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Exposed roots as indicators of geomorphic processes: A case-study from *Polylepis* mountain woodlands of Central Argentina

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ABSTRACT

Soil erosion is a serious problem of land degradation in many parts of the world, and particularly in mountain rangelands. To understand this process it is necessary to develop methods to assess soil erosion rate in a quick, economic and accurate manner. Based on the analysis of exposed *Polylepis australis* roots, we tested a dendrogeomorphological method for determining soil loss rate in rills and gullies. Few studies considered non-coniferous tree rings in soil erosion analysis and we used, for the first time, an experimental procedure of root exposure and provided a comparison with roots exposed by gully erosion. Our main results showed that as a consequence of soil erosion, exposed roots changed from root-like to a more stem-like wood anatomical structure. The percentage of vessel area per tree-ring area decreases by an average of 22% to 43% during the first and second year after exposure, respectively. Moreover, and during the same time interval, the mean vessel area decreased 32% and 65%, and the number of vessels increased 7% and 48%, respectively. Scars formed at the upper side of the exposed roots are coincident with changes in wood anatomy, and both evidences may be applied to reconstruct an erosion process. This study confirms that the wood anatomy analysis of partially exposed roots can be used to determine the year in which roots are exposed and provides a useful tool to monitor soil erosion rates with a high accuracy.

1. Introduction

Soil erosion is an important process of land degradation and has been considered one of the most serious worldwide environmental concerns (Lal, 2001). Although considerable effort has been made in estimating soil erosion rates by using various methods, ranging from prediction models to field measurements, approaches are usually complex, expensive and/or of limited accuracy (Lal, 1994; Weltz et al., 2011). Conventional measurement techniques to infer erosion rates are also limited in their temporal resolution or extent (Stoffel et al., 2013). As an alternative to the traditional methods, dendrogeomorphology (Alestalo, 1971) has been used for estimating the rate of gully erosion using tree rings. Additionally, information in growth rings has been combined with data from dated scars on exposed roots or on above-ground parts of fallen trees, exposed and dead root ends, root suckers, stems, branches and leading shoots of fallen trees and the age of trees living within a gully (Vandekerckhove et al., 2001; Stoffel and Bollschweiler, 2008; Bodoque et al., 2011). However, dendrogeomorphological approach would have limited scope in regions where datable tree cover is scarce or absent.

The determination of the vertical distance between the upper portion of an exposed root and the actual soil surface can offers an estimation of the erosion rate (Gärtner et al., 2001; Chartier et al., 2009; Stoffel et al., 2013). On the other hand, the occurrence of scars and sudden growth suppression or release in tree rings have also been used to date and reconstruct earth surface processes like mass movements (Braam et al., 1987), debris flows (Gärtner et al., 2003; Bollschweiler et al., 2007; Brayshawa and Hassan, 2009), rock falls (Stoffel et al., 2005; Perret et al., 2006), landslides (Gers et al., 2001; Stefanini, 2004), shore erosion events (Bégin, 2001), or even rill erosion and gully events (Vandekerckhove et al., 2001; Malik, 2008; Stoffel et al., 2012). However, change in the tree ring-growth pattern may not always be coincident with root exposure. This gen-

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erates uncertainties and errors in the estimation of erosion rates (Vandekerckhove et al., 2001).

Roots of various tree species show anatomical changes after exposure, such as the cell diameter size (Hitz et al., 2006; Gärtner, 2007; Stoffel et al., 2013). Research on changes in the anatomical structure of roots was primarily focused on earlywood and latewood tracheids in conifers (e.g., Gärtner et al., 2001; Bodoque et al., 2005; Rubiales et al., 2008; Wrońska-Wałach, 2014) and on vessel lumen size of broadleaved species (Hitz et al., 2008). These anatomical features in the xylem of exposed roots have helped to determine the time of exposure at an annual resolution (Gärtner, 2006; Corona et al., 2011). Nevertheless, with the exception of a few studies (e.g., Malik, 2006; Hitz et al., 2006, 2008; Chartier et al., 2009; Stotts et al., 2014; Sun et al., 2014), species other than coniferous have been scarcely studied by dendrogeomorphologists. Therefore, further analyses are needed to define more comprehensively the species-specific wood structure changes occurring during and after an angiosperm root exposure.

