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Soil erosion rates in rangelands of northeastern Patagonia: A dendrogeomorphological analysis using exposed shrub roots

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ABSTRACT

Soil erosion is an important process of land degradation in many rangelands and a significant driver of desertification in the world's drylands. Dendrogeomorphology is an alternative to traditional methods for determining soil erosion rate. Specifically, the vertical distance between the upper portion of exposed roots and the actual soil surface can be used as a bioindicator of erosion since plant establishment. In this study, we determined (i) the soil erosion rate from exposed roots of the dwarf shrub *Margyricarpus pinnatus* [Lam.] Kuntze in two ecological sites in the northeastern rangelands of Patagonia and (ii) the relationship between shrub age and upper root diameter. We selected two ecological sites, a pediment-like plateau and a flank pediment, where the dominant soils were Xeric Haplocalcids and Xeric Calciargids, respectively. The soil erosion rates in the pediment-like plateau and in the flank pediment were 2.4 and 3.1 mm yr^{-1}, respectively. Data clearly indicate a high rate of soil erosion during the mean 8-year life span of the dwarf shrubs in degraded patches, which represent ~10% of surface cover in the study area. Simple linear regression analysis yielded a highly significant predictive model for age estimation of *M. pinnatus* plants using the upper root diameter as a predictor variable. The measurement of ground lowering against datable exposed roots represents a simple method for the determination of soil erosion rates. In combination with other soil surface features, it was used to infer the episodic nature of soil erosion. This approach could be particularly useful for monitoring the effects of land management practices on recent soil erosion and for the establishment of records in regions where historical data regarding this process are scarce or absent.

1. Introduction

Soil erosion is an important process of land degradation in many rangelands and has been considered a significant driver of desertification in the world's drylands (Schlesinger et al., 1990; Le Houérou, 1992). Sheep grazing, introduced in Patagonia at the end of the nineteenth century, has produced changes in vegetation structure and accelerated soil erosion (Soriano et al., 1980; Beeskow et al., 1995). Sustainable land management depends primarily on conservation of the soil (Trimble and Crosson, 2000), so measuring soil erosion to improve management of land and water resources is critical.

Numerous techniques to determine soil erosion rates exist. For water erosion, measuring sediment yield from river basins can provide a useful perspective on the rates of erosion in the watershed upstream (Walling, 1988). However, soil erosion rates traditionally have been determined by means of runoff plots (Morgan, 1986). Estimates of soil erosion based on change in surface level, irrespective of the process involved, have been accomplished by driving iron nails or stakes into the ground and measuring the distance from the top to ground level over time (Hennessy et al., 1986).

Alternatively to the traditional methods for determining soil erosion, dendrogeomorphology (Alestalo, 1971; Stoffel and Bollschweiler, 2008) represents a powerful tool to determine recent (<25 years) as well as long-term (over some centuries) rates of soil erosion against datable exposed roots. The potential for analyzing root sections to date plants was already known in the first half of the last century (e.g., Schulman, 1945) and again reconsidered in detail in the last decade (Keeley, 1993; Krause and Eckstein, 1993; Krause and Morin, 1999). In the 1960s the focus was strong on applying dendrochronological analyses on roots to study soil erosion (Eardley and Viavant, 1967; LaMarche, 1968). Dunne et al. (1978) revived the method of measuring the minimum depth of soil erosion via the degree of root exposure on datable trees. Carrara and Carroll (1979) added the idea of dating scars of exposed roots and stated this to be the first year of exposure. More recently, Gärtner et al. (2001), Bodoque et al. (2005), and Hitz et al. (2008) determined the first year of exposure by the characterization of the wood anatomical changes in the microscopic structure of the roots.

The vertical distance between the upper portion of the exposed root (close to the stem-root interface) and the actual soil surface can be

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used as an indicator of soil erosion since plant establishment (Villalba, 2000). Age determination of exposed roots enables one to assess the magnitude of soil loss over time as well as to develop detailed chronologies of the geomorphologic events. Eardley and Viavant (1967) used exposed tree roots to determine the rate of landscape denudation in an area north of Cedar Breaks National Monument, Utah; and LaMarche (1968) used the same techniques to determine rates of slope degradation in the White Mountains of California. These studies involved long-lived species of pines, but shrub species that show similar root growth characteristics should provide equally reliable data for shorter time periods.

In principle, roots of all tree and shrub species could be used for the determination of soil erosion rates (Gärtner et al., 2001). In this sense, trees and other plants having annual ring structures (including dwarf shrubs, shrubs, and herbs) (Schweingruber and Poschlod, 2005) can play a key role in many dendrogeomorphological studies. However, according to Winchester et al. (2007), apart from the work of Gers et al. (2001), plants other than trees have been largely ignored by dendrogeomorphologists.

In the Patagonian rangelands, soil erosion has been considered the main soil degradation process and is cited as the main cause of desertification (del Valle et al., 1998). However, few studies, generally planned for no more than 3 years, have determined the rate of soil erosion (Rostagno et al., 1999). The high cost and long time frames needed for the traditional methods may be the primary reasons for the dendrogeomorphological approach. The use of exposure and datable shrub roots to document the soil loss rates offers new options for the study of erosion in rangelands.

The objectives of this study are (i) to determine the soil erosion rate from exposed roots of the dwarf shrub *Margyricarpus pinnatus* [Lam.] Kuntze in two ecological sites in the northeastern rangelands of Patagonia and (ii) to assess the relationship between the age and the upper root diameter of this species. If the age of *M. pinnatus* could be determined from its upper root diameter, the assessment of the soil erosion rate from areas characterized by this species could be quickly and directly determined in the field. This work represents part of a regional effort to identify soil erosion indicators to assess the magnitude and rate of the erosion process in Patagonia.

2. Study area

Field work was carried out in the Punta Ninfas area in the northeastern rangelands of Patagonia, Argentina (Fig. 1). The climate is arid and windy with a mean annual precipitation of 258 mm (1995–2004) (Chartier and Rostagno, 2006), a mean annual atmospheric temperature of about 12.5 °C, and an evapotranspiration of 680 mm (Barros, 1983). The highest mean wind velocity (6 m s^{-1}) occurs during summer when SW winds are dominant (data from the weather station located in Puerto Madryn, 50 km westward of the study area) (CENPAT, 2005).

