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Original article

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.

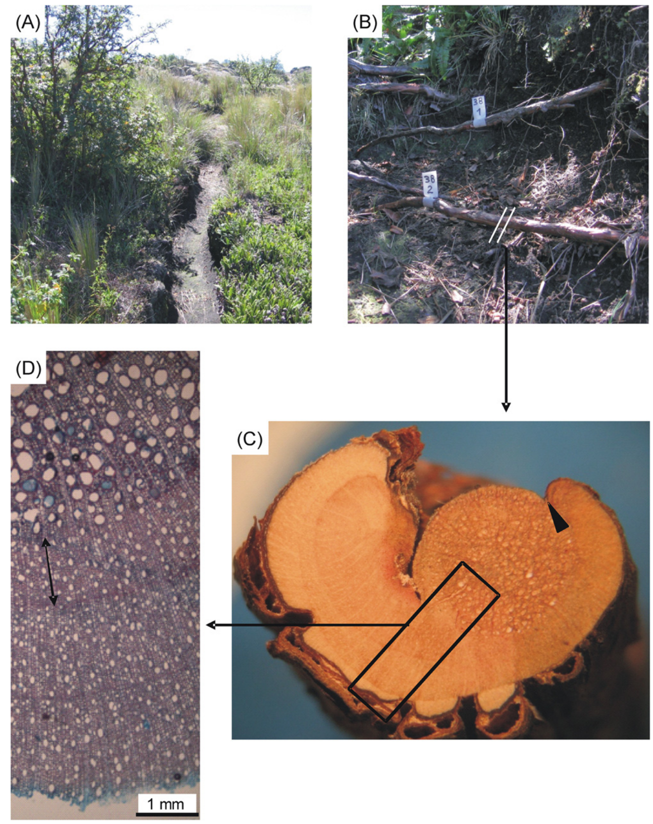

Fig. 1. (A) Rills and gullies formed on slopes in the Córdoba mountain rangelands, central Argentina; (B) *Polylepis australis* roots exposed by gully erosion; (C) overview of the root cross-section after sanding, note that the scars are clearly visible (black arrows); (D) cross-section showing anatomical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

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).

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).