The aim of the study was to describe the tree-ring width and wood anatomical changes attributed to the effect of exposure of roots in *Polylepis australis* Bitter (Rosaceae) and to compare these anatomical changes between an experimental procedure and roots exposed by gully erosion in a mountain range of central Argentina. This mountain range is the southernmost distribution of the *Polylepis* woodlands, which are found along the Andes for an impressive 5400 km-long patchwork of high altitude forests intermingled in a grassland matrix extending from Venezuela to Argentina. These woodlands include a large number of endemic species, providing numerous ecological services such as maintenance of biodiversity, provision of clean water and carbon capture but are greatly affected by soil erosion mainly due to livestock and fires (Gareca et al., 2010; Renison et al., 2010, 2015). The novelty of this study is the analysis of wood anatomical structure in experimentally exposed roots for determining the first year of exposure.

2. Study area and species

The study was carried out in the Quebrada del Condorito National Park (31°34′S, 64°50′W), located between 1800 and 2300 m a.s.l. at the Córdoba mountains in central Argentina. This is a region without a frost-free period, where mean temperature at 2100 m a.s.l. ranges between 5.0 and 11.4 °C (coldest and warmest month, respectively). Annual precipitation reaches a mean of 900 mm, mostly concentrated in the warmest months, from October to April (Cabido, 1985; Colladon, 2010).

The landscape is a mosaic of woodlands, tussock grasslands, granitic outcrops and eroded areas with exposed rock surfaces (Cingolani et al., 2004, 2013). Woodlands are generally small patches dominated by *P. australis*, a small tree reaching 3–14 m tall. Domestic grazing and prescribed fire management were restricted inside the National Park since 1997. The dominant soil is Mollisol derived from the weathering of the granite substrate and fine-textured aeolian deposits. Due to the cold climate, soils are dark, with high organic matter content (Cabido et al., 1987). At upper topographic positions, soils rarely exceed the meter in depth while at deep valleys soils reach several meters deep, as was observed at gullies or in soil profiles near stream banks (Cabido et al., 1987; Cingolani et al., 2003, 2013).

Livestock production is the main economic activity and has been traditionally managed through fires to clear woodlands and induce grass regrowth. Four centuries of these practices have produced significant soil erosion and woodland retraction, processes which are still active in large portions of the area (Renison et al., 2010; Cingolani et al., 2013). In this sense, active soil erosion is mainly evidenced in small gullies, usually less than 200 cm deep and parallel to the slope gradient, with the presence of partly exposed roots of *P. australis* trees (Fig. 1A,B).

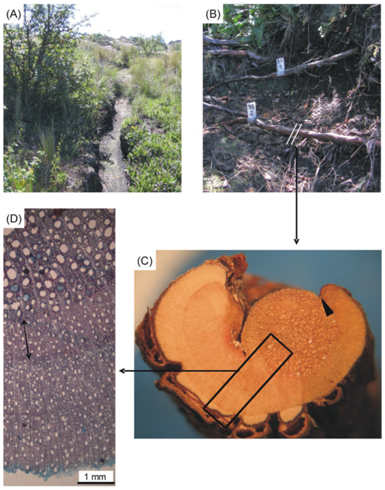

Fig. 1. (A) Rills and gullies formed on slopes in the Córdoba mountain rangelands, central Argentina; (B) *Polylepis australis* roots exposed by gully erosion; (C) overview of the root cross-section after sanding, note that the scars are clearly visible (black arrows); (D) cross-section showing anatomical changes as a result of sudden root exposure, black arrows mark the first ring after exposure.

3. Materials and methods

3.1. Field sampling procedure

We described the wood structure in stems and unexposed roots of *P. australis* trees growing at sites without evidence of soil erosion to use as a reference material for wood anatomical comparison. During the spring of 2010, three young trees (average basal stem diameter about 5 cm) were selected at sites without evidence of soil erosion. Each of the selected trees was transversely sectioned at 20, 10, 5, and 2.5 cm above and below ground level.