In this area we selected two contiguous ecological sites, a pediment-like plateau and a flank pediment, that differed in soil type and vegetation physiognomy and composition, although grazing management was similar. Beeskow et al. (1987) described a pediment-like plateau as an erosional surface of low relief covered by alluvium that locally are called “mesetas” or plateaus, whereas flank pediments (as described by Fidalgo and Riggi, 1970) are short slope transport surfaces, generally developed between a plateau covered by a gravel mantle and a lower zone with a base level controlled by a playa lake. The dominant soils in the pediment-like plateau (1–5% slope) and in the flank pediment (2–3% slope) are Xeric Haplocalcids and Xeric Calciargids, respectively. The Xeric Haplocalcid is a deep, fine sandy loam, well- to moderately well-drained, moderately permeable soil. The Xeric Calciargid is moderately deep with a sandy clay loam Bt horizon (10 to 15 cm thick) and a calcic Bk horizon 20 to 30 cm thick, moderately drained, with a moderate to slow permeability. The bulk density of the A horizons for the Haplocalcids and Calciargids was 1.20 and 1.24 Mg m^{-3}, respectively. Classification of soils was according to the Soil Survey Staff (1999).

Fig. 1. Study area in northeastern rangelands of Patagonia, Argentina.

The dominant plant community in the flank pediment is shrub-grass steppe (Fig. 2). *Chuquiraga avellanedae* Lorentz (quilembai) is the dominant shrub, and the perennial grasses *Stipa tenuis* Phil. (flechilla) and *Piptochaetium napostaense* [Speg.] Hackel ap Stuckert (flechilla negra) are the dominant herbaceous species. The pediment-like plateau is characterized by grass with scattered shrub steppe, where *S. tenuis* and *S. speciosa* Trin. and Rupr. (coirón amargo) are the dominant grass species and *Mulinum spinosum* [Cav.] Pers. (neneo) the dominant shrub.

In the study area, no fire has been recorded during the last 50 years. Wind and water erosion are important geomorphic processes structuring the patchy soil and vegetation. Sheep grazing for wool production is the main use of these rangelands where continuous grazing is practiced extensively at moderate to heavy intensity (0.3 sheep ha^{-1}) in paddocks commonly exceeding 2500 ha in size (Beeskow et al., 1995).

3. Material and methods

3.1. Growth ring measurement and M. pinnatus chronology

In a first step to verify the annual formation of growth rings of *M. pinnatus*, sampling was undertaken within an exclosure in the spring of 2004. Grazing was excluded for a 10-year period in the exclosure. The exclosure was located ca. 3000 m from the sampled areas, in similar terrain and soils. Fifteen *M. pinnatus* plants were randomly selected inside the exclosure. In the laboratory, the plants were transversely sectioned by sawing at the upper root portion, at the stem–root interface (Fig. 3), to ensure that the pith and first annual growth ring were included (Ferguson, 1964). The root cross sections were allowed to air-dry for ~30 days and then sanded sequentially with 60, 80, 320, 600, and 1500 grit sanding belts.

Next, the slices of root samples were photographed at a resolution of 72 dpi using a digital camera mounted on a binocular scope at 10 to 50 power. The ImageJ 1.37v software (Rasband, 2006) was used to determine the ring widths with a precision of 0.01 mm. To determine

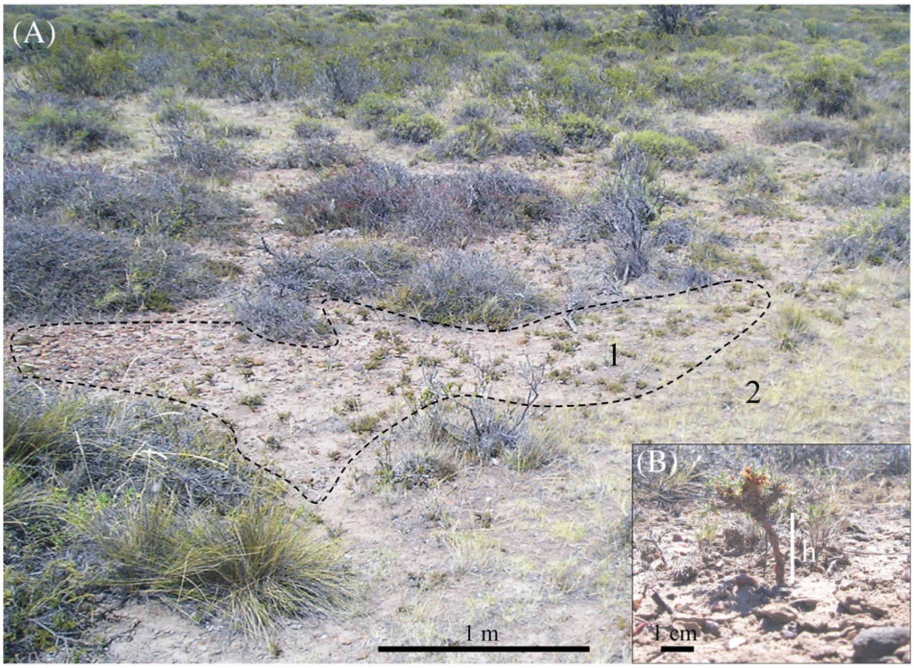

Fig. 2. (A) Photograph showing a general view of the flank pediment site in the Punta Ninfas rangelands, northeastern Patagonia. The dominant plant community is shrub-grass steppe. (1) A degraded patch dominated by *M. pinnatus* with exposed roots is denoted by the dashed line. (2) The adjacent undegraded matrix where perennial grasses dominate. (B) Detail of an *M. pinnatus* dwarf shrub with exposed root (h).

pointer years, the ring widths of the selected *M. pinnatus* were crossdated using the skeleton plot method (Stokes and Smiley, 1968; Schweingruber et al., 1990). Crossdating ensured that patterns of ring widths were matched among several series to identify the correct formation date for every ring in all samples (Swetnam et al., 1985). Finally, a master chronology was obtained as a comparison pattern of the ring width to verify the ring counting in the age determination.

