Soil erodibility and quality of volcanic soils as affected by pine plantations in degraded rangelands of NW Patagonia

Ludmila La Manna, Carlos Guillermo Buduba & César Mario Rostagno

European Journal of Forest Research

ISSN 1612-4669

Eur J Forest Res
DOI 10.1007/s10342-016-0961-z

ONLINE FIRST

Springer

Eur J Forest Res
DOI 10.1007/s10342-016-0961-z

ORIGINAL PAPER

Soil erodibility and quality of volcanic soils as affected by pine plantations in degraded rangelands of NW Patagonia

Ludmila La Manna[1,2] · Carlos Guillermo Buduba[1,3] · César Mario Rostagno[2,4]

Received: 3 January 2016 / Revised: 20 April 2016 / Accepted: 2 May 2016

Abstract NW Patagonia in Argentina has high potential for planting fast-growing exotic conifers, supported by its volcanic soils. Nonetheless, many aspects related to the effects of pine plantations on soil are still unknown. We aimed to evaluate the quality and erodibility of volcanic soils under the hypothesis that *Pinus ponderosa* plantations increase the quality and decrease the erosion rate of soils compared to degraded rangelands. Rainfall simulation experiments were performed in degraded rangeland soils and in pine plantations with none, partial and complete removal of fresh litter and duff layers. Results showed that rangeland soils were highly susceptible to water erosion. Sediment production in the rangeland varied between 144 and 750 g m^{-2}. Loamy sand soils, poor in organic matter (OM) and without non-crystalline aluminosilicates, were the most erodible soils. The plantations improved soil quality, with positive changes in OM content and total and effective porosity, mainly in soils without non-crystalline materials. Soil erosion in pine plantations was negligible when fresh litter was either conserved or removed, with erosion rates as low as 6.2 ± 1.5 and 23.7 ± 7.9 g m^{-2}, respectively. Even when fresh litter and duff layers were totally removed, soil erosion rates in the pine plantations (129.1 ± 23.2 g m^{-2}) were lower than in the rangeland sites; however, this reduction was significant only for the most erodible soils. The high erodibility of volcanic soils and the low soil cover in overgrazed rangelands revealed the fragility of the soils in the study area. We show that pine plantations, an alternative land use of rangelands, improve some aspects of soil quality, provide a mulching effect through the litter layer and became a mean for controlling soil erosion.

Keywords Soil erosion · Runoff · Simulated rainfall · *Pinus ponderosa* · Volcanic ash

Introduction

The landscape and soils in the Patagonian Andean region in Argentina are characterized by a west–east descendent pluviometric gradient (50 mm per year per kilometer; Barros et al. 1979), the geomorphologic action of the pleistocenic glaciers, and the later deposition of volcanic ash which is the main soil parent material (Apcarian and Irisarri 1993). Soils formed over volcanic ejecta have many distinctive physical, chemical and mineralogical properties, largely attributable to the formation of non-crystalline minerals (e.g., allophane, imogolite) (Dahlgren et al. 2004; McDaniel et al. 2012). Since pedological processes suffered by ash vary according to the landscape position and the amount of precipitation (Parfitt et al. 1984), the development of non-crystalline materials varies from west to east (Colmet Daage et al. 1988). Mineralogical studies support that in the west, allophane is formed, whereas to

Communicated by Dr. Agustín Merino.

✉ Ludmila La Manna
llamanna@unpata.edu.ar

[1] Laboratorio de Estudios Ambientales Integrados, Facultad de Ingeniería, Universidad Nacional de la Patagonia San Juan Bosco (UNPSJB), Ruta 259 km 16,4, 9200 Esquel, Chubut, Argentina

[2] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina

[3] Instituto Nacional de Tecnología Agropecuaria (INTA), 9200 Esquel, Chubut, Argentina

[4] Centro Nacional Patagónico (CENPAT), Bvard. Brown s/n 9120, Puerto Madryn, Chubut, Argentina

Published online: 17 May 2016

the east—subhumid sector—soils are enriched in imogolite or/and halloysite (crystalline) (Colmet Daage et al. 1988).

The subhumid sector corresponds to the transition (ecotone) between the Andean forests and the Patagonian steppe, and the dominant plant community is a grass steppe with scattered shrubs. Livestock and sheep grazing were the main land use in these rangelands, which has suffered human pressure and overgrazing for most than a century, accelerating the soil erosion processes (Ares et al. 1990). Soil erosion is a widespread problem in Patagonia, with more than 67 % of the area suffering severe desertification (Del Valle et al. 1998).

The subhumid sector of Patagonian Andean region has high potential for forest production based on its fertile volcanic soils (Irisarri and Mendía 1997). The afforestation with exotic conifers with rapid growth, mainly *Pinus ponderosa* Douglas ex Lawson, used for construction, is being promoted as an economic activity. Plantations might represent an effective mean to control soil erosion (Morgan 2005); however, this topic is under discussion. In semiarid areas of Spain, for example, afforestation with Aleppo pine has not significantly reduced erosion at a long-term scale (30 years), in comparison with the natural vegetation of thorn shrublands and dry grassland communities (Maestre and Cortina 2004; Chirino et al. 2006). Studies in China also revealed that many of the afforested areas are still suffering from moderate to intense soil erosion processes (Gu et al. 2013; Cao et al. 2015).

Although the effects of afforestation in ecosystem health and soil quality are under discussion (Raffaele and Schlichter 2000), the ability of plantations to control wind erosion and to trap the particles carried by the wind has been demonstrated in Patagonia (Broquen et al. 2003; Buduba 2006; Tarabini et al. 2014). Pine plantations can also reduce soil erosion due to the rainfall interception by the canopies. Studies showed that pine plantations in NW Patagonia can intercept, on average, 50 % of the incident rain, varying according to forest management (Buduba 2006; Gómez et al. 2015). Forest canopy alters both the rainfall magnitude and the kinetic energy reaching soil surface. Nevertheless, raindrop size and kinetic energy in plantations are largely dependent on rainfall intensities, canopy heights and the forest species involved (Hall and Calder 1993; Zhou et al. 2002).

The key variable governing soil erosion is the soil erodibility, which expresses the susceptibility of a soil to raindrop impacts and runoff. As a factor in soil erosion models (i.e., USLE and RUSLE), only inherent soil properties are considered determinants of the erodibility (Renard et al. 1997). It is generally related to texture, organic matter content and aggregate stability (Bryan 2000). Mature volcanic soils generally have high physical fertility and are considered resistant to water erosion (Shoji et al. 1993). However, the erosion behavior of tropical volcanic soils generally varies according to soil maturity, pedological development, organic matter content and land use (Jungerius 1975; Poulenard et al. 2001; Zehetner and Miller 2006). Immature volcanic soils are highly susceptible to erosion, and even well-developed Andisols are highly susceptible to erosion when surface cover is removed or degraded (Dahlgren et al. 2004). Rainfall simulation experiments, developed in allophanic soils of Patagonia, showed a dramatic increase in sediment production where the native forest was affected by wildfire (Morales et al. 2013).

There is little information about the erodibility of volcanic soils and the effects of pine plantations on soil erodibility in NW Patagonia. Even more, in the subhumid sector, with more severe environmental restrictions, there is a knowledge gap on these topics.

In this study, we carried out several rainfall simulations experiments in volcanic soils of the subhumid sector of NW Patagonia. We aimed (1) to evaluate the influence of intrinsic soil properties (e.g., non-crystalline materials, organic matter content, soil texture) on the erodibility of degraded rangelands with dominance of bare soil and (2) to evaluate the changes in soil quality and erodibility associated with plantations of exotic conifers, under the following hypothesis:

Hypothesis Plantations of exotic conifers increase the erosion resistance of soils compared to degraded rangelands, by increasing litter cover and improving the physical properties of the mineral soil.