In order to determine the influence of geomorphic process on the root anatomy of *P. australis*, we performed two field sampling procedures. In the first sampling, during winter 2010, we experimentally exposed roots of five young trees (10–20 cm in basal stem diameter) growing in absence of soil erosion. In the following winter season (2011), we collected one cross-section of the experimentally exposed roots (of about 2 cm wide) from each plant (Fig. 1C). In the second sampling, we selected nine *P. australis* young trees (similar basal stem diameter) with partly exposed roots in small gullies and we collected one root cross-section sample per plant. In all cases, samples were collected only in partly exposed roots which presented a horizontal growth direction. It is important to consider that if the root tip gets exposed, the root dies back and cannot be used for dendrogeomorphological analyzes (Fig. 1B).

3.2. Laboratory methods

In each cross-section, 1 × 1 cm wood blocks were obtained with a blunt knife along the radial and tangential planes. After this, wood blocks were softened by immersion in boiling water and glycerin (1:1) for 1–2 h. Wood cross-sections of 10–15 μm thickness were obtained using a Leica SM 2000R sliding microtome. These sections were emptied of their protoplasmic contents using hypochlorite, rinsed with water and then dehydrated in increasingly concentrated alcohol solutions, to be stained with Safranin and Alcian Blue (1% solution in alcohol) and mounted with synthetic resin between glass slide and coverslips (Tolivia and Tolivia, 1987). From the histological micro-sections, wood images were captured in a ring by ring sequence using a digital camera (Micrometrics SE Premium) mounted on a microscope (Nikon Eclipse E200) with a magnification of 10×/0.25. Photographs were taken in TIFF format with a 420 pixels high × 567 pixels wide resolution.

Tree-ring widths were measured with a precision of 0.001 mm by using the Image Pro Plus 4.5 v software (Media Cybernetics, USA). From these cross-dated samples, high-resolution images were analyzed to determine the area occupied by tree-ring conducting vessels using the PC-Image program (Scion Corporation). For further details see Giantomasi et al. (2009). The following were the anatomical measurements considered in this study: tree-ring width (mm), mean vessel area (μm^2), number of vessels per mm^2 and percentage of vessel area in relation to each tree-ring area (total vessel area/tree-ring area). In addition, we dated the year formation of scars present in all exposed roots (Fig. 1C).

3.3. Data analysis

A reference chronology was prepared from stem and unexposed roots using standard dendrochronological methods (Stokes and Smiley, 1968). Using the COFECHA program (Holmes, 1983), the annual growth series were filtered with a cubic spline function for a period of 10 years, each one of them being divided into 12-year segments with an overlap of 6 years. Annual growth series of the exposed roots were too short and did not permit a reasonable degree of statistical correlation using COFECHA, therefore similarities between the chronologies were based on visual cross-dating via the reference chronology.

An ANOVA analysis was used to determine the statistical difference in the tree-ring width and in the anatomical measurements (mean vessel area, number of vessels per mm^2 and total vessel area/tree-ring area) among successive years before and after root exposure. To accomplish this analysis, two groups of measurements were defined: the first consisted of the series of experimentally exposed roots (one root cross-section per plant in five sampled plants, total 5 sections) and the second consisted of the series of roots exposed by gully erosion (one root cross-section per plant in nine sampled plants, total 9 sections). A preliminary Shapiro–Wilk test was carried out to determine whether the population data followed a normal distribution. In those cases in which important deviations in normal distribution were noted, a logarithmic transformation was applied from the data in order to achieve a lognormal type distribution. Mean separation with the Fisher's protected LSD test was used (Sokal and Rohlf, 1981). Statistical analyses were performed with the package SPSS 7.5 (Norusis, 1977). Significant level was determined at $P \leq 0.05$.