3.2. Sampling and erosion rate determination

The sampling was carried out in the grazed area during spring of 2004 and early summer of 2005. The proportion of the total study area covered by degraded, eroding patches was determined as a basis for estimating the spatial extent of the erosion process (Fig. 2). In each ecological site, four 200-m transects were randomly located to determine the cover of degraded patches by using the length interception method (Mueller-Dombois and Ellenberg, 1974). The degraded patches were clearly identified in the field by the presence of several signs of soil erosion, such as an incipient desert pavement, grass plants, and gravels in pedestal, vesicular crust, a high percentage of bare ground and exposed roots of woody plants. To establish a relationship between accelerated erosion and soil surface characteristics, we determined the cover of *M. pinnatus* dwarf shrubs, grasses, litter, gravels, and bare soil of the degraded patches and the adjacent undegraded matrix using five 50 × 50-cm quadrats (subsamples) per patch.

In order to determine the erosion rate in the degraded patches of each ecological site, we selected the first five intercepted patches along each of the four transects. In each of these patches, we selected the three individuals of *M. pinnatus* with the highest and thinnest exposed root. For each selected plant ($n = 120$), the distance between the upper root portion and the soil surface was measured with a ruler. These plants were harvested, put in a plastic bag, and taken to the laboratory to be prepared following the same methodology as described above. Then, the age of each plant was determined by simply counting annual growth rings contained in the transverse sections using a binocular scope at 10 to 50 power. A minimum of three radii per sample were counted by using one section per plant. The mean annual soil erosion rate was determined by dividing the height of the exposed root by the numbers of years the plant has lived. Upper root diameters were measured with a caliper across transverse sections, and regression analysis was used to test for relationship between upper root diameter and dwarf shrub age. Voucher specimens were deposited in the Centro Nacional Patagónico — CONICET, Jardín Botánico de la Patagonia Extraandina, Puerto Madryn, Argentina (CNP-JBPE 2512).

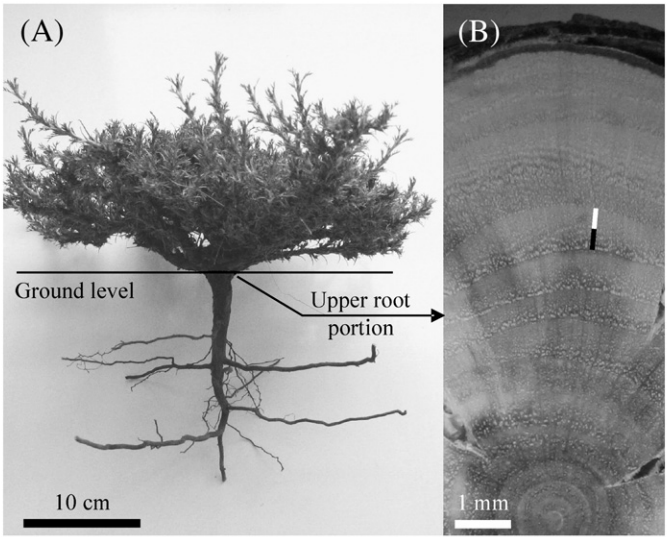

Fig. 3. (A) Lateral view of *M. pinnatus* indicating the location of upper root portion where cross sections were taken. (B) Cross section of an *M. pinnatus* exposed root with clearly defined growth rings. The black and white bars indicate the early and late wood of a growth ring, respectively.

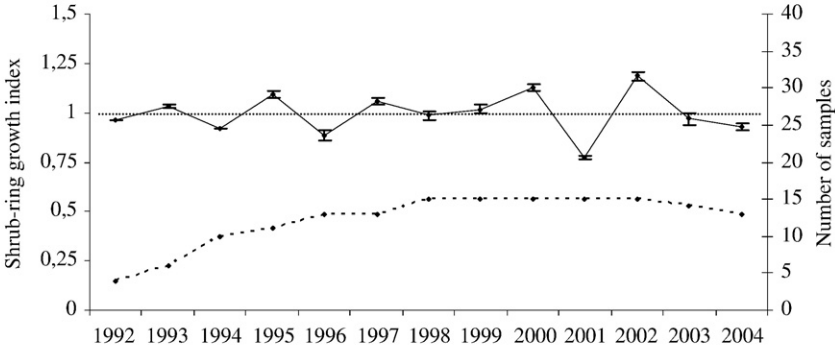

Fig. 4. Shrub-ring chronology based on the mean (standard error) annual growth ring index (black line) and corresponding number of samples (dashed line) for the *M. pinnatus* growing within the exclosure at the Punta Ninfas area, northeastern Patagonia.

3.3. Data analysis

A chronology for *M. pinnatus* was developed from 15 ring width measurement series following standard procedures described by Stokes and Smiley (1968). After visual crossdating of the prepared samples, ring widths were measured to the nearest 0.01 mm.

The quality of this crossdating was verified by means of the COFECHA program (Holmes, 1983). Similarities between the chronologies were evaluated using correlation coefficients for the common interval 1992–2004. We evaluated the quality of the chronology using the mean sensibility and the standard deviation (Fritts, 1976).

The statistical difference in the dwarf shrub age (year), the height of exposed root (mm), and the soil erosion rate (Mg ha^{-1} yr^{-1}) between ecological sites was tested by a balanced, nested analysis of variance. To compare the cover of degraded patches between sites, a fixed effect one-way analysis of variance was employed. Regression analysis was performed to determine the relationship between age and upper root diameter of *M. pinnatus* dwarf shrub. Upper root diameter was the predictor variable and age the dependent variable in simple linear regression analyses. An *F*-test for homogeneous variances and an analysis of covariance were performed to compare the slopes and *Y*-intercepts, respectively, for the age prediction models from pediment-like plateau and flank pediment study sites (Sokal and Rohlf, 1981). Significant levels were determined at $P \leq 0.05$.

4. Results

4.1. Margyricarpus pinnatus chronology

The transverse sections at the upper root portion of *M. pinnatus* produced recognizable annual growth rings (Fig. 3). The vessels of major diameter were located in the earlywood, but they decreased in size as they entered the latewood zone forming a semiring porosity pattern. In the boundary between two vegetative periods, the vascular tracheids were clearly distinguished from the vessels formed at the beginning of the cambial activity.