Prediction Soils under pine plantations will show thicker organic layers, and higher organic matter content, aggregate stability and water retention capacity with respect to the soil of the degraded rangeland patches.

Under a given rainfall event, soils under plantations will show a lower sediment production than soils in degraded rangelands, and this condition will persist after removing the fresh litter and even after removing the duff layer completely.

Materials and methods

Study area

The study area is located in the subhumid sector of the Andean Patagonian region, close to Esquel city, in the Chubut Province, Argentina. Average annual temperature is around 8 °C, and annual precipitation is approximately 600 mm, concentrated mainly in autumn and winter. The parent material of soils is mainly holocenic volcanic ashes, dominated by volcanic glass and constituted by an association of hyalopilitic groundmass, feldspar, hypersthene and hornblende (Valenzuela et al. 2002). Dominant soils are the suborders Xerands (Andisols) and Xerolls (Mollisols) (Irisarri et al. 1995; Soil Survey Staff 2014).

Vegetation of the study area belongs to the transition between the Sub-Andean Patagonic District of the Patagonian Phytogeographical Province and the Deciduous Forest District of the Subantarctic Phytogeographical Province (Cabrera 1971). The dominant plant community is a grass steppe with scattered shrubs. Sheep grazing was the main land use in these rangelands with an average stocking rate of 0.6 sheep ha^{-1}, greatly variable along the time (Golluscio et al. 1998).

Four study sites, corresponding to degraded rangelands, adjacent to *P. ponderosa* plantations, were selected. Slopes varied between 16 and 19 %.

Degraded rangelands were characterized by varying percentage of bare soil and increasing cover of shrubs (Table 1). Vegetation and litter cover were the main soil protection factors. The dominant grass species was *Festuca pallescens* (St.Yves) Parodi (v.n. coirón dulce), and the dominant shrub was Molinum spinosum (Cav.) Pers.) (vn. neneo), a low-quality forage shrub associated with degraded soils (Bertiller 1993; Beeskow et al. 1995).

The *P. ponderosa* plantations—20 years old—were characterized by a closed canopy and represented the most common situation in the study area. The pine plantations had low to null bare soil (Table 1). Soil was mainly covered by non-decomposed litter of pine needles; beneath the fresh litter layer, a duff layer in varying stages of decomposition developed.

Rainfall simulations experiments

Simulated rainfall applications were carried out in degraded patches of the rangelands, with dominance of bare soil, covering between 59 and 76 % (Table 2). Gravel cover, the main soil protection factor in rangeland plots, was between 16 and 29 %. Both variables are good indicators of degraded areas (Rostagno and Degorgue 2011).

In the pine plantations, three treatments were considered: T_1) The original condition, that is, plots completely covered by fresh litter and partially decomposed litter or duff layer; T_2) plots where the fresh litter layer was removed (i.e., removing the non-decomposed or slightly decomposed pine needles, easily separable and distinguishable from the rest of the organic materials); and T_3) plots where the fresh litter and the duff layers were completely removed, leaving the mineral soil exposed.

In the original condition (T_1), litter formed a continuous layer. Its thickness, considering the fresh litter and the duff layers, varied from 3.1 to 9.3 cm (Table 2). Since the presence and thickness of the organic material in plantations are largely related to forest density (Kurka and Starr 1997; Berger and Berger 2012), the different treatments in the plantation plots simulated different plantation management. Higher forest densities imply thicker litter and duff layers; conversely, low-density plantations have thin or even absent organic layers (Buduba 2006).

Rain was applied using a drip-type rainfall simulator, similar to the one described by Irurtia and Mon (1994) on five plots per treatment. A total of 80 simulated rainfalls were performed (4 sites × 4 treatments × 5 replicates). Plots of 1.564 cm^2 (46 × 34 cm) were bordered by a sheet-metal frame and were provided with a runoff collector in the lower side. The applied rainfall intensity was 100 mm h^{-1} for 30 min. Drop diameter of the simulated rainfall was 2.5 mm. Falling 2 m, water drops of this size reach a velocity of 5.3 ms^{-1} or 70 % of the terminal velocity of natural rainfall drops of this diameter (Epema and Riezebos 1983). Simulated rainfall experiments were carried out in late summer, with initial dry conditions.

Runoff was collected at 5-min intervals in 1-L containers. The infiltration rate was determined as the difference between the applied rainfall and the collected runoff

Table 1 Topography and surface characteristics of the study sites

Site	S Latitude W Longitude	Slope (%)	Rangelands					Plantations					
			Surface cover (%)					Surface cover (%)					
			Bare soil	Gravel	Litter	Shrubs	Perennial grasses	Bare soil	Gravel	Litter	Shrubs	Grass	GII
1	42°51′49″ 71°24′22″	19	81	12	0	6	1	7	4	76	10	3	2.3
2	42°55′06″ 71°15′56″	16	30	1	44	1	24	0	1	99	0	0	3.9
3	42°52′48″ 71°22′09″	19	41	1	5	39	14	0	0	100	0	0	3.3
4	43°04′33″ 71°21′25″	16	46	11	29	5	9	4	7	79	2	8	3.1

GII growth intercept index (Gonda and Cortez 2001). This index is based on the length of the first five inter-nodes over the diameter at breast height

Table 2 Ground cover in the rangelands and pine plantations simulated rainfall plots

Site	Rangelands			Plantations		
	Bare soil cover %	Coarse fragments cover (%)	Litter + vegetation cover (%)	Litter cover (%)	Litter[a] layer thickness (cm)	Duff[b] layer thickness (cm)
1	67 ± 9	29 ± 8	4 ± 1	100 ± 0	4.8 ± 1.2	3.1 ± 1.1
2	72 ± 11	22 ± 10	6 ± 1	100 ± 0	4.5 ± 0.6	4.8 ± 1.1
3	76 ± 8	16 ± 7	8 ± 2	100 ± 0	4.1 ± 0.4	3.7 ± 0.6
4	59 ± 7	25 ± 7	16 ± 2	100 ± 0	2.1 ± 0.7	1.0 ± 0.2

[a] "Litter" in plantations refers to non-decomposed pine needles

[b] "Duff layer" refers to organic material in varying stages of decomposition

for each interval. Sediment production was determined from the total runoff collected for each simulation. The sediment production was obtained after suspended solid decantation (72 h) by carefully discarding most of the runoff. Sediments were collected in 500-mL beakers and dried for 48 h at 60 °C and weighed.

Litter, vegetation and rock fragments cover were visually estimated by vertical projection in each sample plot before rainfall application. The sediment obtained in the rangeland plots and in the pine plantations without duff layer (T_3) was analyzed for organic matter content (OM) by the loss-on-ignition method (Davies 1974). The enrichment ratio (ER) of OM was calculated by dividing the content of OM in the sediments by its content in the original soil material (Avnimelech and McHenry 1984). This variable allows determining whether the sediments were enriched with OM, as compared to the contributing soils.

Soil sampling and analysis

In each site and vegetation type, six mineral soil samples at 0–5 cm depth were randomly collected adjacent to the runoff plots before applying the simulated rainfall for determining OM by the loss-on-ignition method (Davies 1974), pH in a soil: NaF suspension as indicator of non-crystalline aluminosilicates (Fieldes and Perrot 1966), texture by the pipette method (Day 1965), aggregate stability by the clay dispersion ratio (Middleton 1930) and bulk density by the core method (Blake 1965) which allowed the determination of the total soil porosity as [1 − (bulk density/particle density)]. Field capacity (FC; 0.01 MPa) and permanent wilting point (PWP; 1.5 MPa) were determined using pressure membrane apparatus (López-Ritas and López-Mélida 1990); the water available capacity was determined by FC-PWP. The effective or macroporosity was calculated as total porosity minus FC (Helalia 1993). Soil moisture content was gravimetrically determined.