4. Results and discussion

4.1. Tree-ring width chronology and wood anatomy of Polylepis australis

Similarities in the tree-ring width patterns were confirmed from the cross-dating of *P. australis* trees growing without evidence of soil erosion. The reference chronology covered the period between 1998 and 2009. A total of three trees (21 series from stem and unexposed roots) make up the chronology with a mean correlation between series of $r = 0.705$ (99% confidence). This correlation indicates a high percentage of common variability among these trees, which is a consequence of the influence of a dominant factor over growth.

The porosity, in both stems and roots of trees growing at sites without evidences of soil erosion, was characterized by a semi-ring to diffuse pattern (Fig. 2). The growth ring boundary was marked by differences in the lumen diameter between earlywood and latewood vessels of contiguous rings. A thin layer of thick-walled and radially flattened latewood fibres also aided in the ring boundary recognition. Although the growth rings of stems were easily distinguished, there was some difficulty in distinguishing growth rings of roots because of the few differences in the vessel lumen area of two contiguous rings. This difficulty was increased when the rings were very narrow in width. Comparatively, stems showed a greater ring width as compared to roots (Fig. 3A). In addition, ring widths in stems and roots decreased as the distance from the ground level increased.

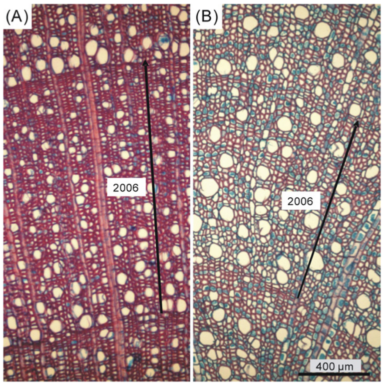

Fig. 2. Histological micro-sections showing wood structure in (A) stem and (B) root of *P. australis* trees growing at sites without evidences of soil erosion. Arrows indicate the growth direction along the tree rings.

Furthermore, differences between stems and roots were also discernible in regard to the vessel distribution pattern (Fig. 2). In stems, wider diameter vessels were mainly along the tree-ring boundary in the earlywood, while in roots vessels were of similar diameter across the entire growth ring. Moreover, the mean vessel area was about 2 times greater and the number of vessels was about 1.5 times smaller in roots than those observed in stems (Fig. 3). The percentage of vessel area per tree-ring area showed a trend with greater values in roots relative to stems. In this context, variations in the anatomical structure of vessels in relation to those patterns found in trees growing at sites without evidences of soil erosion can be used to corroborate wood anatomical reactions after exposure.

4.2. Wood anatomy of exposed roots

The cross-section of exposed roots resulted in significant changes in the wood anatomical features following the soil erosion process. For example, as shown in Figs. 1 D and 2 B, the tree-rings formed in advance of the root exposure showed wide-lumened, thin-walled cells. In addition, the growth ring boundaries were characterized by a very thin (eventually only one) latewood row of cells that were flattened in their radial direction. As a consequence, growth ring boundaries are visible, but often vague. From the first year of exposure onwards (Fig. 1D), the latewood/earlywood boundaries become clearly visible, similar to those observed in unaffected stems (Fig. 2A).

Exposed roots of *P. australis* trees within the gullies showed an evident change in tree-ring width in the second year after exposure, while in the experimentally exposed roots where only a single year after exposure was measured, we would expect a greater change in ring width in the following years (Figs. 4 A and 5 A). Although previous studies have shown that roots of various coniferous tree species increases their ring widths as a consequence of exposure (Gärtner et al., 2001; Bodoque et al., 2011), the ring width decrease observed in our study could be related to the loss of lateral fines roots after the roots are exposed. However, the reduction in ring width could be also related with the occurrence of wider rings in