Similarities in the ring patterns were confirmed from the crossdating skeleton plots of 15 *M. pinnatus* dwarf shrubs growing within the exclosure. The chronology obtained using the plants harvested in the exclosure covers the period 1992–2004 and is based on the mean annual growth ring index of 15 dwarf shrubs (Fig. 4). The ring width ranged from a minimum of 0.13 to a maximum of 1.46 mm yr^{-1} (mean 0.47, standard error 0.02) and showed a positive trend with dwarf shrub age. The statistics used to measure the quality of the chronology indicate a common signal in the interannual variations of radial growth among the individual samples that integrated the chronology. The chronology showed a high (*r*-bar = 0.77) correlation among the 15 dwarf shrubs. The mean sensitivity of standardized ring width indices for standard chronology was 0.30, and the standard deviation was 0.16.

4.2. Cover and surface characteristics of M. pinnatus patches

The mean cover of degraded patches was 10.4% (S.E. 2.3) for the pediment-like plateau and 8.9% (S.E. 1.7) for the flank pediment and was not statistically different between them ($P > 0.61$, $n = 8$). A total of 26 and 33 degraded patches were intercepted in the pediment-like plateau and in the flank pediment, respectively.

Stands of *M. pinnatus* dwarf shrubs were included into either undegraded matrix or degraded patches, and they were common in both the pediment-like plateau and the flank pediment study sites. Degraded patches were characterized by exposed roots of *M. pinnatus* associated with a low grass and litter cover and a high gravel and bare soil cover (Fig. 5).

4.3. Soil erosion rate

The mean age of the individuals of *M. pinnatus* harvested in the degraded patches was similar in the two ecological sites (Table 1).

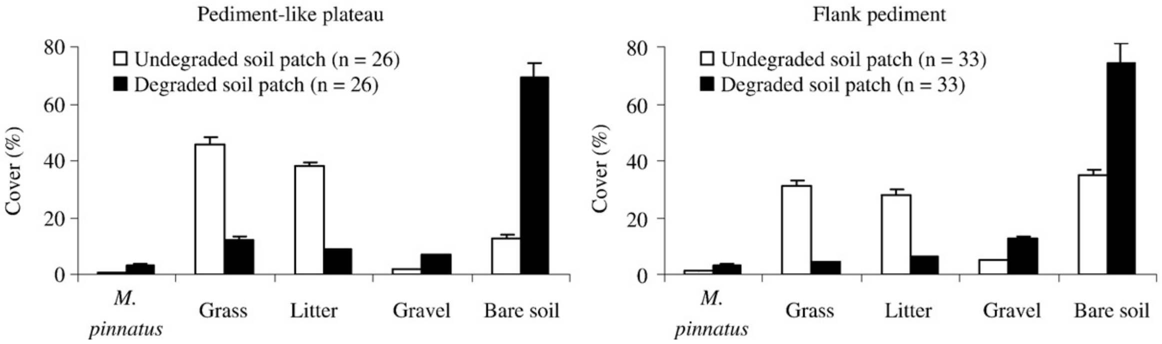

Fig. 5. Different surface cover factors (mean and standard error) for the undegraded and degraded patches in (A) the pediment-like plateau and (B) the flank pediment at the Punta Ninfas rangelands, Patagonia.

However, the mean height of the exposed roots and therefore the mean soil erosion rate was significantly greater in the flank pediment than the pediment-like plateau ($P<0.05$, $n=40$).

Based on the cover of degraded patches, we estimate that the measured erosion rate pertains to about 10% of the area in each ecological site. The erosion occurred during the mean life span (~8 years) of the *M. pinnatus* individuals harvested.

4.4. Relationship between age and upper root diameter

The comparison of linear regression parameters, *F*-tests for equality of slopes ($F_{(1,100;0.95)}=1.59$, $P=0.21$, $n=104$) and *Y*-intercept ($F_{(1,101;0.95)}=0.55$, $P=0.46$, $n=104$), showed that the age-upper root diameter relationship of *M. pinnatus* was not significantly different between ecological sites. Accordingly, we developed only one age prediction model of this dwarf shrub on the study area, as presented in Fig. 6. Thus, the simple linear regression analysis yielded the following significant predictive model for the annual growth rings estimation:

Shrub age (years) = 2.95 (S.E. 0.56) + 2.03 (S.E. 0.18) upper root diameter (mm); ($R^2=0.56$, $P<0.0001$, $n=104$).

5. Discussion

5.1. Margyricarpus pinnatus chronology

The analysis of the transverse root sections of *M. pinnatus* presented an accurate chronology based on annual ring width measurements of 15 dwarf shrubs selected from the ungrazed (exclosure) area. However, some portions of root transverse sections showed wedge rings as observed for *Empetrum rubrum* dwarf shrub in the austral Patagonia (Roig, 1988). The transverse root sections showed eccentric growth, and the more external rings were often laid down in waves. As common with many desert shrubs (Ginzburg, 1963), the root–stem interface of *M. pinnatus* tends to segment and split with age or with the death of some cambium tissue in drought conditions. This feature reveals the importance in using a complete transversal section for dendrochronological analysis in this dwarf shrub species.

Because the canopy of *M. pinnatus* dwarf shrub is browsed by sheep and probably by wild herbivores, dendrochronological studies based on aerial portions of the plant could be biased to the absence of the first rings in the stem cross section. Thus, the use of superficial or subterranean parts of plants for dendrochronological analysis becomes relevant in grazed and/or burned areas.

The ring widths found in *M. pinnatus*, ranging between 0.13 and 1.46 mm yr^{-1}, were within the range reported for other desert shrubs (Webber, 1936). However, the mean ring width of *M. pinnatus* (0.47 mm) was lower than the mean radial growth of 0.82 mm reported by Vasek (1980) for *Larrea tridentata*, a tall shrub characteristic of the Mojave Desert in California, or 0.83 mm reported by Milton et al. (1997) for *Pteronia pallens*, a typical dwarf shrub of the Karoo rangelands of South Africa.

