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Soil conservation in *Polylepis* mountain forests of Central Argentina: Is livestock reducing our natural capital?

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Abstract Mountain forests and their soils provide ecological services such as maintenance of biodiversity, provision of clean water, carbon capture and forage for livestock rearing, which is one of the principal economic activities in mountain areas. However, surprisingly little is known about livestock impact in South American mountain forest soils. With the aim of understanding how livestock and topography influence patterns of forest cover, soil compaction, soil loss and soil chemical properties, we analysed these parameters in 100 *Polylepis australis* woodland plots situated in the humid subtropical mountains of Central Argentina. We used distance from the nearest ranch as an objective index of historical livestock impact and measured standard topographic variables. Our main results reveal that distance from ranch in all cases partly explains tree canopy cover, soil loss, soil compaction and soil chemical properties; suggesting a strong negative effect of livestock. Intermediate altitudes had more tree canopy cover, while landscape roughness – a measure of the variability in slope inclination and aspect – was negatively associated to soil impedance and acidity, and positively associated to soil organic matter content. Finally, flatter areas were more acid. We conclude that livestock has had a substantial influence on forest soil degradation in the Mountains of Central Argentina and possibly other similar South American mountains. Soil degradation should be incorporated into decision making when considering long-term forest sustainability, or when taking into account retaining livestock for biodiversity conservation reasons. Where soil loss and degradation are ongoing, we recommend drastic reductions in livestock density.

Key words: Córdoba, domestic grazing, land use, nutrient loss, *Polylepis australis*, soil erosion.

INTRODUCTION

Mountain forests worldwide are well-known for the ecological services they provide to humans such as maintenance of biodiversity, provision of clean water and carbon capture, all of which ultimately depend on good-quality soils (Körner 2002; Mannerkoski *et al.* 2005; Paul *et al.* 2008). Soils support seed banks, water and nutrients necessary for germination and re-sprouting of trees after disturbances. In climates with seasonal rains, soils store water which, during the dry season, is delivered to streams and rivers. In addition, large amounts of organic carbon are effectively fixed in soils of cold mountain ecosystems – thus reducing atmospheric carbon accumulation and global warming (Hunter 1990; Richards 1997; Körner 2002; Hertel *et al.* 2003; Núñez *et al.* 2006). Mountain soils may therefore be considered an important component of our natural capital, and their conservation provides substantial benefits. Managing economic activities in mountain areas to prevent soil loss and maintain soil integrity is thus of foremost importance.

The main economic activity in most mountain regions of the world is livestock grazing (Price 1981), which may produce soil compaction because of pressure exerted by hooves, and soil loss because of a combination of removal of protecting vegetation together with an increase in water surface runoff (Greenwood & McKenzie 2001). In the past, it was generally considered that in ecosystems with long evolutionary histories of large herbivore grazing, livestock did not produce irreversible ecosystem processes such as soil loss because the protective vegetation had adapted to grazing through tolerance or avoidance mechanisms (Milchunas *et al.* 1988; Cingolani *et al.* 2005). However, in many South American high mountain areas which are supposed to have a long history of large herbivore grazing, there is also evidence of extensive land degradation because of high grazing pressure (Fjeldså & Kessler 1996; Busnelli *et al.* 2006; Cingolani *et al.* 2008). Some authors have suggested that this soil loss is mainly related to climate, geology and topography rather than to the influence of livestock

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(e.g. Cabido *et al.* 1987 for Central Argentina), or that soil loss and deposition are at equilibrium (e.g. Preston *et al.* 2003 for the Tarija Altiplano in Bolivia).

According to Cingolani *et al.* (2005), it is not the length of the evolutionary history of grazing per se, but rather any difference between present and past evolutionary grazing pressure that determines the susceptibility of the system to domestic livestock. Thus, soil loss in the mountains of South America may result from the unnaturally high stocking rates combined with the relatively higher pressure exerted on soils by European domestic livestock than that of the native camelids, and the extensive use of fire to promote pasture regrowth (Cingolani *et al.* 2005, 2008). In particular, recent studies in the mountains of Central Argentina show very strong evidence that domestic livestock caused important and widespread soil losses. A positive correlation was found between livestock density and active soil loss in grasslands resulting in a complete loss of the soils in around 20% of the area (Cingolani *et al.* 2003, 2004), while a landscape scale study corroborated that most soil loss had occurred near roads and rancher houses where livestock pressure is highest (Cingolani *et al.* 2008).