Data analysis

In order to analyze the soil properties associated to the different rangeland soils, principal component analysis (PCA) was applied. In the PCA, all the soil variables were considered. It was conducted using a correlation matrix to avoid variation due to differences in measurement units (Escofier and Pagès 1992). Variables associated with sediment production were determined by multiple regression, applying stepwise method with bidirectional elimination approach for variables selection, which avoids multicollinearity. Correlation between variables was evaluated by Pearson test.

Differences in soil properties between rangelands and plantations were analyzed by analysis of variance with block design, considering each study site as a block. Differences in sediment production and runoff between rangelands and the different treatments considered in plantations were also analyzed by analysis of variance with block design.

For analyzing parameters within a study site, nonparametric tests were conducted, since assumptions of parametric tests were not met in most of the cases. Differences in soil properties, sediment production and runoff between rangelands and plantations (considering the different experimental treatments) were analyzed, for each study site separately, by Kruskall–Wallis test. Correlation between sediment production and litter thickness in each studied plantation was evaluated by Spearman test.

Analyses were carried out with the Infostat software (Di Rienzo et al. 2013).

Results

Soil properties and erodibility associated to the different rangeland soils

Soils of the four study sites had a coarse-to-medium texture (sandy loam to loam). The standard PCA carried out for the rangeland soils using all the physical variables produced a clear discrimination of the four sites into three groups (Fig. 1). Site 1 plots, grouped toward negative values of axis 1, corresponded to coarse-textured soils, with greater influence of sand (69 %) and high effective porosity. Plots of Site 3 were grouped toward the positive values of axis 2. Although this site also presented a high sand content (58 %), it was the only soil that evidenced the presence of non-crystalline aluminosilicates [i.e., probably imogolite, according to pH NaF values (Irisarri 2000)]. As it is shown in Fig. 1, the presence of non-crystalline aluminosilicates was associated with the highest organic matter contents, total porosity, field capacity and available water capacity values.

Sites 2 and 4 were grouped toward the positive values of axis 1 and negative values of axis 2. Soils in both sites presented a finer texture, with sand contents lower than 50 %. Site 4 presented the highest values of clay fraction (up to 16 %) and showed the highest aggregate stability.

Runoff varied between 10 and 32 % of the incident rainfall and was significantly lower in soils with non-crystalline materials (Site 3) than in the other sites (Table 3). Accordingly, mean infiltration rate at the end of the 30-min simulated rainfall event was the highest for Site 3 (81.5 ± 10.7 mm/h).

Sediment production was relatively high for the four studied rangeland sites, and high differences among sites were found (Table 3). Sandy soils of Site 1 showed the highest sediment production.

According to the regression model (Table 4), soils with low values of pH NaF (i.e., without non-crystalline materials), field capacity, aggregate stability and coarse silt fraction are prone to have higher erosion rates. These variables most effectively predicted sediment production. Besides their direct effect on erosion, these variables integrate other soil variables. For example, organic matter was significantly correlated with pHNaF ($r = 0.57$, $p < 0.001$), field capacity ($r = 0.89$, $p < 0.001$) and coarse silt fraction ($r = 0.52$, $p = 0.01$).

Table 3 Means and standard errors of runoff rate and sediment production in inter-patches of rangeland soils

Study sites			
1	2	3	4
Runoff (mm)			
14.6 ± 1.2a	15.7 ± 3.9a	5.3 ± 2.8b	15.0 ± 0.4a
Sediment production (g m^{-2})			
750.0 ± 217.2b	335.5 ± 90.3ab	143.9 ± 70.6a	163.9 ± 28.0a

Different letters indicate significant differences ($p < 0.05$) among the study sites. The applied rainfall was 50 mm in 30-min experiments

The influence of pine plantations on soil quality

The analysis of variance, considering each site as a block, showed that pine plantation soils had significantly higher organic matter content, total porosity and effective porosity than rangeland soils (Table 5). Changes in the mineral soil associated with the plantation of pines were more marked in those soils without non-crystalline materials (Sites 1, 2 and 4). In these soils, we recorded not only the changes detailed in Table 5 (highlighted in bold), but also significant increases in the field capacity, permanent wilting point and aggregate stability. Most of these changes involved properties associated to a greater resistance to erosion.

Changes in soils with non-crystalline materials under pine plantations (Site 3) were opposite to the others. In this site, the soil had significant lower values of organic matter, field capacity, wilting point, available water and aggregate

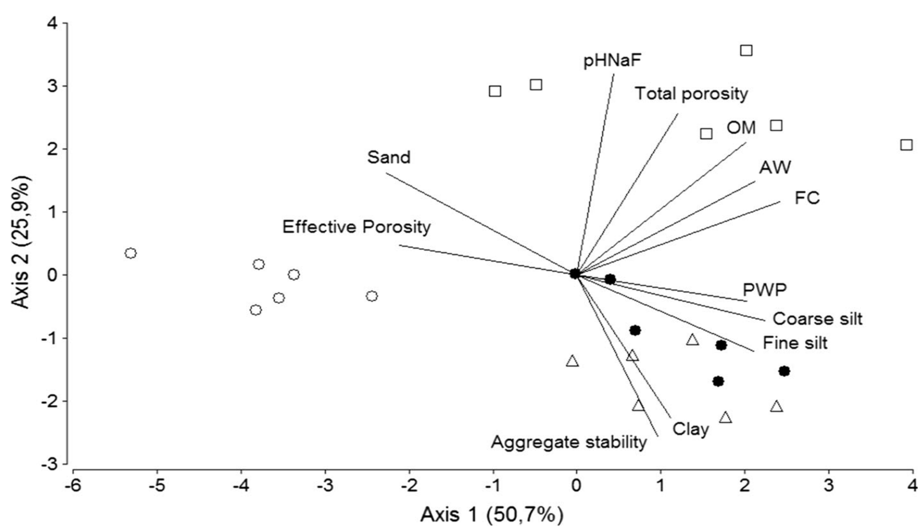

Fig. 1 Plot ordination according to the first and the second components of principal components analysis (PCA). *Symbols* represent the range plots of the study sites: Site 1 (*white circle*), Site 2 (*black circle*), Site 3, (*white square*) and Site 4 (*white triangle*)

Table 4 Parameters of the linear regression for sediment production in rangelands as dependent variable

	Linear model $R^2 = 0.90$ Coefficients	p value
Constant term	8998.81 ± 1761.45	<0.001
FC	−25.46 ± 9.41	0.014
Aggregate stability	−17.70 ± 4.06	<0.001
pH NaF	−661.10 ± 187.17	0.002
Coarse silt	−36.71 ± 14.92	0.024

Independent variables were selected according to the stepwise procedure

stability than the rangeland soils. Soils also had higher sand proportions than rangeland soils.

The influence of plantations on runoff and potential erosion rates

Differences in mean runoff and infiltration rates at the end of the rainfall events (with initial dry conditions) between the degraded rangeland soils and the pine plantation soils were not significant for none of the treatments (Fig. 2). However, there was a trend of increasing runoff in the plantation for plots where litter and the duff layer were completely removed (T_3) ($p < 0.1$).

On the other hand, the pine plantations significantly diminished the sediment production (bars in Fig. 2). Unmodified pine plantations plots, completely covered by litter and duff (T_1), had minimal sediment production for the four study sites (light gray bars in Fig. 3), with a mean value of 6.2 ± 1.5 g m^{-2}. Sediment production for these treatments was always lower than 3 % of the sediment production in rangelands. Even in the Site 4, which had the lowest organic material thickness (Table 2), soil loss was very low. In this site, a significant, negative correlation between soil erosion and the organic material thickness (i.e., litter + duff) was found ($\rho = -1.00$; $p < 0.001$). For the other study sites, with organic material thickness higher than 7 cm, no consistent relationship was found ($p > 0.05$).

Removing litter (T_2) slightly increased the sediment production. However, it remained significantly lower than the erosion rates of the rangeland plots for the four study sites (dark gray bars in Fig. 3). For this treatment, sediment production varied between 0.5 and 15 % of the sediment production in rangelands.