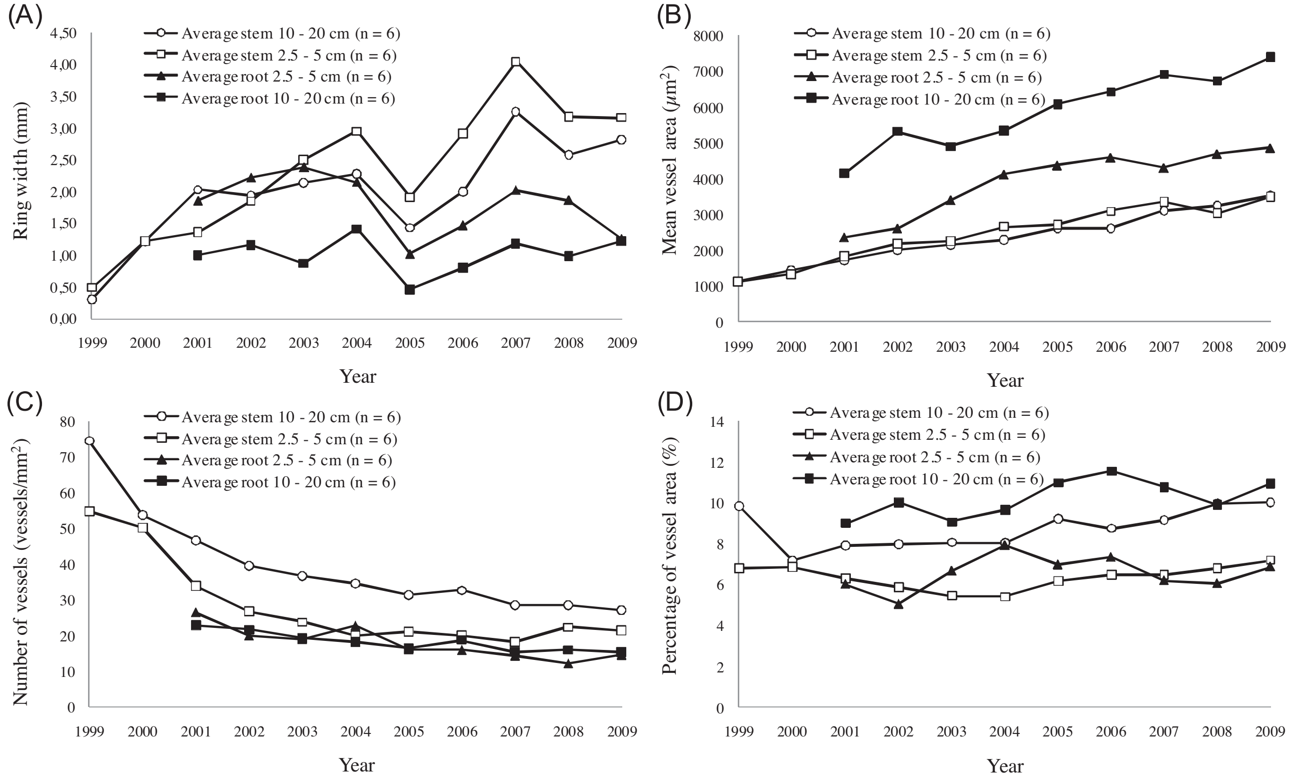

Fig. 3. Mean annual values of (A) ring width, (B) vessel area, (C) number of vessels, and (D) percentage of vessel area in *Polylepis australis* trees growing in absence of soil erosion. Variations in vessel features are presented regarding their distance above and below the ground level. Note that successive distances from ground level (i.e., 20 and 10 cm) were averaged into a single point ($n = 6$).