Because forest cover is extremely important in reducing soil loss – and livestock tend to avoid areas of forest cover – it could be argued that within forest areas livestock impact on soils is negligible. Supporting this argument, we have found only a limited number of studies on the impacts of livestock in mountain forest soils, while studies related to the impacts of the forestry industry, or on the conversion to agricultural land are more frequent (Belsky & Blumenthal 1997; Carpenter *et al.* 2001; Strunk 2003; Shrestha *et al.* 2004; Celik 2005; Navas *et al.* 2005; Sharrow 2007). In Central Argentina, several authors have observed high quantities of soil loss within forests, suggesting an impact of domestic livestock (Renison *et al.* 2006; Torres *et al.* 2008) – but no specific study determining the drivers of soil degradation within forests has been performed. In these mountain areas, the conservation and restoration of forests and their soils are especially important as several studies have shown that soil degradation hampers forest recovery because of a reduction in seed viability, seedling recruitment and growth patterns of the dominant species (Renison *et al.* 2004, 2005, 2006; Torres *et al.* 2008).

Our aim was to examine the drivers of soil degradation in the *Polylepis* mountain forests of Central Argentina and to suggest soil conservation measures. Specifically, we (i) describe *Polylepis* forest canopy cover, soil loss, soil compaction and soil chemical properties; and (ii) analyse whether these response variables are explained by indicators of domestic livestock impact and topography. As a proxy for livestock impact, we used 'distance from ranch' (as in Cingolani *et al.* 2008). We expected to find more soil compaction, higher top-soil loss and lower nutrient contents near ranches and in level areas which are more accessible to livestock than far from ranches and in areas with a high local terrain roughness. We also expected more soil loss in steep areas and valley bottoms with increased water surface runoff (Morgan 1979), and less soil loss and more organic matter and nutrients at intermediate altitudes where tree canopy cover is highest in our study area because of optimal growth conditions for *P. australis* (Cingolani *et al.* 2004; Marcora *et al.* 2008).

As soil degradation is widespread in other similar mountain ecosystems including most of the endangered *Polylepis* forests endemic to the mountains of South America (Fjeldså 2002; Hensen 2002; Ibisch 2002; Busnelli *et al.* 2006), our findings may contribute to a general understanding of soil degradation processes in high-mountain forest ecosystems and provide a better understanding of their causes.

METHODS

Study area

The study was carried out in the mountains of Central Argentina (humid subtropical, province of Córdoba; max. elevation 2884 m a.s.l.; 31°34′S, 64°50′W, Fig. 1). At 2100 m a.s.l., mean temperatures of the coldest and warmest months are 5.0 and 11.4°C, respectively, with no frost-free period (Cabido 1985). Mean annual precipitation is 920 mm, with 83% of the rainfall concentrated in the warmer months between October and April (Colladon 2000; Renison *et al.* 2002). Soil parent material in the mountain range is composed of pink granite with potassium feldspar and quartz dominating over biotite. Soils are derived from the weathering of the granite substrate and fine-textured aeolian deposits (Cabido *et al.* 1987). The landscape consists of a mosaic of tussock grasslands, grazing lawns, eroded areas with exposed rock surfaces, granite outcrops and forests, which occupy 12% of the area. Forest canopies are almost exclusively dominated by *Polylepis australis* and are usually restricted to rocky areas, steep slopes in mid to low topographic positions where fires, which are mainly caused by humans, are less frequent (Renison *et al.* 2002, 2006). Livestock grazing began early in the 17th century and is the main economic activity in the mountains of Central Argentina (mainly cattle; but also sheep, horses and goats). Livestock grazing together with vegetation burning is the main cause of forest retraction, and at present stocking rates range from 0.2 to 2.2 cattle equivalents per ha and fire is used extensively to promote grass regrowth (Cingolani *et al.* 2004; Teich *et al.* 2005; Renison *et al.* 2006).

In 2003, as part of an ongoing monitoring programme, we established 146 permanent study plots in *Polylepis* forests, from which we have published an analysis on the drivers of forest canopy cover and tree growth forms as well as an analysis on the drivers of forest structure (Renison *et al.* 2006, 2009).

