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Measuring medium-term sheet erosion in gullies from trees: A case study using dendrogeomorphological analysis of exposed pine roots in central Iberia

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ABSTRACT

The assessment of gully erosion poses a great challenge because of the complexity and connectivity of the geomorphic processes involved. This study focuses on the quantification of sheet erosion rates in a set of slope gullies located on the northern piedmont of the Guadarrama Mountains (Spanish Central System). In order to delineate accurately the gully areas in which sheet erosion was predominant, the Hydrologic/Erosion Response Unit (HRU/ERU) approach was used and a dendrogeomorphological analysis of exposed tree roots was carried out to quantify sheet erosion rates in one selected HRU/ERU. Identification of the first year of exposure by erosion from anatomical criteria was therefore critical. The 29 samples taken were prepared for anatomical analysis and cross-dated. Anatomical analysis of the samples showed a reduction in the lumen area of earlywood tracheids following root exposure and also, in most cases, a slight increase in growth rings. Moreover, at the end of the ring, latewood tissue and visible annual borders were very clearly defined by several rows of thick-walled tracheids. A non-parametric test was used on the findings derived from this qualitative analysis to objectify determination of the first year of exposure. Estimates of sheet erosion were obtained by dividing the height of eroded soil by the number of years that each root was exposed. The mean value of soil erosion for the entire study site was then determined from statistical inference. Using this procedure, a range of sheet erosion rates between 6.2 and 8.8 mm y^{-1} (125.2 and 177.8 t ha^{-1} $year^{-1}$) was obtained for the dominant HRU/ERU of these gullies in central Iberia. These estimates of eroded soil thickness were adjusted based on the recent finding that root anatomical changes occur prior to their exposure by erosion.

1. Introduction

Gully erosion has become a global issue as a consequence of its academic and applied implications (Valentín et al., 2005), and has been the focus of numerous studies during the last decade (e.g., Poesen et al., 2003; Smith, 2008; Reid et al., 2010). Notwithstanding the abundance of studies recently undertaken on this matter, it is important to understand the complexity and connectivity of geomorphic processes involved in so-called 'gully erosion'. These processes operate on different time scales and at different topographical positions within the gullies. In general, the materials to be eroded are prepared by weathering processes at the gully walls and within the internal topography of the hillslope. From then on, different processes of hydric erosion and mass movement transport the materials from the slopes onto dry washes and gully bottoms. Finally, fluvial processes deliver these sediments to nearby fluvial networks. Connectivity between hillslope gullies and fluvial systems has been well illustrated by Harvey (2001). Nevertheless, the connectivity between geomorphic processes in gullies and badlands has been described in only a few studies, of which Godfrey et al. (2008) is an example.

In order to gain a deeper knowledge of the various geomorphic processes operating within gullies, this paper proposes the use of Hydrologic Response Units or HRUs (Uhlenbrook, 2003; Cammeraat, 2004; Beighley et al., 2005), also known as Erosion Response Units, ERUs (Flügel et al., 1999; Märker et al., 2001; Sidorchuk et al., 2003) when active forms of erosion and their related processes are characterized. Delineation of HRUs/ERUs depends on the spatial distribution of land use, residue and vegetation cover, topography and type of soil, as well as erosion processes and related features, since, for a given rainfall, all these factors determine the response of soil water dynamics by influencing infiltration and runoff rates (Kosmas et al., 1997). As a result, specific erosion and sediment transport processes are generated (Märker et al., 2001).

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Soil erosion can be quantified by using dendrogeomorphic analysis of exposed tree roots. Dendrogeomorphology (Alestalo, 1971) is one of the most accurate non-systematic data sources for dating events. It has an annual or even seasonal precision over several centuries (Wiles et al., 1996; Bollschweiler et al., 2008). This branch of science is a subdiscipline of dendrochronology, which uses different characteristic sequences of tree rings and other measurements as indicators to characterize geomorphological processes from both spatial and temporal standpoints. The method is based on determining how active geomorphological processes affecting tree growth are reflected in variations in width measurements of growth rings, in the tree morphology (Corominas and Moya, 1999; Pelfini and Santilli, 2006; Zielonka et al., 2008) and in certain anatomical properties of wood (Gärtner et al., 2001; Bodoque et al., 2005; Malik and Matyja, 2008; Rubiales et al., 2008; Ballesteros et al., 2010a,b). The use of this technique in gullies is also promising in that it expands the antecedents on estimated gully erosion rates, although its applications have been limited. Vandekerckhove et al. (2001) and Malik (2008) are two examples of these. A thorough review of the state of the art regarding quantification of erosion rates using dendrogeomorphology can be found in Corona et al. (2011) and references therein.