Table 1
Mean (standard error) values of physical and dendrochronological parameters of *M. pinnatus* dwarf shrub to estimate the soil erosion rate at the Punta Ninfas rangelands, Patagonia.

Site (dominant soil)	Individual age determination (yr)	Height of the exposed root (mm)	Soil erosion rate (mm yr^{-1})
Pediment-like plateau (Xeric Haplocalcids)	8.3 (0.4)	19.1 (1.5)*	2.4 (0.2)*
Flank pediment (Xeric Calciargids)	9.3 (0.8)	26.4 (2.2)	3.1 (0.3)

* Symbols indicate significant statistical differences ($P<0.05$, $n=40$) between ecological sites.

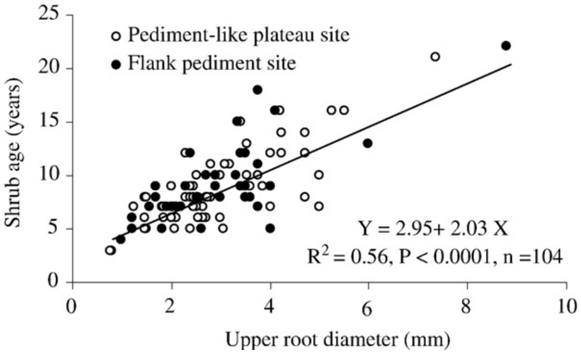

Fig. 6. Upper root diameter–age relationship of *M. pinnatus* dwarf shrubs harvested in the degraded patches of the two ecological sites in the Punta Ninfas rangelands, northeastern Patagonia.

In the years 1996 and 2001, a large decrease in ring width was evident (Fig. 4). Because soil erosion and grazing were insignificant in the exclosure area, the decrease in ring width might have been controlled by precipitation as has been found for other shrubs growing in southern Patagonia (Roig, 1988). In these water-limited ecosystems, the rain falling and stored in the soil profile before the beginning of the growing period is of fundamental importance for plant growth. Hence, the lower radial growth of the main root of *M. pinnatus* in 1996 and 2001 was coincident with a precipitation decrease of about 40% for the April to December months relative to the precipitation recorded for the same months during the previous two years. In these ecosystems the water recharge into the soil profile occurs mainly during the fall and winter (Ares et al., 1990). On the basis of this preliminary study, we conclude that *M. pinnatus* produces annual growth rings and that the width of the rings is in part influenced by water availability.

5.2. Cover and surface characteristics

In the two ecological sites, a reduction in perennial grass cover was evident in patches where *M. pinnatus* dominates (see Fig. 5). This reduction was more marked in those patches where *M. pinnatus* was associated with evidence of soil erosion. Moreover, the degraded patches dominated by *M. pinnatus* with exposed roots additionally presented other signs of accelerated soil erosion, such as incipient desert pavement, vesicular crust, and plants with pedestals, mainly individuals of *Stipa tenuis*, the dominant perennial grass in the area. Because the root system of *M. pinnatus* dwarf shrub is characterized by a deep, main root, we speculate that some individual plants may be accessing available water deep in the soil profile, resulting in differential survival rates compared with the grass species (Noy-Meir, 1973; Schlesinger and Gill, 1980).

In this context, soil erosion may create a mosaic of land conditions that represents the various states of soil loss or gain (Pickup, 1985). The continuous soil loss eventually changes a functional landscape that efficiently captures, retains, and utilizes water and nutrients into a dysfunctional one that no longer can efficiently capture these resources (Tongway and Ludwig, 1997).

5.3. Soil erosion rate

The soil erosion rate in the degraded patches characterized by *M. pinnatus* with exposed roots was significantly different between ecological sites (Table 1). The soil erosion rate was 1.3 times higher in the flank pediment than in the pediment-like plateau site. This difference can be mainly attributed to the more favorable soil superficial conditions recorded in the pediment-like plateau as compared with the flank pediment (Fig. 5). The higher ground cover may account for the greater protection from raindrop impact and the lower water and wind erosion rates (Schlesinger et al., 1990; Whitford, 2002). In contrast, soils with less surface protection and hydrological limitations in the subsurface horizons can promote higher runoff production and soil erosion, as occurs in the Xeric Calciargids (Chartier and Rostagno, 2006).

Our data clearly indicate that soil erosion was severe during the mean 8-year life span of the sampled plants. Wind and water erosion, accelerated by sheep grazing, have probably been important processes in generating the degraded patches dominated by *M. pinnatus*. As in other semiarid rangelands of Patagonia, the rate of soil erosion has increased as a consequence of unsustainable grazing management practices (Soriano et al., 1980; Ares et al., 1990; Parizek et al., 2002; Chartier and Rostagno, 2006). The erosion rate in the degraded patches, which represent about 10% of surface cover of the study area, was equivalent to 28.8 and 38.4 Mg ha^{-1} yr^{-1} of sediment in the pediment-like plateau and the flank pediment, respectively. These rates were about two times greater than the maximum soil loss rate previously reported for some Patagonian rangelands (Rostagno et al., 1999). The earlier study examined soil erosion under natural rainfall conditions by means of runoff plots in a nearby region and reported maximum soil loss values of 16 Mg ha^{-1} yr^{-1} for an erosion scarp landform. In the same area, Coronato and del Valle (1993) estimated sediment yield using the Universal Soil Loss Equation prediction model (Wischmeier and Smith, 1978) and reported maximum extreme values of 11.3 Mg ha^{-1} yr^{-1}.

The soil loss rate currently estimated in the degraded patches with *M. pinnatus* was between 5.7 and 7.7 times greater than the soil loss tolerance (*T*-value) of 5 Mg ha^{-1} yr^{-1} cited in the literature for rangeland soils (USDA Soil Conservation Service, 1992). Based on previous studies in the Punta Ninfas rangelands (Beeskow et al., 1995; Chartier and Rostagno, 2006), we consider that degraded patches, in which the A horizon has not been totally eroded, represent an unstable and transitional ecological state. Without management intervention to halt soil erosion, this transitional state will likely change into a severely degraded and stable state characterized by a well-developed desert pavement with little or no perennial grass cover.