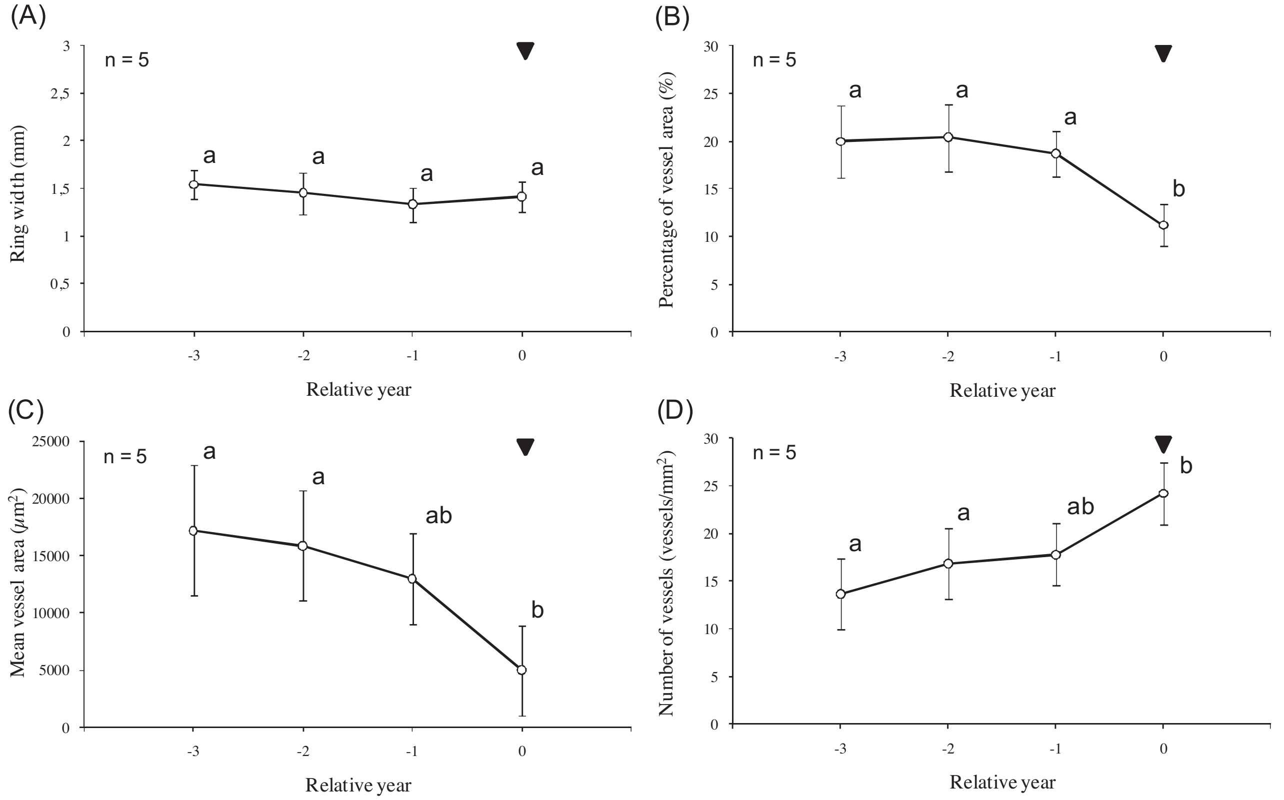

Fig. 4. Mean (±standard error) variation across years in (A) the ring width, (B) the percentage of vessel area, (C) the mean vessel area, and (D) the number of vessels per tree ring of *Polylepis australis* roots which were experimentally exposed. The first year of exposure is year zero. Negative values refer to non-exposed root rings and positive values refer to exposed root rings. Means with different letters indicate significant statistical differences among relative years ($P < 0.05$, $n = 5$). Black arrows mark the first year of scar formation as a result of root exposure.