Removing litter and the duff layers, leaving the mineral soil exposed (T_3), determined an increase in erosion rate, remaining, however, significantly lower than in the rangeland plots (Fig. 2). For this treatment (T_3), the protective effect of pine plantations was highly dependent on the characteristics of the soils (black bars in Fig. 3). In those soils with high erosion rates (Sites 1 and 2; Table 3), sediment production in the pine plantation under T_3 was significantly lower than the sediment production in the adjacent rangeland sites, with values lower than 30 % respect with rangelands (Fig. 3). On the other hand, in soils with lower erosion rates (Sites 3 and 4; Table 3) sediment production in the plantation under T_3 was around 70–80 % with respect to rangelands, and no significant differences were found for this treatment.

Sediment enrichment ratio

While pine plantations involved an increase in OM for most of the sites, in soils with non-crystalline materials (Site 3), the rangeland soils showed higher values of OM than the soils in *P. ponderosa* plantation (Fig. 4a). OM content in sediments (Fig. 4b) followed a similar pattern

Table 5 Mean and standard deviation values of some selected soil properties under rangeland and *Pinus ponderosa* plantations

Soil properties	Rangeland soils	Pine plantation soils	p value
Sand	55.2 ± 2.2	56.8 ± 3.5	0.531
Total silt	36.7 ± 1.8	34.3 ± 2.6	0.260
Coarse silt	17.4 ± 0.9	16.2 ± 1.0	0.224
Fine silt	19.3 ± 1.1	18.0 ± 1.7	0.370
Clay	8.1 ± 0.7	9.0 ± 1.1	0.325
Organic matter	**5.7 ± 0.4**	**7.5 ± 0.8**	**0.046**
Aggregate stability	65.5 ± 2.3	61.0 ± 4.5	0.115
Total porosity	**55.4 ± 1.0**	**60.1 ± 1.4**	**0.003**
Effective porosity	**29.8 ± 1.3**	**35.3 ± 2.3**	**0.016**
FC	25.6 ± 1.6	24.8 ± 1.8	0.693
PWP	9.7 ± 0.5	11.1 ± 1.0	0.119
AW	16.0 ± 1.4	14.0 ± 1.1	0.129

Significant differences ($p < 0.05$) between soils of the different vegetation types are highlighted in bold

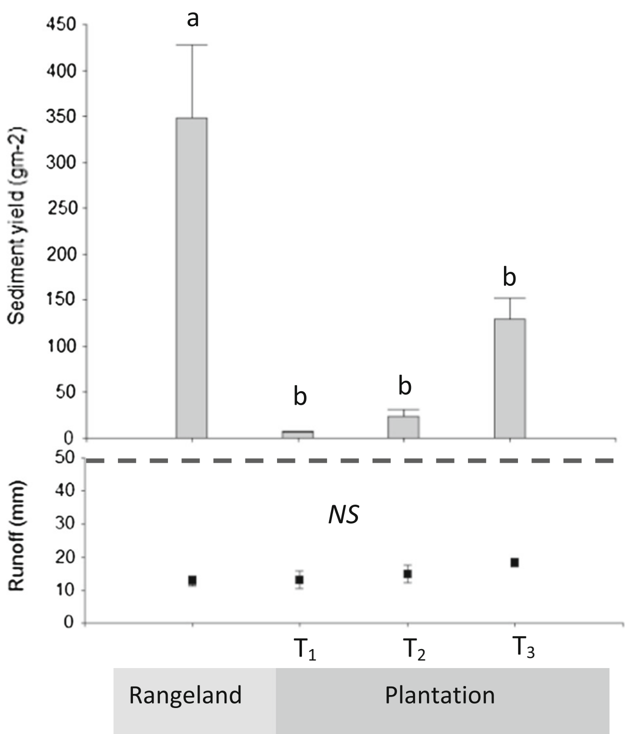

Fig. 2 Mean sediment production and runoff rates in rangeland and Ponderosa pine plantations of Patagonia under three treatments: T_1 without alteration (i.e., plots completely covered by fresh litter and duff layer; T_2 removing the fresh litter layer (i.e., removing the non-decomposed or slightly decomposed pine needles); T_3 completely removing the fresh litter and the duff layers (i.e., leaving the mineral soil exposed). The *dashed line* represents the applied rainfall in the 30-min experiments

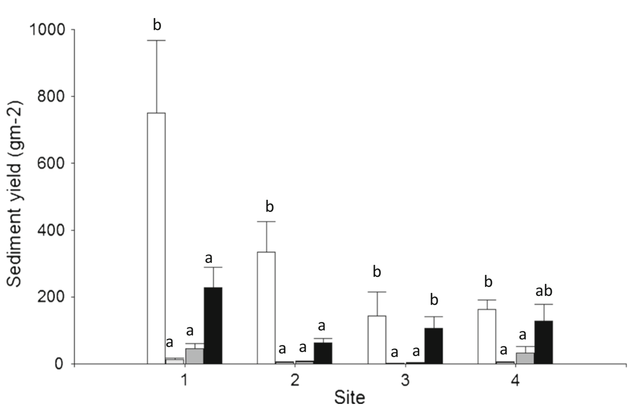

Fig. 3 Mean and standard error of sediment production for the four study sites for different treatments: *white square* rangelands; pine plantations: *gray square* without alteration (T_1); *dark gray* removing the fresh litter layer (T_2); *black square* completely removing the fresh litter and the duff layers (T_3). *Different letters* indicate significant differences between the treatments for each site

than in the superficial soil (Fig. 4a), being significantly greater ($p < 0.001$) in plantations with removal of duff layer (T_3) (11.59 ± 0.92) than in rangelands (7.60 ± 0.61). There were differences in the OM content of the sediments among the study sites, as occurred with OM in soil. In most of the sites, OM increased in the plantation; Site 3 was the exception (Fig. 4a, b).

Although OM content in sediments showed a pattern similar to OM in soils, the absolute values differed and the enrichment ratio for sediments, which can be understood as a soil depletion rate, was higher than 1 for most situations (Fig. 4c). In the rangeland Site 1, the sediment enrichment ratio was slightly greater than 1, probably because of the high erosion rate of these soils (Table 3).

For most of the sites, the enrichment ratio tended to increase in the soils under pine plantations when the duff layer was removed (T_3) as compared to rangeland soils (Fig. 4c). On the other hand, in Site 4, where soils showed the highest values of clay content and aggregate stability (Fig. 1), sediment enrichment ratio in pine plantation was significantly lower than in the adjacent rangeland sites (Fig. 4c).

Discussion

Soil erosion in degraded rangelands

Degraded rangeland sites presented a high proportion of bare soil. This condition, along with a predominantly sandy loam texture with high silt contents, makes the soils of the study area prone to water erosion, as shown by the relatively high erosion rates ranging between 144 and 750 g m^{-2} after the simulated rainfall events. In the east Patagonia, in a shrub steppe with soils poor in organic matter, the sediment production reached values of 29.2 and 61.6 g m^{-2} for uneroded and eroded sites, respectively (Rostagno 1989). Although these values were obtained using a drip-type rainfall simulator similar to the one used in the present study, they corresponded to plots with lower slopes (4 %) and simulated rainfalls of lower intensity, 68 mm/h, and similar duration. On the other hand, in volcanic soils in the Ecuadorian Andes, the maximum sediment production found in non-allophanized soils was 464 g m^{-2} (Zehetner and Miller 2006), lower than the values recorded in the most erodible soil of our study area.