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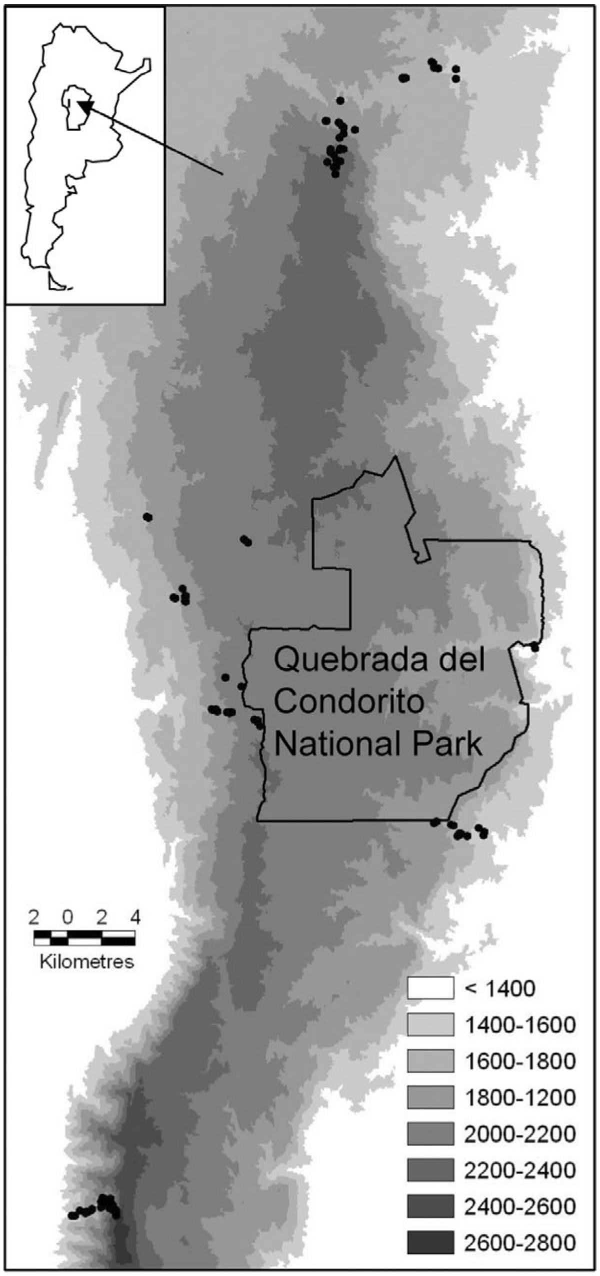

Fig. 1. Map of the mountains of Central Argentina with plot locations marked as solid circles. In grey scale is represented the altitudes above sea level.

Plot establishment

For the present study, we used 100 of the 146 study plots of 30 × 30 m described in Renison *et al.* (2006, 2009) corresponding to plots where no livestock exclusion had been performed (National Park Area, Fig. 1). The plots are distributed throughout five river basins at altitudes of between 1200 and 2700 m a.s.l. and separated by at least 200 m (Fig. 1). For plot establishment we randomly chose areas from the map that contained *Polylepis* forest or open shrubland, and stratified the sampling to obtain an even distribution of samples within each altitudinal belt. In the field, we located plots using a Global Positioning System and selected them for the study when there was at least one adult *P. australis* individual >2 m tall, all occurring individuals were accessible to researchers (and hence, domestic livestock).