In northeastern Patagonia rangelands, as in other arid and semiarid ecosystems, the decrease in the cover of perennial grasses generally results in an acceleration of the soil erosion process from positive feedbacks. The feedback mechanism maintains or reinforces the degraded plant community and limits reversal to the previous plant community (Scheffer et al., 2001; van de Koppel et al., 2002). Technologies to estimate and monitor soil erosion are needed to help prescribe management practices so as to maintain existing rangelands in an ecologically healthy state and to return degraded rangelands to a resource-conserving condition. The use of datable exposed shrub roots may serve as a quantitative indicator of soil erosion rate. Moreover, this approach, although less precise than continuous monitoring, represents a simple, rapid method for estimating recent soil erosion rates without the need for expensive instrumentation.

5.4. Inferences about the soil erosion dynamic

We present three possible models to describe the dynamic of the erosion process in degraded patches dominated by *M. pinnatus* (Fig. 7A).

(i) The linear model would indicate a constant soil erosion rate during the period indicated by the age of the *M. pinnatus* with exposed root. However, the soil resistance and the erosivity of the erosion agents (wind and rainfall) show a high interannual variation (Rostagno et al., 1999). Thus, we speculate that the total soil loss as indicated by the height of the exposed roots must be accounted for by a few, large events as shown in models (ii) and (iii).

(ii) The logarithmic model would indicate an early soil stability period where the establishment of *M. pinnatus* individuals occurs, followed by a short period with a high soil erosion rate just before our sampling. This model does not adequately reflect the erosion process because the 3-to-4 years old established perennial grass (1) shown in Fig. 7B indicate a stability period.

(iii) We suggest that the logistic model best reflects the dynamic of soil erosion in Fig. 7A. The short stability period during the first years after the plant establishment would allow the *M. pinnatus* individual to develop a deep root system and guarantee its survival under the stressful conditions produced by the soil erosion process and the removal of the upper fine, lateral roots (2 in Fig. 7B). Years with relatively low rainfall can lead to lowered competitive potential of grasses (Schlesinger et al., 1990). The collapse of the perennial grasses results in a sparse cover of shrubs (Parizek et al., 2002) and acceleration of soil erosion. This sequence may have occurred in the year 1996 in the study area, soon after the establishment of the *M. pinnatus*

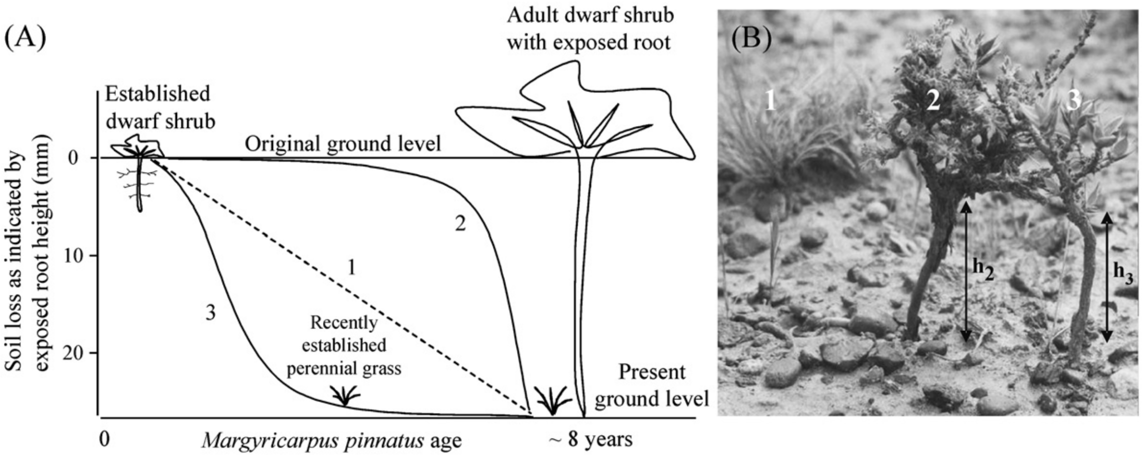

Fig. 7. (A) Alternative models (1 — linear, 2 — logarithmic, and 3 — logistic) for the soil erosion dynamics in the degraded patches as indicated by the height of exposed root in the Punta Ninfas rangelands. (B) Typical situation with respect to degraded patches including (1) grass tussock of *Stipa tenuis*, (2) *M. pinnatus* with its root exposed (h2), and (3) young individual of *Chuquiraga avellanedae* with its root exposed (h3). Note the incipient desert pavement developed on the soil surface.

(Fig. 7A). This catastrophic behavior has been described by van de Koppel et al. (1997) to explain the occurrence of alternative vegetation states in terrestrial grazing systems. In addition, the presence of recently established perennial grasses (1 in Fig. 7B) in the present soil surface level would indicate a stability period after intense soil loss.

5.5. Root diameter and age relationship

Simple linear regression analysis yielded a highly significant predictive model for age estimation of *M. pinnatus* plants at the Punta Ninfas rangelands using the upper root diameter as a predictor variable (Fig. 6). The predictive models for the Haplocalcid and Calciargid soils were not significantly different. However, we expected the higher soil erosion rate recorded in the Calciargids would negatively affect plant development and lead to reduced root diameter for a given plant age relative to plants growing on Haplocalcids. The great stress produced by grazing and soil erosion could have masked the effects of soil type.

Dunne et al. (1978) described the exposure of tree roots as a rapid means of field measurement of soil erosion. With suitable species, a calibration curve between the age of shrub and the root diameter at ground level can be developed. This predictable response could be used to determine soil erosion rate in a nondestructive and rapid sampling. Thus, range managers can use this method to identify areas that are in an unstable ecological state (i.e., a state characterized by high soil erosion rate) requiring a change in grazing management. However, a given relationship between upper root diameter and age may only be valid within a given area and should be determined for different ecological sites or environmental conditions (e.g., climatic conditions).

6. Conclusion

The results of our study demonstrate that the short-term local soil erosion rate from exposed roots of *M. pinnatus* can be determined with an acceptable precision in the rangelands of northeastern Patagonia. In the degraded patches of the two ecological sites, covering ca. 10% of the study area, the soil erosion rates recorded during the mean life span (~8 years) of the *M. pinnatus* sampled plants were well above (from 6 to 8 times) the assigned soil loss tolerance value for rangeland soils.