Although sediment production rates were high for all the rangeland soils, values varied according to soil properties. Maximum values were found in loamy sand to sandy loam soils of Site 1. Coarse-textured soils are considered more resistant to erosion because of the greater weight of the particles (Morgan 2005). However, in these volcanic soils, sand fraction has a high content of volcanic glass (Valenzuela et al. 2002), which is strongly vesicular or pumiceous, and is considered a light fraction (Schoeneberger et al. 1998; McDaniel et al. 2012). Sand fraction may be

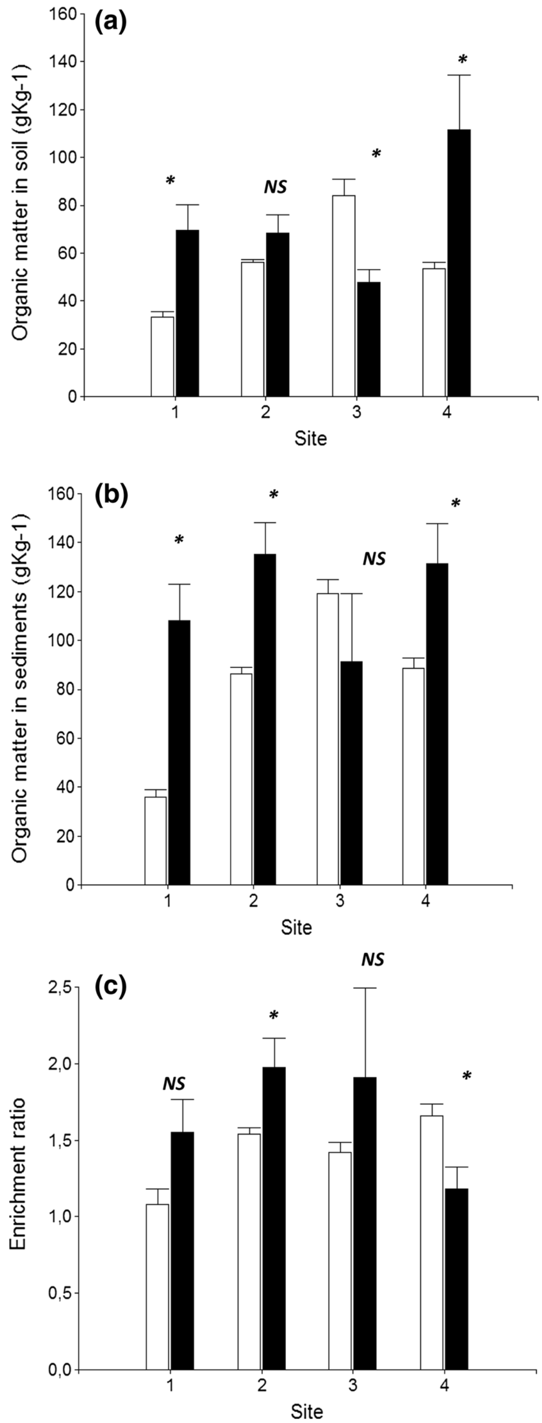

Fig. 4 Organic matter in soils (**a**), sediments (**b**) and enrichment ratio of sediments (**c**) for simulation rainfall assays carried out in degraded rangeland soils (*white bars*) and plantations with removal of the fresh litter and the duff layers (T_3) (*black bars*). Results of Kruskall–Wallis test run for each site are shown. *NS* no significant differences ($p > 0.05$); *Significant differences ($p < 0.05$)

highly sensitive to water erosion, mainly when associated with a low organic matter content, aggregate stability and vegetation cover. The rangeland Site 1 also presented the highest bare soil cover and the lowest perennial grass cover, representing the most degraded condition from a forage production perspective (Beeskow et al. 1995).

On the other hand, sandy loam soils of Site 3 with non-crystalline materials showed the lowest sediment production rates. Although the increasing cover of unpalatable shrubs, which is highest in Site 3, is considered an evidence of degradation (Beeskow et al. 1995), these soils showed the highest organic matter content, total porosity, field capacity and available water capacity values. These properties are associated with the presence of non-crystalline materials (Warkentin and Maeda 1980; Wada 1985; Takahashi and Dahlgren 2016), since they have high surface areas and variable surface charge, which explains their strong affinity for water and organic molecules (Wada and Aomine 1973; McDaniel et al. 2012). These properties would determine the lowest erodibility and runoff rate of these soils. Our results agree with studies carried out in other environmental conditions, which have shown that the erosion behavior of the volcanic ash soils was strongly affected by their pedological development (Zehetner and Miller 2006). Tropical volcanic soils with non-crystalline materials and accumulation of organic matter were significantly less erodible than other volcanic soils (Jungerius 1975). In soils with non-crystalline materials, erosion rates varied between 0 and 351 g m^{-2} h^{-1} (Zehetner and Miller 2006), with maximum values similar to the mean value found in Site 3 of our study area (i.e., 288 g m^{-2} h^{-1}). Although this study was performed on sites with lower slopes, the applied simulated rainfall events, with a varying intensity during 30 min and a kinetic energy of 19.5 J m^{-2} mm^{-1}, were similar to the considered in our study.

On the other hand, the erodibility of the rangeland loam soils analyzed in the present study, both without non-crystalline materials, varied according to their clay contents. Thus, loam soils with highest values of aggregate stability (Site 4), associated with higher contents of clay, showed sediment production rates similar to those found for soils with non-crystalline materials.

Although grass, shrub–grass and shrub steppes represent a degradation gradient in NE Patagonia from a forage production perspective (Beeskow et al. 1995), it is not clear whether these plant communities also represent a vulnerability gradient to soil erosion. Soils in the shrub steppes (Site 1) showed the highest erosion rate. On the contrary, Chartier and Rostagno (2006) found that degraded shrub steppes represented stable states with present erosion rates lower than in more conserved communities, for example grass–shrub steppes. This was attributed to the surface protection afforded by a continuous gravel cover (desert pavement) developed in eroded areas.

The influence of pine plantations on soil quality

The main influence of pine plantation on soils was through an abundant provision of leaf litter that seems to decompose slowly. Leaf litter represents the main source of topsoil organic carbon gains in the plantations, whereas in rangeland soils, roots are the primary input to soil organic matter (Dormaar 1992). The effects of pine plantations on soil quality greatly varied among soils. In superficial soils without non-crystalline materials (Sites 1, 2 and 4), with either sandy or loamy textures, the organic matter content increased 32 % respect to the rangeland soils. Other physical variables closely related to organic matter content such as field capacity, total porosity, effective porosity and aggregate stability also increased.

Soil organic matter content is a good indicator of soil quality because of its influence on some important functional properties, such as soil fertility, soil structure, infiltration rates and soil erosion resistance (Ogle and Paustian 2005). Several decades of livestock grazing, the historical economic activity in these rangelands, has caused large losses of perennial grasses cover and soil organic matter leading to intense land degradation. The complement of pine plantations and livestock grazing, as in other similar ecological areas, might accelerate the decomposition of the abundant leaf litter and favor the incorporation of organic carbon in the topsoil. In a *P. ponderosa*-based silvopastoral systems in Chile, Dube et al. (2013) found that soil organic carbon contents in the 0–40 cm depth was higher in the silvopastoral system as compared to those from adjacent 18-year-old managed pine plantations and natural prairie.

The changes of physical and chemical properties found in soils without non-crystalline materials suggest that plantations could imply long-lasting improvements in soil quality.

On the contrary, changes produced by pine plantations in the soil with non-crystalline materials were opposite to the other soils. Depletion in soil fertility was found, with lower values of organic matter, available water and aggregate stability than the rangeland soils. Similar results were found in Patagonia where plantations were established on fertile soils replacing native forests, recording decrease in organic matter, total N and exchangeable cations (Gobbi et al. 2002). Soil fertility prior to planting would determine the effect of the pines on soil, and plantations would generate increases in the content of organic matter and N, only when they are established on low fertility soils (Gobbi et al. 2002). Although Site 3 was a degraded rangeland, with high shrub cover, soils were fertile, rich in organic matter and non-crystalline materials.