Data collection

In each plot as response variables, we quantified tree canopy cover, indicators of long-term soil loss, soil compaction and soil chemical properties. Tree cover (%) was visually estimated as the projection of the tree canopy cover within the plot. As an indicator of long-term soil loss, we estimated rock exposed by soil loss (%). Exposed rock could be easily differentiated from natural outcrops because of the occurrence of surrounding erosion gullies and because of its sparser lichen cover (Cingolani *et al.* 2003, 2004). Soil compaction was estimated by measuring impedance (kg cm^{-2}) by insertion of a pocket penetrometer (Forestry Suppliers Inc.) at 20 randomly chosen points per plot up to a depth of 0.7 cm. A composite soil sample of ten subsamples 10 cm in depth was collected per plot to measure soil pH, total C and N, cation exchange capacity, and lactate-extractable phosphorous. After oven-drying for 48 h at 105°C and removal of coarse soil particles (>2 mm), the samples were subjected to the following chemical analyses: Soil pH was measured in a 1:5 soil water extract with a standard probe (SenTix 21, WTW); total carbon (corrected for carbonate-borne C) and total nitrogen content were analysed with the Dumas method (CN Analyser Vario EL, ELEMENTAR); cations were extracted with 0.1M NH_4Cl solution; Ca^{2+} and Mg^{2+} were analysed with Atomic Absorption Spectrometry and K^+ and Na^+ with flame spectrometry using a Flame-AAS (Vario EL, Analytik Jena); and, available phosphate was extracted with Ca-Lactate at pH 3.6 and measured with a photometer (EPPSTEIN).

As independent variables, in the field we recorded slope inclination (degrees) and elevation above sea level (m). Using a Geographic Information System of the area (Cingolani *et al.* 2008), we also measured distance from the closest ranch to each study plot (km), an index of land roughness and an index of topographic position, in both cases using a circular kernel of 315-m radius. The land roughness index represents variance in slope inclination and aspect, while the index of topographic position varies from 0 for the lowest to 1 for the highest topographic positions in relation to the surrounding landscape (Cingolani *et al.* 2008). We used distance from ranch as a proxy for long-term livestock impact as most ranching activities including vegetation burning are concentrated around ranches. The reasons for this concentration are that a large portion of the mountains remain unfenced, so cattle and horses are periodically driven to the proximities of the ranch, and, irrespective of fencing, sheep and goats are kept overnight close to ranches to avoid predation by pumas (*Puma concolor*). We checked if distance from ranch was a good indicator of present livestock densities in our study plots by randomly placing 50 times a 30 × 30 cm square and registering the presence of cattle, horse, and sheep dung.

Data were collected from March to December 2003, except for soil impedance. As impedance varies temporarily

Table 1. Soil chemical properties of 100 *P. australis* woodland plots and the results of a Principal Component Analysis (loadings > 0.40 in bold to ease comparison)

Variable	Mean ± SE		Axis 1	Axis 2	Axis 3
		Eigenvalues	3.95	1.33	1.04
		Percentage	49	17	13
		Cum. percentage	49	66	79
		Loadings for			
C (%)	7.8 ± 0.4		**0.45**	0.31	−0.06
N (%)	0.7 ± 0.03		**0.42**	0.39	−0.03
K^+ (mmol kg^{-1})	0.6 ± 0.1		0.38	−0.26	−0.11
Ca^{++} (mmol kg^{-1})	3.1 ± 0.1		**0.45**	−0.12	0.04
Mg^{++} (mmol kg^{-1})	0.3 ± 0.02		**0.43**	−0.21	0.24
P (p.p.m.)	37.5 ± 1.7		0.27	0.21	−0.19
pH (H_2O)	4.9 ± 0.4		0.16	**−0.74**	0.10
Na^+ (mmol kg^{-1})	0.3 ± 0.02		−0.01	0.19	**0.94**

Variables represent total C and N, cation exchange capacity for Na^+, Ca^{++}, Mg^{++} and K^+, and lactate-extractable phosphorous (P).

with water availability, we measured it during the middle of the dry season by revisiting all plots from July to August 2005.

Data analysis

For our main analysis, we performed six multiple linear regressions, with response variables as follows: (1) tree canopy cover; (2) proportion of rock exposed by soil loss; (3) soil impedance; and, (4–6) three synthetic variables representing the main axes of variation in soil chemical properties as assessed with Principal Component Analysis (PCA). The independent variables were: distance to the closest rancher settlement; slope inclination; altitude; and, the indices of land roughness and topographical position. Because tree canopy cover has an optimum at intermediate altitudes, we added the term altitude squared to all regressions. As we only had six independent variables, no selection procedure was applied and all independent variables were left in the final model. All crude response variables, including the chemical variables used for PCA (except pH), had a few exceptionally high values and their ln transformation was necessary to meet normality and homocedasticity assumptions (Underwood 1997). We also checked that all pairs of independent variables had absolute correlation coefficients below 0.55 (Afifi & Clark 1984). Data analysis was performed using the InfoStat (2001) software.