This paper focuses on the quantification of sheet erosion rates at one HRU/ERU (open woodland on silica sand bare soil hillslopes with slopes averaging 24°) in a set of gullies in Central Spain. The formation of gullies in this kind of lithologic configuration is uncommon and therefore only a few studies have been carried out on them. Examples of these include Lindquist (1980), Osterkamp and Toy (1997), Boardman et al. (2003) and Nichols (2007). Linking these two subjects, dendrogeomorphology and gully erosion, the aim of this study is to demonstrate the usefulness of the former as a tool for quantifying hydric erosion activity in gullies. Several specific objectives were derived from this overall goal. The HRU/ERU approach was used to design the sampling of exposed roots so that the sheet erosion rates obtained were representative of the entire study site. In addition, with respect to sheet erosion estimates, the highest level of certainty was pursued for studying anatomical changes occurring in roots as a response to soil erosion. In this way, the first year in which tree-ring anatomically responds to soil denudation was preliminarily dated. Finally, cross-dating of root samples was carried out in order to locate the presence of discontinuous or multiple rings and thereby it improved the reliability of dating.

2. Study area and physical setting

On the northern piedmont of the Guadarrama Mountains in the Central System of the Iberian Peninsula (Segovia province, Central Spain), the scarp slopes of a set of mesas and cuestas developed on Cretaceous sediments are deeply dissected by sand slope gullies (Fig. 1). The mesas and cuestas are capped by limestone and dolostone rocks. Their hillslopes are underlain by horizontally-bedded silica sand deposits, with some thin layers of clay and gravel, and covered with a carbonate colluvium. The silica sands only crop out in gullies on slopes, in an area covering about 18 km^2, and in quarries, which are common in the region.

Two characteristics make these slope gullies stand out in a global context: (a) they are developed on poorly consolidated sands. Gullies developed on sandy lithologies are rare; they are usually associated with clayey lithologies; and (b) their formation has been interpreted as being triggered by quarrying activities dating back to at least 800 years ago (Moreno, 1989).

The fact that they are developed on highly erodible materials (sands) results in a geomorphic system at disequilibrium. It therefore offers extraordinarily high erosion and sediment yield rates which are derived from different geomorphic processes taking place in various spatial contexts within the gullies (Lucía et al., 2008).

It is also worth noting that these gullies are not a consequence of arid or semi-arid environments. Although the climate is characteristic of the Mediterranean Basin, there is a moderate average annual precipitation (680 mm) and temperature (11.4 °C). As a result, the gullies coexist with dense formations of native vegetation where the slopes are not dissected. Intense human use of the land, which started more than a thousand years ago, led to overgrazed hillslopes and very open woodlands (Moreno, 1989).

However, during recent decades there has been a generalized abandonment of these rural areas and this has allowed spontaneous recovery of the woodlands (Rey Benayas et al., 2007; Vicente et al., 2009). As a consequence, the vegetation cover is dense outside the gullies and has a tendency to colonize them, although instability of the substratum makes this difficult. Nevertheless, colonization of the incised areas is possible, mainly by *Pinus pinaster* Ait.

The above conditions favor the formation of mosaic structures in which vegetation patches are combined with erosive landforms. Nevertheless, the magnitude to which erosive processes act has been blocking an effective vegetal colonization (Fig. 2). In this respect, the presence of exposed roots, both on the inner slopes and divides of the gullies, is an evidence of the high erosion rates existing in the study site.

3. Material and methods

3.1. Sampling strategy

In order to guarantee that all the roots sampled responded similarly to sheet erosion, the HRU/ERU approach was taken into account. To this end, lumped land areas within the study site, comprising homogeneous geological substratum, soil, surface deposits, canopy cover and vegetative residue surface cover, with an established range of slope gradient, were identified. Therefore, a small variation in the erosive dynamic within a given response unit could be assumed. Among all the HRUs/ERUs established for these gullies, the one in which the sheet erosion process was predominant was selected (Fig. 2). Additionally, the HRU/ERU studied is characterized by the geomorphological and edaphic properties shown in Table 1. All the properties assigned with the letter