Changes in soil properties associated to exotic conifers plantations have been controversial. While some studies have documented decreases on soil fertility (i.e., lower values of pH, Ca and exchangeable Mg, and higher values of exchangeable *H* and Al) (Amiotti et al. 2000), other studies found improvements in soil porosity and permeability (Broquen et al. 2000).

The influence of pine plantations on potential erosion

The important role of the litter layer in protecting the topsoil from erosion by intercepting raindrops and absorbing their kinetic energies has been recognized (Geißler et al. 2012). Thus, under pine plantations with 100 % litter cover, soil detachment and sediment production were very low (6.2 ± 1.5 g m^{-2}), with values lower than 3 % of the sediment production in the rangelands. These values are similar to those reported for simulated rain assays carried out in native forests near to the study area (Morales et al. 2013). Studies of pine plantations in other areas worldwide also showed that this type of vegetation had negligible soil losses in comparison with other vegetation types like row crops or grasslands (El Kateb et al. 2013). In our study, thicker organic horizons were also related to lower runoff.

The removal of organic materials represents different degrees of canopy opening, associated with increasing forest management intensities. Removing litter (T_2) slightly increased the sediment production (23.7 ± 7.9 g m^{-2}), remaining, however, significantly lower than the sediment production in the rangeland plots. Removing litter and the duff layer (T_3) determined a further increase in sediment production (129.1 ± 23.2 g m^{-2}), but remained significantly lower than erosion rates in the rangeland sites, when the four study sites were analyzed together.

However, the quantitative effect of pine plantations on protecting the soil, when experimentally bared soils were considered, varied according to soil properties and to sediment production in rangelands. The higher the erodibility of the steppe soils, the greater the relative effect of pine plantations. Thus, sediment production in artificially bared soils of the pine plantations was between 30 and 80 % respect to the sediment production in the adjacent rangeland soils. For this treatment (T_3), significant differences were found only for the most erodible soils (Sites 1 and 2). On the contrary, differences were neither significant for soils with non-crystalline materials (Site 3) nor for soils well provided with clay and high aggregate stability (Site 4). These soils could better support managements that lead to thinner organic horizons (for example, heavy thinning or silvopastoral agroforestry systems). However, since these soils also presented high erosion rates in bare conditions of the steppe, any forest management should conserve a minimum soil cover.

Although improvements in mineral soil associated with plantations were found, our results highlight the importance of litter in pine plantations as a protecting soil factor, in agreement with other studies (Maestre and Cortina 2004; Chirino et al. 2006; Geißler et al. 2012; Gu et al. 2013; Montenegro et al. 2013; Cao et al. 2015). Moreover, since throughfall drops under forest vegetation can be more erosive than open field rainfall, litter layers in forests are essential to protect the soil against erosion (Hall and Calder 1993; Zhou et al. 2002; Geißler et al. 2012), and it should be considered for planning forest management and logging strategies.

No significant difference was found in infiltration and runoff between bare soils and under pine plantations, which might be due to the fact that only one rainfall simulation test was conducted on initial dry conditions. However, runoff in experimentally bared pine plantation plots tended to increase, reaching values even higher than those documented in the rangelands. The unexpectedly high runoff production in the pine plantations plots could be related to the water repellency of hydrophobic compounds leached from pine litter (Doerr et al. 1998; Jaramillo Jaramillo 2005). Besides, water repellency increases with increasing organic matter content in soils (Harper et al. 2000; Jaramillo et al. 2000). On the other hand, surface soil disturbance when removing the duff layer also could have affected the runoff production. The enhancement in soil water repellency could also have influenced the decrease observed in soil erosion rates under plantations. Since changes in soil water repellency can change the hydrological cycle in the area, this aspect should be aboard in future studies.

This study, the first one in evaluating the erodibility of volcanic soils under pine plantations in west Patagonia, focused on the most frequent situations in the study area. These are, *P. ponderosa* plantations, approximately 20 years old, with null or slight management and adjacent degraded rangelands. Future studies should evaluate other management conditions, density and age of plantations, and also non-degraded rangelands and different vegetation covers in degraded rangelands, since perennial grasses and shrubs could also have a protective effect (Zhao et al. 2014).

Sediment enrichment ratio

While some studies documented that pines plantation involved an increase in organic matter (Nosetto et al. 2006), as occurred in most of our study sites, others found greater organic matter content in rangelands than in plantations (Laclau 2003; Buduba 2006), as occurred in Site 3. The decrease in organic matter content was attributed to the high canopy cover which prevents light reaching the soil surface and the development of the understory vegetation and, therefore, the input of labile organic matter linked to the mineral fraction (Laclau 2003; Buduba 2006).

Organic matter content in sediments followed a similar pattern than organic matter in the superficial soil. The greater organic matter content in sediments than in soils would suggest that the sediments were enriched with organic matter, as compared to the contributing soils, indicating its selective removal. The enrichment ratios found in our study could be related to the detachment of soil microaggregates. In volcanic soils was proved that erosion processes affect mainly microaggregates, which are mobilized with no previous dispersion (Rodriguez Rodríguez et al. 2002, 2006). Selective process of organic carbon loss has been reported in other studies (Avnimelech and McHenry 1984; Sharpley 1985; Chartier et al. 2013). In our study, the enrichment ratio of organic matter decreased with increasing soil loss, agreeing with the previous studies (Schiettecatte et al. 2008).

The selective removal of organic matter, a key component in semiarid soils (Evans and Young 1970) could be considered an important nutrient depletion process that, combined with the high erodibility of the soils, reveals the fragility of the ecosystem under study.

For most of the sites, the enrichment ratio tended to increase in the pine plantations when the organic horizon was removed as compared to rangelands. These potential carbon losses should be considered for logging procedure, in order to prevent the soil remains bare.

Conclusions

The high erodibility of rangeland soils with dominance of bare soil suggested the high fragility of these ecosystems when they are submitted to continuous and heavy grazing. Our results showed the importance of conserving the soil cover to avoid accelerated erosion. Where the soils under pine plantations were covered by litter and/or duff layers, soil erosion rates were negligible, regardless of the physical–chemical conditions of the mineral soil. The protective effect of the organic materials in these vulnerable soils is essential, and its conservation should be considered a management target in logging practices.

However, the protective effect of pine plantations was not exclusively afforded by a mulching effect, since erosion rates in some plantations were lower than in rangelands even when both litter and duff layers were removed. This result could be attributed to an improvement in soil quality associated with pine plantations.

Our results showed that some aspects of soil quality have been effectively improved in degraded rangelands after being under pine plantation for 20 years, mainly associated to a significant increase in soil organic matter and some associated soil physical variables. This improvement in soil quality, closely linked to a higher resistance to soil erosion, was restricted to soils without non-crystalline minerals.

The decrease in vegetation cover favored by livestock grazing, as well as the selective removal of organic matter as erosion proceeds, reveals the fragility of these soils and limit the natural recovery of the soil physical and hydrological properties, affecting the natural re-establishment of perennial grasses. Thus, restoring the soil cover through different management strategies becomes a key factor to mitigate the erosion process. In this context, *P. ponderosa* plantations can be considered an alternative land use that favors soil conservation and could improve livestock industry through agroforestry in addition to forest production.

Acknowledgments We acknowledge Agustín Gigli for his invaluable help with the fieldwork. We appreciate the valuable comments of two anonymous reviewers. This research was supported by PICT 1715 of the National Agency for Scientific and Technological Promotion (ANPCyT) and by PIP 11420100100290 of the National Research Council of Argentina (CONICET).