RESULTS

Tree canopy cover of *P. australis* and estimations of soil loss evidence, impedance and soil chemical properties were highly variable. Tree canopy cover ranged from 1% to 96% (average 16.9%; SE = 2.2), rock exposed by soil erosion from 0 to 30% (average 5.9%; SE = 0.7) and soil impedance per plot from 0.18 to 3.79 kg cm^{-2} (average 1.40 kg cm^{-2}; SE = 0.08). The three main axes of the PCA explained 79% of the variation in soil chemical properties (Table 1), and there was high co-linearity between total C, total N, Ca^{2+} and Mg^{2+}. These measures for soil organic matter and nutrient content had high positive loadings on the PCA axis 1. The pH value had a high negative loading on PCA axis 2, while Na^+ had a high positive loading on PCA axis 3 (Fig. 2; Table 1).

Results of the six linear multiple regression models are shown in Table 2. Tree canopy cover was positively related to distance from ranch and was highest at intermediate altitudes (both altitude and its quadratic term were significant), with no significant effect of local terrain roughness, slope or topographical position. Rock exposed by soil erosion was negatively associated with distance from ranch, and was not significantly related to local terrain roughness, slope, topographical position or altitude (Fig. 3a). Soil impedance declined with distance from ranch and in landscapes with a higher roughness index, with no significant effect of slope, topographical position or altitude (Fig. 3b). PCA axis 1 (organic matter) had an inverse pattern to soil impedance, with soils having more organic matter with distance from ranch and in rough landscapes (Fig. 3c). PCA axis 2 (acidity) increased with distance from ranch and decreased with landscape roughness and slope inclination, with no effect of topographic position and altitude (Fig. 3d). PCA axis 3 (salinity) only decreased with distance from ranch, with no significant effects of any of the other variables (Fig. 3e, Table 2). The explained variances were always low and ranged from a maximum of 32% for PCA axis 2 (acidity) to only 7% for rock exposed by soil erosion (column 2, Table 2).

Dung counts were negatively correlated with distance from ranch ($r_S = -0.47$, $P < 0.001$, $n = 100$), confirming our assumption that livestock is (and probably was already in the past) more concentrated close to ranches. Moreover, distance from ranch was not

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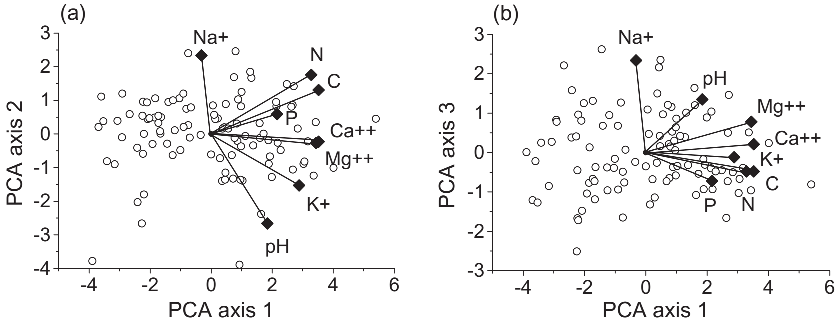

Fig. 2. Diagrams of Principal Component Analysis (PCA) summarizing soil chemical properties of 100 *P. australis* woodland plots; (a) shows PCA axes 1 and 2, while (b) shows PCA axes 1 and 3. Input variables were soil pH, total C and N, cation exchange capacity for Na^+, Ca^{++}, Mg^{++} and K^+, and lactate-extractable phosphorous (P). The position of each plot is represented by open circles, and the relative contribution of each variable to the axes is represented by solid diamonds.

significantly correlated with any of the other explanatory variables ($P > 0.08$), suggesting that distance from ranch was not replacing one of the other measured explanatory variables.

DISCUSSION

Our main results support the hypothesis that the degradation of *P. australis* forests and their soils is in part triggered by domestic livestock rearing, as distance from ranch (used as a proxy for long-term livestock grazing intensity) was always related to forest canopy cover and soil variables, indicating a general deterioration of forests and soil properties with decreasing distance from ranch. This finding is in line with the results of Renison *et al.* (2006) for forest canopy and Cingolani *et al.* (2008) for soil loss in non-forested sites of the same study area.