The regression model using the root diameter as an independent variable accurately predicted the age of dwarf shrubs for the study area and could be used to determine soil erosion rates in a nondestructive and rapid sampling.

The present study confirms the usefulness and importance of dendrogeomorphological studies regarding the soil erosion possesses. The measurement of ground lowering against datable exposed roots represents an advantageous method for a soil erosion estimate. This approach could be particularly useful for monitoring the effects of land management practices on soil erosion and for the establishments of records in regions where historical data regarding this process are scarce or absent.

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References

Alestalo, J., 1971. Dendrochronological interpretation of geomorphic processes. Fennia 105, 1–140.
Ares, J., Beeskow, A.M., Bertiller, M.B., Rostagno, C.M., Irisarri, M.P., Anchorena, J., Defossé, G.E., Merino, C.A., 1990. Structural and dynamic characteristics of overgrazed lands of northern Patagonia, Argentina. In: Breymeyer, A. (Ed.), Managed Grasslands: Regional Studies. Elsevier, Amsterdam, The Netherlands, pp. 149-175.
Barros, V., 1983. Atlas del potencial eólico de la Patagonia. Contribución No. 69. Centro Nacional Patagónico, Puerto Madryn, Argentina. 80 pp.
Beeskow, A.M., del Valle, H.F., Rostagno, C.M., 1987. Los sistemas fisiográficos de la región árida y semiárida de la provincia de Chubut. Secretaria de Ciencia y Tecnología Bariloche, Río Negro, Argentina, pp. 33–37.
Beeskow, A.M., Elissalde, N.O., Rostagno, C.M., 1995. Ecosystem change associated with grazing intensity on the Punta Ninfas rangelands of Patagonia, Argentina. Journal of Range Management 48, 517–522.
Bodoque, J.M., Díez-Herrero, A., Martín-Duque, J.F., Rubiales, J.M., Godfrey, A., Pedraza, J., Carrasco, R.M., Sanz, M.A., 2005. Sheet erosion rates determined by using dendrogeomorphological analysis of exposed tree roots: two examples from central Spain. Catena 64, 81–102.
Carrara, P.E., Carroll, T.R., 1979. The determination of erosion rates from exposed tree roots in the Piceance Basin, Colorado. Earth Surface Processes 4, 307–317.
CENPAT, 2005. Estación meteorológica. Área de física ambiental. CENPAT-CONICET. (available at http://www.centropatagonico.com).
Chartier, M.P., Rostagno, C.M., 2006. Soil erosion thresholds and alternative states in northeastern Patagonian rangelands. Rangeland Ecology and Management 59, 616–624.
Coronato, F.R., del Valle, H.F., 1993. Methodological comparison in the estimate of fluvial erosion in an arid closed basin of northeastern Patagonia. Journal of Arid Environments 24, 231–239.
del Valle, H.F., Elissalde, N.O., Gagliardini, D.A., Milovich, J., 1998. Status of desertification in the Patagonian region: assessment and mapping from satellite imagery. Arid Soil Research and Rehabilitation 12 (2), 1–27.
Dunne, T., Dietrich, W.E., Brunengo, J., 1978. Recent and past erosion rates in semi-arid Kenya. Zeitschrift für Geomorphologie N. F. Suppl. 29, 130–140.
Eardley, A.J., Viavant, W., 1967. Rates of Denudation as Measured by Bristlecone Pines, Cedar Breaks, Utah. Special Studies, vol. 21. Utah Geological and Mineralogical Survey, Cedar Breaks, Utah, pp. 3–13.
Ferguson, C.W., 1964. Annual rings in big sagebrush. Papers of the Laboratory of Tree-Ring Research No. 1. The University of Arizona Press, Tucson.
Fidalgo, F., Riggi, J.C., 1970. Consideraciones geomórficas y sedimentológicas sobre los Rodados Patagónicos. Revista de la Asociación Geológica Argentina 25 (4), 430–443.
Fritts, 1976. Tree-ring and Climate. Academic Press, London. 567 pp.
Gärtner, H., Schweingruber, F.H., Dikau, R., 2001. Determination of erosion rates by analyzing structural changes in the growth pattern of exposed roots. Dendrochronologia 19 (1), 81–91.
Gers, E., Florin, N., Gärtner, H., Glade, T., Dikau, R., Schweingruber, F.H., 2001. Application of shrubs for dendrogeomorphological analysis to reconstruct spatial and temporal landslide movement patterns. A preliminary study. Zeitschrift für Geomorphologie N.F. Suppl.-Bd. 125, 163–175.
Ginzburg, C., 1963. Some anatomic features of splitting of desert shrubs. Phytomorphology 13, 92–97.
Hennessy, J.T., Keis, B., Gibbens, R.P., Tromble, J.M., 1986. Soil sorting by forty-five years of wind erosion on a southern New Mexico range. Soil Science Society of America Journal 50, 3.
Hitz, O.M., Gärtner, H., Heinrich, I., Monbaronet, M., 2008. Application of ash (*Fraxinus excelsior* L.) roots to determine erosion rates in mountain torrents. Catena 72, 248–258.
Holmes, R.L., 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bulletin 43, 69–78.
Keeley, J.E., 1993. Utility of growth rings in the age determination of chaparral shrubs. Madroño 40, 1–14.
Krause, C., Eckstein, D., 1993. Dendrochronology of roots. Dendrochronologia 11, 9–23.
Krause, C., Morin, H., 1999. Root growth and absent rings in mature black spruce and balsam fir, Quebec, Canada. Dendrochronologia 16–17, 21–35.
LaMarche Jr., V.C., 1968. Rates of Slope Degradation as Determined from Botanical Evidence, White Mountains, California. U.S. Geological Survey Professional Paper 352-I. U.S. Government Printing Office, Washington DC, pp. 341–377.
Le Houérou, H.N., 1992. An overview of vegetation and land degradation in world arid lands. In: Dregne, H.E. (Ed.), Degradation and Restoration of Arid Lands. International Center for Arid and Semi-Arid Lands Studies, Texas Tech University, Lubbock, USA, pp. 127–163.
Milton, S.J., Gourlay, I.D., Dean, W.R., 1997. Shrub growth and demography in arid Karoo, South Africa: inference from wood rings. Journal of Arid Environments 37, 487–496.
Morgan, R.P.C., 1986. Soil Erosion and Conservation. Longman, New York.
Mueller-Dombois, D., Ellenberg, H., 1974. Aims and Methods of Vegetation Ecology. Wiley and Sons, New York.
Noy-Meir, I., 1973. Desert ecosystem: environment and producers. Annual Review of Ecology and Systematic 4, 25–52.
Parizek, B., Rostagno, C.M., Sottini, R., 2002. Soil erosion as affected by shrub encroachment in northeastern Patagonia. Journal Range Management 55, 43–48.
Pickup, G., 1985. The erosion cell — A geomorphic approach to landscape classification in range assessment. The Australian Rangeland Journal 7, 114–121.
Rasband, W.S., 2006. ImageJ. National Institutes of Health, Bethesda, MD, USA. (available at http://rsb.info.nih.gov/ij/).
Roig, F.A., 1988. Growth conditions of *Empetrum rubrum* Vahl. ex Will. in the south of Argentina. Dendrochronologia 6, 43–59.

