of discussion and research.

5. Conclusions

Soils of the study area consist of a mosaic of sandy-textured and fine-textured volcanic soils. Soils seem to be the result of natural processes in an area affected by volcanic ashes and a rugged topography, but also of degradation processes associated to land use.

Magnetic susceptibility, together with other measured variables, as soil organic matter content, texture, and pH NaF, changed under the different land uses and slope positions. We interpret that these changes were produced by soil degradation processes in a dynamic environment. Detrimental changes in soil, generally considered to affect the productive potential of soils, were shown to affect also pedogenetic processes, as the formation of non-crystalline minerals.

The loss of native forest implied not only a decrease in organic matter, but also changes in mineralogy, resulting from soil desiccation and to the selective removal of fine particles by erosion. Both non-crystalline minerals formation, conditioned by soil desiccation, and the differential mineralogy of the grain size fractions, resulted in changes of magnetic susceptibility, according to land use and slope position. Since mineralogy directly affected magnetic susceptibility of the soils, our results suggest that this variable can be used as an indicator of soil degradation in this region. However, magnetic susceptibility interpretation was complex, and it was differentially related to fine or coarse grain fractions, according to the origin of the magnetic enhancement.

The integrated characterization of magnetic susceptibility, organic matter content, texture, and pH NaF resulted key for understanding soil degradation processes in these dynamic landscapes of the Patagonian ecotone.

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