The result that percent tree canopy cover was highest at greater distances from ranches and at intermediate altitudes is consistent with Renison *et al.* (2006), who used the amount of rock exposed by soil erosion in the surroundings of the forests as an indicator of livestock grazing pressure. Close to ranches, the forests are presumably opened by fires, and forest succession is delayed by livestock browsing, resulting in larger proportions of grasslands (Renison *et al.* 2002, 2006, 2009; Teich *et al.* 2005). The higher woodland cover at intermediate altitudes of around 1850 m a.s.l. is probably due to the faster growth rate of *P. australis* at these altitudes, possibly as a result of increased orographic precipitation, or a balance between temperature and increasing evapotranspiration at lower altitudes as discussed in Marcora *et al.* (2008).

Forest opening in combination with livestock being attracted to open deforested habitats (Arnold & Dudzinski 1978) probably involves a series of feedbacks which give rise to soil deterioration. In our study, proximity to ranches was associated with several non-desirable soil attributes such as higher soil impedance, lower soil organic matter content and higher soil salinity. Higher soil impedance is probably due to soil compaction in response to livestock hoof pressure (Greenwood & McKenzie 2001), which is highest in closer vicinity to ranches because of forest canopy opening combined with higher stocking rates. Soil compaction may reduce water infiltration and plant growth, which, together with increased biomass removal by grazing, leave soils bare of their protective plant cover, which in turn almost certainly triggers loss of soil organic matter. In addition, bare soils, at least under conditions of high solar radiation, dry out and accumulate Na^+ more rapidly than soils covered by vegetation (Belsky & Blumenthal 1997; Edeso *et al.* 1999; Greenwood & McKenzie 2001; Hobbs 2001; Martínez & Zinck 2004; Powers *et al.* 2005). Several studies confirmed the negative influence of ongoing soil degradation in the natural and assisted regeneration of *P. australis* forests. Adult trees grow more slowly in rocky environments with shallow soils (Marcora *et al.* 2008; Suarez *et al.* 2008), their seeds are characterized by decreased germination capacity (Renison *et al.* 2004) and seedling establishment is reduced in degraded soils (Renison *et al.* 2005; Torres *et al.* 2008). Thus, once forests are opened and soils partially degraded, the difficulties in forest regeneration may lead to further degradation, as described by Ludwig *et al.* (2005) for other plant communities. Similar results have been found in other trees inhabiting mountain forests such as the Mediterranean *Quercus ilex*, which exhibits several reproductive traits that are negatively influenced by grazing (Cierjacks & Hensen 2004).

In accordance with our results, Vanacker *et al.* (2003), who studied a mountain catchment in Ecuador, highlighted the importance of deforestation in triggering soil loss and afforestation in stopping it, while Hertel *et al.* (2003) found that old growth forests

Table 2. Linear regression models for six response variables in relation to human and topographical variables

		Independent variable					
1. Response variable	2. Model	3. Distance (km)	4. Roughness (index)	5. Slope (degrees)	6. TP (index)	7. Altitude (m a.s.l.)	8. Altitude^2 (m a.s.l.)
1. Tree canopy cover (%)	**r^2 = 0.21** ***P* < 0.001**	**0.171** ***P* = 0.01**	2.391 *P* = 0.10	−0.006 *P* = 0.42	−0.002 *P* = 0.70	**0.015** ***P* = 0.003**	**−4.0E-06** ***P* = 0.002**
2. Rock exposed by erosion (%)	**r^2 = 0.07** ***P* = 0.04**	**−0.021** ***P* = 0.03**	0.02 *P* = 0.94	−0.002 *P* = 0.06	0.000 *P* = 0.62	−0.001 *P* = 0.16	2.7E-07 *P* = 0.13
3. Soil impedance (kg.cm^{-2})	**r^2 = 0.30** ***P* < 0.001**	**−0.070** ***P* = 0.001**	**−1.878** ***P* < 0.001**	−0.003 *P* = 0.12	0.001 *P* = 0.40	−0.002 *P* = 0.08	6.2E-07 *P* = 0.10
4. PCA axis 1 (organic matter)	**r^2 = 0.16** ***P* = 0.009**	**0.314** ***P* = 0.03**	**8.750** ***P* = 0.008**	0.027 *P* = 0.11	0.010 *P* = 0.38	0.008 *P* = 0.46	−1.7E-06 *P* = 0.54
5. PCA axis 2 (acidity)	**r^2 = 0.32** ***P* < 0.001**	**0.217** ***P* = 0.002**	**−7.738** ***P* < 0.001**	**−0.016** ***P* = 0.04**	0.009 *P* = 0.11	0.009 *P* = 0.08	−2.4E-06 *P* = 0.06
6. PCA axis 3 (salinity)	**r^2 = 0.21** ***P* < 0.001**	**−0.114** ***P* = 0.02**	−1.265 *P* = 0.36	0.003 *P* = 0.69	−0.001 *P* = 0.85	−0.007 *P* = 0.13	2.2E-06 *P* = 0.08