References

Amiotti NM, Zalba P, Sánchez LF, Peinemann N (2000) The impact of single trees on properties of loess-derived grasslands soils in Argentina. Ecology 81:3283–3290

Apcarian A, Irisarri J (1993) Caracterización mineralógica de suelos desarrollados sobre cenizas volcánicas en las provincias de Neuquén y Río Negro (R.A.). II Jornadas de Vulcanología, Medio ambiente y Defensa Civil. Zapala, Neuquén

Ares J, Beeskow AM, Bertiller M, Rostagno M, Irisarri M, Anchorena J, Defossé GE, Merino C (1990) Structural and dynamic characteristics of overgrazed lands of northern Patagonia, Argentina. In: Bremeyer A (ed) Managed grasslands: regional studies. Elsevier, Amsterdam, pp 149–175

Avnimelech Y, McHenry J (1984) Enrichment of transported sediments with organic carbon nutrients and clay. Soil Sci Soc Am J 48:259–266

Barros V, Scian B, Matto H (1979) Campos de precipitación en la provincia de Chubut (período 1931–1960). Geoacta 10:175–192

Beeskow AM, Elissalde NO, Rostagno CM (1995) Ecosystem change associated with grazing intensity on the Punta Ninfas rangelands of Patagonia, Argentina. J Range Manage 48:517–522

Berger TW, Berger P (2012) Greater accumulation of litter in spruce (Picea abies) compared to beech (Fagus sylvatica) stands is not a consequence of the inherent recalcitrance of needles. Plant Soil 358:349–369

Bertiller MB (1993) Estepas graminosas de Festuca pallescens en el SW del Chubut. In: Paruelo JM, Bertiller MB, Schlichter TM, Coronato F (eds) Secuencias de deterioro en distintos ambientes Patagónicos. Su caracterización mediante el modelo de Estados y Transiciones, Cooperacion INTA-GTZ, S.C, de Bariloche, pp 14–22

Blake B (1965) Bulk density. In: Black CA (ed) Methods of soil analysis Monogr Ser Part 1 No 9 Am Soc Agron, Madison, Winscousin, pp 374–390

Broquen P, Falbo G, Frugoni C, Girardin JL, Guido M, Martinese P (2000) Estructura y porosidad en Andisoles con vegetación natural y con plantaciones de Pinus ponderosa Dougl. en el Sudoeste de Neuquén, Argentina. Bosque 21:25–36

Broquen P, Falbo G, Apcarián A, Candan F, Girardin J, Pellegrini V (2003) Relaciones entre las forestaciones, la erosión del suelo, y la potencialidad productiva en la transición bosque-estepa (Andinopatagonia, Argentina). Inv Agr Sist y Rec Ftales 12(2):99–110

Bryan RB (2000) Soil erodibility and processes of water erosion on hillslope. Geomorphology 32:385–415

Buduba CG (2006) Modificaciones en el pH y contenido de materia orgánica en suelos del ecotono estepa/bosque andino patagónico por implantación de pino ponderosa. Dissertation, Universidad de Buenos Aires

Cabrera A (1971) Fitogeografía de la República Argentina. Boletín de la Sociedad Argentina de Botánica XIV, p 50

Cao L, Liang Y, Wang Y, Lu H (2015) Runoff and soil loss from Pinus massoniana forest in southern China after simulated rainfall. Catena 129:1–8

Chartier MP, Rostagno CM (2006) Soil erosion thresholds and alternative states in Northeastern Patagonian Rangelands. Rangeland Ecol Manage 59:616–624

Chartier MP, Rostagno CM, Videla LS (2013) Selective erosion of clay, organic carbon and total nitrogen in grazed semiarid rangelands of northeastern Patagonia, Argentina. J Arid Environ 88:43–49

Chirino E, Bonet A, Bellot J, Sánchez J (2006) Effects of 30-year-old Aleppo pine plantations on runoff, soil erosion, and plant diversity in a semi-arid landscape in south eastern Spain. Catena 65:19–29

Colmet Daage F, Marcolin A, López C, Lanciotti M, Ayesa J, Bran D, Andenmatten E, Broquen P, Girardin J, Cortés G, Irisarri J, Besoain E, Sadzawka A, Sepúlveda G, Massaro S, Millot G, Bouleau P (1988) Características de los suelos derivados de cenizas volcánicas de la cordillera y precordillera del norte de la Patagonia. Convenio INTA – ORSTOM. S. C. de Bariloche, Río Negro

Dahlgren RA, Saigusa M, Ugolini FC (2004) The nature, properties and management of volcanic soils. Adv Agron 82:113–182

Davies BE (1974) Loss-on ignition as an estimate of soil organic matter. Soil Sci Pro 38:150

Day P (1965) Particle fractionation and particle-size analysis. In: Black CA (ed) Methods of soil analysis Monogr Ser Part 1 No 9 Am Soc Agron, Madison Winscousin, pp 545–567

Del Valle HF, Elissalde N, Gagliardini D, Milovich J (1998) Status of desertification in the Patagonian region: assessment and mapping from satellite imagery. Arid Land Res Manag 12(2):95–121

Di Rienzo JA, Casanoves F, Balzarini MG, Gonzalez L, Tablada M, Robledo CW (2013) InfoStat versión 2013. Grupo InfoStat, FCA, Universidad Nacional de Córdoba, Argentina. http://www.infostat.com.ar

Doerr S, Shakesby R, Walsh R (1998) Spatial variability of soil hydrophobicity in fire-prone Eucalyptus and Pine forests, Portugar. Soil Sci 163:313–324

Dormaar JF (1992) Decomposition as a natural process in grasslands. In: Coupland RT (ed) Natural grasslands: introduction and Western Hemisphere. Elsevier, New York, pp 121–136

Dube F, Thevathasan NV, Stolpe NB, Zagal E, Gordon AM, Espinosa M, Sáez K (2013) Selected carbon fluxes in Pinus ponderosa-based silvopastoral systems, exotic plantations and natural pastures on volcanic soils in the Chilean Patagonia. Agrofor Syst 87:525–542

El Kateb H, Zhang H, Zhang P, Mosandl R (2013) Soil erosion and surface runoff on different vegetation covers and slope gradients: a field experiment in Southern Shaanxi Province, China. Catena 105:1–10

Epema GF, Riezebos HT (1983) Fall velocity of water drops at different heights as a factor influencing erosivity of simulated rain. Catena Supp 4:1–18

Escofier B, Pagès J (1992) Análisis factoriales simples y múltiples: objetivos, métodos e interpretación. Servicio Editorial Argitarapen-Zerbitzua, Bilbao, España

Evans RA, Young JA (1970) Plant litter and establishment of alien annual weed species in rangeland communities. Weed Sci 18:697–703

Fieldes MP, Perrot KW (1966) The nature of allophane in soils. III. Rapid field and laboratory test for allophane. N Z J Sci 9:623–629

Geißler C, Kühn P, Böhnke M, Bruelheide H, Shi X, Scholten T (2012) Splash erosion potential under tree canopies in subtropical SE China. Catena 174:596–601

Gobbi ME, Mazzarino MJ, Ferrari J (2002) Efecto de plantaciones de coníferas sobre la fertilidad del suelo en la Región Andino Patagónica. XVIII Congreso Argentino de la Ciencia del Suelo. Pto, Madryn

Golluscio R, Deregibus A, Paruelo J (1998) Sustainability and range management in the Patagonian steppes. Ecol Austral 8:265–284

Gómez F, Tarabini M, Buduba C, La Manna L (2015) Distribución de la precipitación en un bosque de pino radiata con manejo silvopastoril versus forestal tradicional. VIII Congreso Internacional de sistemas agroforestales y III Congreso Nacional de sistemas silvopastoriles. Iguazú, Argentina

Gonda HE, Cortés GO (2001) Ecuaciones para el manejo de las plantaciones de pino ponderosa en Neuquén. Publicación técnica N° 30. CIEFAP. Esquel, Argentina. p 24

Gu ZJ, Wu XX, Zhou F, Luo H, Shi XZ, Yu DS (2013) Estimating the effect of Pinus massoniana lamb plots on soil and water conservation during rainfall events using vegetation fractional coverage. Catena 109:225–233