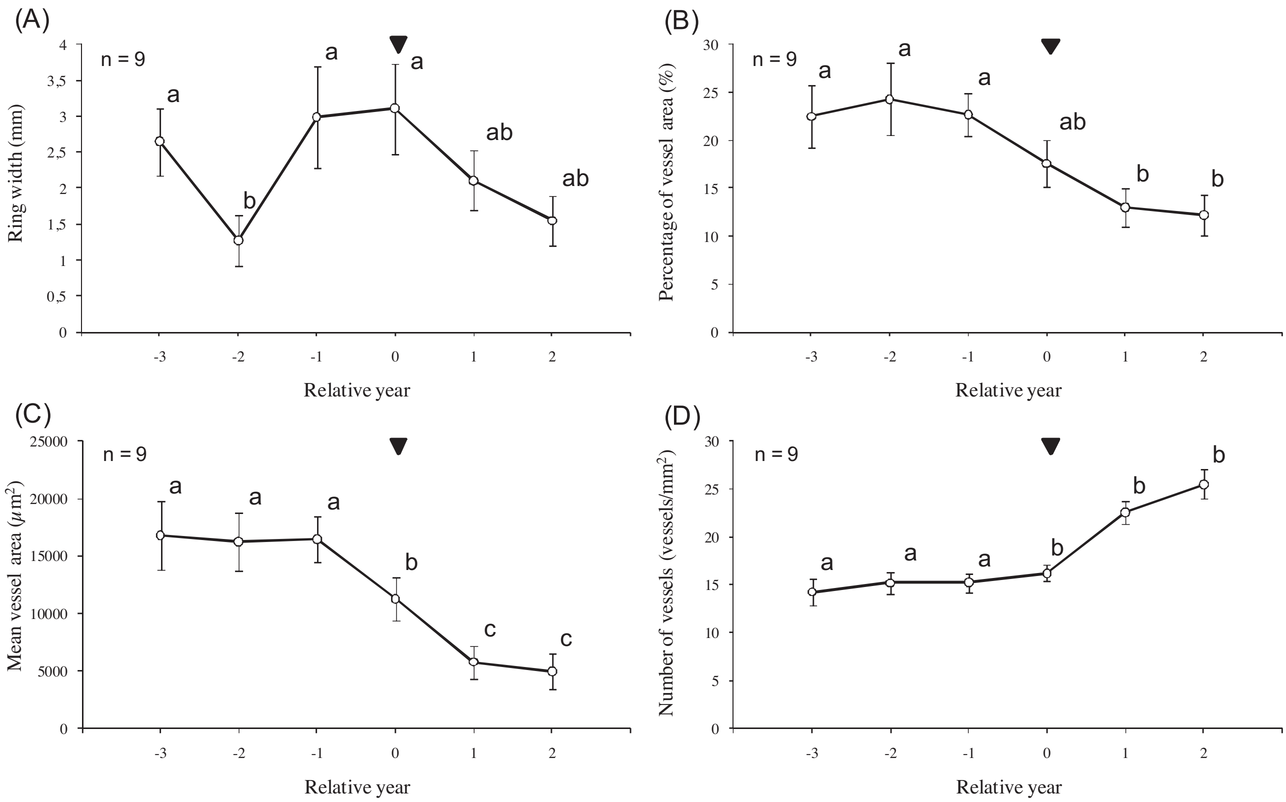

Fig. 5. Mean (±standard error) variation across years in (A) the ring width, (B) the percentage of vessel area, (C) the mean vessel area, and (D) the number of vessels per tree ring of *Polylepis australis* roots exposed by gully erosion. The first year of exposure is year zero. Negative values refer to non-exposed root rings and positive values refer to exposed root rings. Means with different letters indicate significant statistical differences among relative years ($P < 0.05$, $n = 9$). Black arrows mark the first year of scar formation as a result of root exposure.

other part of root. In effect, considering that exposed root samples had relatively severe environmental conditions after exposure, ring widths could vary in longitudinal profile of the root as a result of different mechanical stresses. In this sense, Wrońska-Wałach et al. (2015) analyzed the tree-ring width and wood anatomy variability of vertical fir roots (*Abies alba* Mill.) exposed to landslide processes and reported that the first ring after root exposure tends to wedge in longitudinal profile and may be very narrow or missing in some location within the root.

On the other hand, the wood anatomical structure of root cross-sections showed an evident change after exposure (Figs. 4 and 5). In this regard, in the experimentally exposed roots the percentage of vessel area per tree-ring area significantly decreased ($P < 0.05$, $n = 5$) in average 40% in comparison with the years before root exposure (Fig. 4B). The mean vessel area decreased 62% and the number of vessels increased 36% in the first year of root exposure ($P < 0.05$, $n = 5$, Fig. 4C,D). In concordance, all these wood anatomical features showed the same patterns than those found in the roots exposed by gully erosion. Thus, the percentage of vessel area per tree-ring area significantly decreased ($P < 0.05$, $n = 9$) in average 22% and 43%, respectively in the first and second year after root exposure (Fig. 5B). The mean vessel area decreased 32% and 65% and the number of vessels increased 7% and 48% in the two years following the root exposure, respectively ($P < 0.05$, $n = 9$, Fig. 5C,D). As evidenced, the percentage of vessel area, the mean vessel area and the number of vessels found in roots exposed by gully erosion (Fig. 5) showed a one-year delay to reach similar values as observed in the experimentally exposed roots (Fig. 4). This finding could be explained due to a more gradual root exposure in the gullies (e.g., roots of *P. australis* growing near the ground level) as compared with a sudden experimental root exposure.