Column 1 shows the response variables, column 2 shows the adjusted r^2 and *P*-value for the total model, and columns 3 to 8 show the independent variables with their regression coefficient and *P*-value. As an indicator of human influence we show 'distance' from ranch; and for topographical influences we show 'roughness' of the landscape, 'slope' of the plot (degrees), topographical position 'TP' ranging from 0 for the relative lower areas to 1 for the highest, 'altitude' above sea level and its quadratic term (see *Methods*). Significant variables are highlighted in bold. PCA, Principal Component Analysis.

in the mountains of Costa Rica have deeper organic topsoil than intermediate and early successional stands. In a comparison between adjacent primary and secondary forest soils, Flinn and Marks (2007) determined that the latter had 15% less organic matter, 16% less total carbon and 29% less extractable phosphorus in the topsoil.

We only found a few significant associations between indicators of soil degradation and topographic features. Soil impedance and acidity were lower while soil organic matter was higher in study plots located in a rougher landscape. These areas may have had lower historical livestock impact because of the difficulties in managing livestock in rough landscapes combined with a livestock preference for level landscapes – thus the influence of land roughness may be mediated through livestock grazing.

Because of the protective effect of denser forests, we expected less soil loss and degradation at intermediate altitudes where tree vitality and growth of *P. australis* is highest (Marcora *et al.* 2008). However, altitude was not associated with any soil variable. It is possible that below the forest optimum, despite the more open canopy, soils are less damaged because of the faster growth of protecting forbs and grasses and reduced frost incidence, which is a very important factor triggering soil loss in mountain areas (Lal 2001). At altitudes above the optimum, it is possible that the more open canopy is compensated by a greater accumulation of non-decomposed organic matter, which might protect the soil from freezing and the erosive force of raindrops (Facelli & Pickett 1991; Belsky & Blumenthal 1997).

It was surprising that slope inclination did not influence most of our variables related to soil integrity. Slope is known to influence soil loss rates in a wide range of vegetation communities (Morgan 1979) including grasslands in more gentle landscapes of the mountains of Central Argentina (Cingolani *et al.* 2003). It is also an attribute used in empirical models for predicting soil erosion (Lal 2001). The lack of a strong relationship between soil loss, topographic position and slope may be due to livestock preferences, as livestock avoid the very steep slopes where most remaining *Polylepis* forests are found. Fu *et al.* (2004) also report on an overriding influence of long-term human disturbances over slope position on soil degradation in a highly modified landscape in Southwest China.

In the best scenario, our models only explained 32% of the variation in our response variables, which means that a great proportion of the variance in forest and soil degradation remained unexplained. The low explained variance could be due to several reasons. First, it could be the result of the predictor used (distance from ranches), which has its limitations. Using this predictor, we lost information at two scales. At a broad