Rostagno, C.M., Coronado, F., Puebla, D., del Valle, H.F., 1999. Runoff and erosion in five land units of a closed basin of northeastern Patagonia. Arid Soil Research and Rehabilitation 13, 281–292.

Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., Walker, B., 2001. Catastrophic shifts in ecosystems. Nature 413, 591–596.

Schlesinger, W.R., Gill, D.S., 1980. Biomass, production, and changes in the availability of light, water, and nutrients during development of pure stands of the chaparral shrub, *Ceanothus megacarpus*, after fire. Ecology 61, 781–789.

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huennke, L.F., Jarrell, W.M., Virginia, R.A., Whitford, W.G., 1990. Biological feedbacks in global desertification. Science 247, 1043–1048.

Schulman, E., 1945. Root growth-rings and chronology. Tree-ring Bulletin 12, 2–5.

Schweingruber, F.H., Poschlod, P., 2005. Growth rings in herbs and shrubs: life span, age determination and ítem anatomy. Forest Snow and Landscape Research 79 (3), 195–415.

Schweingruber, F.H., Eckstein, D., Serre-Bachet, F., Bräker, O.U., 1990. Identification, presentation and interpretation of event years and pointer years in dendrochronology. Dendrochronologia 8, 9–39.

Soil Survey Staff, 1999. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. Agricultural Handbook 436, USDA Soil Conservation Service. U.S. Government Printing Office, Washington, DC.

Sokal, R.R., Rohlf, F.J., 1981. Biometry. Freeman, San Francisco, CA.

Soriano, A., Sala, O.E., León, R., 1980. Vegetación actual y vegetación potencial en el pastizal de coirón amargo (*Stipa* spp.) del SW del Chubut. Boletín de la Sociedad Argentina de Botánica 19, 309–314.

Stoffel, M., Bollschweiler, M., 2008. Tree-ring analysis in natural hazards research — an overview. Natural Hazards and Earth System Sciences 8, 187–202.

Stokes, M.A., Smiley, T.L., 1968. An Introduction to Tree-Ring Dating. University of Chicago Press, Chicago, IL, USA.

Swetnam, T.W., Thompson, M.A., Sutherlan, E.K., 1985. Using dendrochronology to measure radial growth of defoliated trees. Agriculture Handbook 639. U.S. Department of Agriculture, Washington, DC.

Tongway, D.J., Ludwig, J.A., 1997. The nature of landscape dysfunction in rangelands. In: Ludwig, J., Tongway, D., Freudenberger, D., Noble, J., Hudgkinson, K. (Eds.), Landscape Ecology, Function and Management: Principles from Australia's Rangelands. CSIRO Publishing, Melbourne, Australia.

Trimble, S.W., Crosson, P., 2000. Land use: U.S. soil erosion rates — myth and reality. Science 14, 248–250.

USDA Soil Conservation Service, 1992. National Soil Survey Interpretations Handbook. U.S. Government Printing Office, Washington, DC.

van de Koppel, J., Rietkerk, M., Weissing, F.J., 1997. Catastrophic vegetation shifts and soil degradation in terrestrial grazing systems. Trend in Ecology and Evolution 12, 352–356.

van de Koppel, J., Rietkerk, M., van Langevelde, F., Kumar, L., Klausmeier, C.A., Fryxell, J. M., Hearne, J.W., van Andel, J., de Ridder, N., Skidmore, A., Stroosnijder, L., Prins, H.H. T., 2002. Spatial heterogeneity and irreversible vegetation change in semiarid grazing systems. American Naturalist 159, 209–218.

Vasek, F.C., 1980. Creosote bush: long-lived clones in the Mojave Desert. American Journal of Botany 67, 246–255.

Villalba, R., 2000. Métodos en dendrogeomorfología y su potencial uso en América del Sur. In: Roig, F.A. (Ed.), Dendrocronología en América Latina. EDIUNC, Mendoza, Argentina, pp. 103–134.

Walling, D.E., 1988. Measuring sediment yield from river basins. Chapter 3. In: Lal, R. (Ed.), Soil Erosion Research Methods. Soil and Water Conservation Society, Ankeny, IA, pp. 39–73.

Webber, I.E., 1936. The woods of sclerophyllous and desert shrubs of California. American Journal of Botany 23, 181–188.

Whitford, W.G., 2002. Ecology of Desert Systems. Academic Press, New York.

Winchester, V., Gärtner, H., Bezzi, M., 2007. Dendrogeomorphological applications. In: Kalvoda, J., Goudie, A.S. (Eds.), Geomorphological Variations: On the Occasion of the 150th Anniversary of Geography and Geoecology. Faculty of Science, Charles University, Prague, The Czech Republic, pp. 182–203.

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses: a guide to conservation planning. Agriculture Handbook 537. U.S. Department of Agriculture, Washington, DC.