Hall RL, Calder IR (1993) Drop size modification by forest canopies: measurements using a disdrometer. J Geophys Res 98:18465–18470

Harper R, Mckissock I, Gilkes R, Carter D, Blackwell P (2000) A multivariate framework for interpreting the effects of soil properties, soil management and land use on water repellency. J Hydrol 231:371–383

Helalia AM (1993) The relation between soil infiltration and effective porosity in different soils. Agr Water Manage 24:39–47

Irisarri J (2000) La propuesta de reclasificación de los Andepts de Argentina, de acuerdo al Orden Andisoles. Workshop Soil Taxonomy. Instituto Nacional de Tecnología Agropecuaria, AICET, Asociación Argentina de la Ciencia del Suelo, pp 18–27

Irisarri J, Mendía J (1997) Relaciones suelo-paisaje en la evaluación de la potencialidad forestal de la región central andino—patagónica, Argentina. Bosque 18:21–30

Irisarri JA, Mendía JM, Roca C, Buduba CG, Valenzuela MF, Epele F, Fraseto F, Ostertag G, Bobadilla S, Andenmatten E (1995) Zonificación de lastierras para la aptitud forestal de la Provincia del Chubut. DirecciónGeneral de Bosques y Parques de la Provincia del Chubut, Chubut

Irurtia CB, Mon R (1994) Microsimulador de lluvia para determinar infiltración a campo. Instituto de suelos INTA-Castelar. Publicación N° 176

Jaramillo Jaramillo DF (2005) Humedad crítica y repelencia al agua en andisoles colombianos bajo cobertura de pinus patula schltdl y cham. Rev Fac Nal Agr Medellín 58(2):2893–2906

Jaramillo DF, Dekker LW, Ritsema CJ, Hendrickx JMH (2000) Occurrence of soil water repellency in arid and humid climates. J Hydrol 231–232:105–111

Jungerius PD (1975) The properties of volcanic ash soils in dry parts of the Colombian Andes and their relation to soil erodibility. Catena 2:69–80

Kurka AM, Starr M (1997) Relationship between decomposition of cellulose in the soil and tree stand characteristics in natural boreal forests. Plant Soil 197:167–175

Laclau P (2003) Biomass and carbon sequestration of ponderosa pine plantations and native cypress forests in northwest Patagonia. For Ecol Manage 180:317–333

López Ritas J, López Mélida J (1990) El diagnóstico de suelos y plantas: métodos de campo y laboratorio, 4th edn. Mundi-Prensa, Madrid, España

Maestre F, Cortina J (2004) Are Pinus halepensis plantations useful as a restoration tool in semiarid Mediterranean areas? For Ecol Manage 198:303–317

McDaniel PA, Lowe DJ, Arnalds O, Ping CL (2012) Andisols. In: Huang PM, Li Y, Sumner ME (eds) Handbook of soil sciences, vol 1, 2nd edn., Properties and processesCRC Press (Taylor & Francis), Boca Raton, FL, pp 29–48

Middleton H (1930) Properties of soils which influence soil erosion. Technical Bulletin 178. United States of Agriculture, Washington

Montenegro A, Abrantes J, de Lima J, Singh V, Santos T (2013) Impact of mulching on soil and water dynamics under intermittent simulated rainfall. Catena 109:139–149

Morales D, Rostagno M, La Manna L (2013) Runoff and erosion from volcanic soils affected by fire: the case of Austrocedrus chilensis forests in Patagonia, Argentina. Plant Soil 370:367–380

Morgan RP (2005) Soil erosion and conservation, 3rd edn. Blackwell, Malden

Nosetto M, Jobbágy E, Paruelo J (2006) Carbon sequestration in semi-arid rangelands: comparison of Pinus ponderosa plantations and grazing exclusion in NW Patagonia. J Arid Environ 67:142–156

Ogle SM, Paustian K (2005) Soil organic carbon as an indicator of environmental quality at the national scale: inventory monitoring methods and policy relevance. Can J Soil Sci 85:531–540

Parfitt RL, Saigusa M, Cowie JD (1984) Allophane and halloysite formation in a volcanic ash bed under different moisture conditions. Soil Sci 138:360–364

Poulenard J, Podwojewski P, Janeau JL, Collinet J (2001) Runoff and soil erosion under rainfall simulation of Andisols from the Ecuadorian Páramo: effect of tillage and burning. Catena 45(3):185–207

Raffaele E, Schlichter T (2000) Efectos de las plantaciones de pino ponderosa sobre la heterogeneidad de micrositios en estepas del noroeste patagónico. Ecol Austral 10:151–158

Renard, KG, Foster GR, Weesis GA, McCool DK,Yoder DC (1997) Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). USDA, Agricultural Handbook No. 703

Rodríguez Rodríguez A, Arbelo C, Guerra J, Mora J (2002) Erosión hídrica en Andosoles de las Islas canarias. Edafologia 9(1):23–30

Rodríguez Rodríguez A, Arbelo C, Guerra J, Mora J, Notario J, Armas C (2006) Organic carbon stocks and soil erodibility in Canary Islands Andosols. Catena 66:228–235

Rostagno CM (1989) Infiltration and sediment production as affected by soil surface conditions in a shrubland of Patagonia, Argentina. J Range Manage 42:382–385

Rostagno CM, Degorgue G (2011) Desert pavements as indicators of soil erosion on aridic soils in north-east Patagonia (Argentina). Geomorphology 134:224–231

Schiettecatte W, Gabriels D, Cornelis W, Hofman G (2008) Enrichment of organic carbon in sediment transport by interrill and rill erosion processes. Soil Sci Soc J 72:50–455

Schoeneberger PJ, Wysocky DA, Benham EC, Broderson WD (1998) Field book for describing and sampling soils. Natural Resources

Conservation Service, USDA, National Soil Survey Center, Lincoln
Sharpley A (1985) The selective erosion of plant nutrients in runoff. Soil Sci Soc Am J 49:1527–1534
Shoji S, Nanzyo M, Dahlgren RA (1993) Volcanic ash soils: genesis, properties and utilization. Elsevier, Amsterdam
Soil Survey Staff (2014) Keys to soil taxonomy, 12th edn. USDA-Natural Resources Conservation Service, Washington, DC
Takahashi T, Dahlgren R (2016) Nature, properties and function of aluminum—humus complexes in volcanic soils. Geoderma 263:110–121
Tarabini M, Gómez F, Buduba C, Rostagno M, La Manna L (2014) Ceniza volcánica reciente: ¿un calibre en el suelo?. XXIV Congreso Argentino de la Ciencia del Suelo, Bahía Blanca
Valenzuela MF, Irisarri J, Ferro L, Buduba CG (2002) Caracterización mineralógica de suelos desarrollados sobre cenizas volcánicas en el noroeste de la Provincia del Chubut. XVIII Congreso Argentino de la Ciencia del Suelo. Pto, Madryn
Wada K (1985) The distinctive properties of Andosols. Adv Soil S 2:173–229
Wada K, Aomine S (1973) Soil development on volcanic materials during the Quaternary. Soil Sci 116:170–177
Warkentin BP, Maeda T (1980) Physical and mechanical characteristics of Andisols. In: Theng BK (ed) Soil with variable charge. New Zealand Society of Soil Science, pp 281–301
Zehetner F, Miller W (2006) Erodibility and runoff-infiltration characteristics of volcanic ash soils along an altitudinal climosequence in the Ecuadorian Andes. Catena 65:201–213
Zhao X, Huang J, Wu P, Gao X (2014) The dynamic effects of pastures and crop on runoff and sediments reduction at loess slopes under simulated rainfall conditions. Catena 119:1–7
Zhou GY, Morris JD, Yan JH, Yu ZY, Peng SL (2002) Hydrological impacts of reafforestation with eucalypts and indigenous species. For Ecol Manage 167:209–222