In comparison, exposed roots revealed similar values in the anatomical structure of the vessels respect to those found in stems of trees growing without evidences of soil erosion (shown in Fig. 3), for example, ranging on average between 1000 and 3000 μm² in mean vessel area and 30–50 vessels per mm². Changes from root-like to a more stem-like wood anatomical structure could be due to the dramatic variation of atmospheric conditions after root exposure (Bodoque et al., 2005; Gärtner, 2007). Based on experimental evidence regarding the vulnerability of larger diameter vessel to water stress- and frost-induced embolism is dramatically increased (Tyree and Sperry, 1989; Tyree et al., 1994), small diameter vessels could be formed in periods of unfavorable conditions after root exposure. In this sense, the extreme temperatures recorded in the upper altitudinal belt of the study area, with an average of minimum temperature of 3.39 °C in the coldest months (from June to August), could probably be an important contributing factor in the wood anatomical changes of exposed roots in *P. australis*. Recent research in coniferous tree species (Gärtner et al., 2001; Corona et al., 2011) showed similar reductions in tracheid lumen area in roots as a result of reduced soil cover and increases in the fluctuations of temperature and humidity.

Moreover, changes from root-like to stem-like wood anatomical structure after exposure is a comparable reaction to that described for coniferous trees in shallow or steep hill slopes (Gärtner et al., 2001; Bodoque et al., 2005; Gärtner, 2007). For example, Gärtner et al. (2003) noted that roots of *Larix decidua* Mill. trees react to exposure by decreasing cell lumen in the earlywood portion of an annual ring. A threshold value of 50% below the tracheid lumen area of the previous years was identified as the wood anatomical signal for root exposure. In concordance to Stotts et al. (2014), the focus of most previous studies concerning erosive processes and root exposure have typically been performed using coniferous species and, to a lesser extent, angiosperm species. However, in comparison with conifers, woody angiosperms are particularly more abundant in subtropical mountains, increasing the potential for estimating gully erosion rates with exposed roots. Furthermore, the complex and specialized wood structure of angiosperm species could provide more detailed information on the anatomical response of exposed root to soil erosion events than coniferous species.

We used an additional element to corroborate the occurrence of reaction wood in exposed roots. In this sense, dating of scars located on the upper side of the exposed roots (Fig. 1C) showed chronological coincidence with the first year of wood anatomical changes after exposure (Figs. 4 and 5). Hence, scars provide additional, complementary information that helps in reconstructing the time of the root exposure with annual resolution. This approach based on the occurrence of scars and the changing wood structure of exposed roots, represents, in comparison with conventional measurement techniques (Lal, 1994; Weltz et al., 2011), a simple, rapid method for estimating recent soil erosion rates without the need for expensive instrumentation.

5. Conclusion

We demonstrate that anatomical changes in exposed *P. australis* roots can be used to determine the first year of exposure after an erosion process. In this sense, exposed roots revealed changes from root-like to stem-like wood anatomical structure after exposure. Furthermore, significant reductions of mean vessel area and percentage of vessel area as well as increases in the number of vessels were identified as the precise time of first root exposure. Scars formed at the upper side of the exposed roots were coincident with changes in wood anatomy. Consequently, analyses of wood anatomical features and scar dating of exposed roots may provide a more comprehensive reconstruction of soil erosion rates.

In this paper we present the use of an angiosperm tree species in the application of an existing dendrogeomorphological method—the analysis of wood anatomical structure in exposed roots—for determining the first year of exposure. Woody angiosperms are particularly more abundant than coniferous in the subtropical mountains, increasing the potential for estimating soil erosion rates. 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 erosion process are scarce or absent.

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