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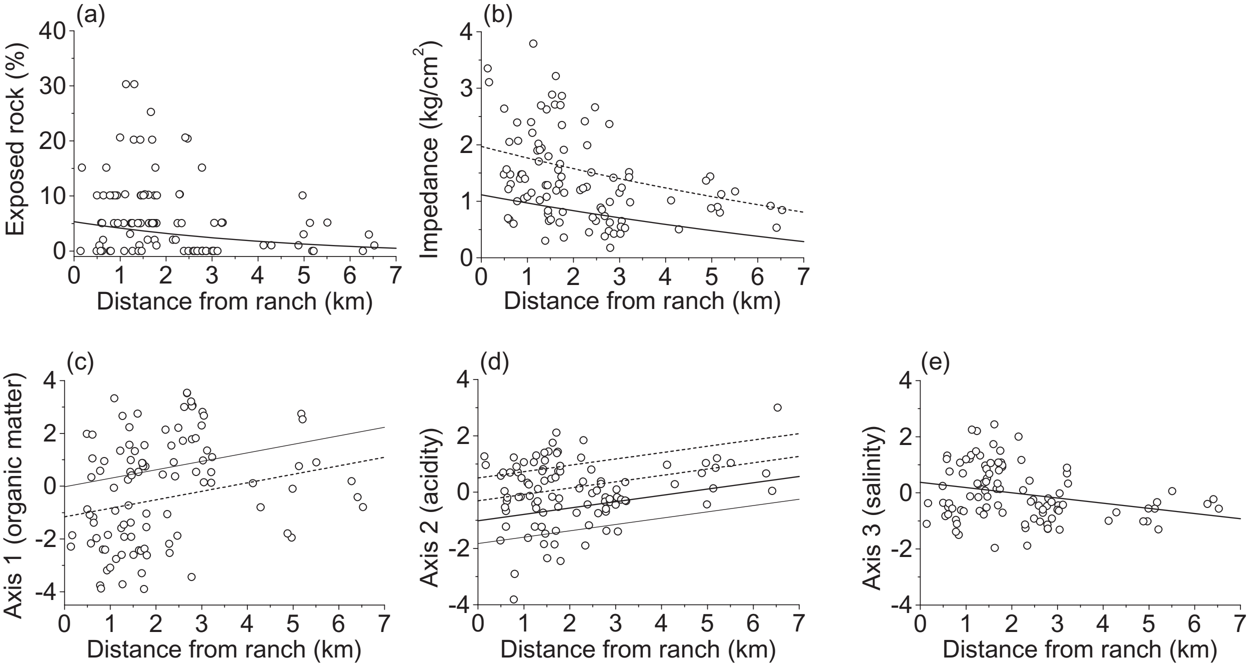

Fig. 3. Distance from ranches as an index of human impact and five response variables related to *Polylepis australis* forests soils: (a) surface of rock exposed by soil erosion (%); (b) soil impedance; (c) PCA axis 1 (organic mater); (d) PCA axis 2 (acidity); and (e) PCA axis 3 (salinity). The trend lines indicate the best linear fit according to the models indicated in Table 2. Where a second or third variable significantly influenced the model they were represented by two or more lines with constant values. Thus, in (b), (c) and (d) the dashed lines represent relatively low landscape roughness (index held constant at 0.05) and the continuous lines represent relatively high landscape roughness (index of 0.25); while in (d) the uppermost of each type of line represent flat slopes and the lowermost 45 degree slopes. PCA, Principal Component Analysis.

spatial scale, we did not take into account differences in management associated with sharp limits between properties or areas used by different stakeholders. Second, our predictor did not assess the temporal scale of disturbances, such as changing livestock grazing intensities or fire occurrence, which in combination with prolonged droughts followed by heavy rains very likely further explain soil degradation by triggering erosion (e.g Davenport *et al.* 1998; Neary *et al.* 1999; Campo *et al.* 2008). Thus, we assume that the relatively poor predictive power of our model is attributed to unaccounted variability in the disturbance history. However, we cannot rule out that we additionally missed some relevant physical variables, for example, hydrological features of importance (Turnbull *et al.* 2008). Another drawback of our study is its non-experimental nature, but the results would only be flawed if rancher houses were selectively constructed in areas where natural soil loss is highest, a scenario that is highly unlikely as distance from ranch was not correlated to any of the variables we measured.

We conclude that both livestock and topography have an impact on *P. australis* forests and on soil degradation. For this reason, land use in *P. australis* forests, and possibly other high altitude South American forests, should always be considered in forest ecological research and soil conservation efforts, with an emphasis on the need to manage livestock adequately, as is the case for other susceptible areas (i.e. the Australian continent: Lunt *et al.* (2007). In order to better preserve mountain soils, the current emigration trends occurring in many South American mountain areas (Grau & Aide 2008) should not be opposed. Remaining ranchers could be encouraged to further reduce livestock densities and fire use, a practice which in other South American mountains, has promoted forest recovery (i.e. Kintz *et al.* 2006).

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