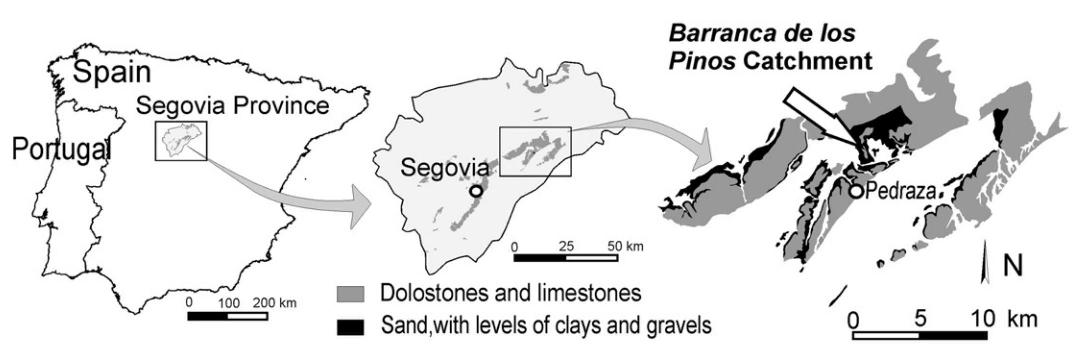

Fig. 1. Location and geologic setting of the study area.

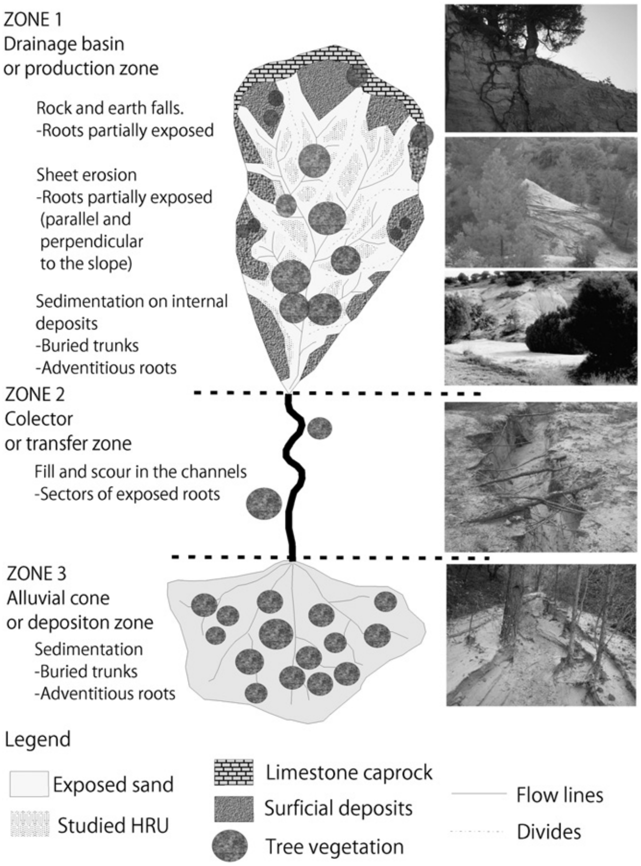

Fig. 2. Effects of different active geomorphic processes on vegetation at the three zones of a typical sand slope gully in the area studied, showing the framework for this dendrogeomorphological analysis. The scheme also shows the HRU/ERU studied, highlighted with dotted polygons, over the exposed sands. It consists of bare sandy exposed hillsides with slopes between 15° and 35°. The main active process that takes place in this HRU/ERU is sheet erosion, which produces root exposure. The second picture from above shows one hillslope with exposed tree roots due to sheet erosion.

(c) in Table 1 are measured at each sampling point and their results are elaborated in Table 2.

At the study site, none of the exposed roots showed abrasion scars that could have caused the shifting wood morphometry pattern in the annual rings. These modifications, together with anatomical changes

Table 1
Land properties that condition a homogeneous hydrological response in the studied HRU/ERU. (a) Properties observed at all sampling points. (b) Properties measured (with a hand penetrometer and ring infiltrometer) on a few representative points in order to describe the HRU/ERU more accurately. (c) Properties measured at each sampling point to check that all samples were taken in the same unit.

Land properties which condition a homogeneous hydrological response	Characterization of the HRU/ERU studied
Geological substratum (a)	Segovia sands and clays formation
Soil (a)	Not developed
Surface deposit (a)	Non-existent
Canopy cover (a)	Open woodland
Vegetative residue surface cover (a)	Non-existent
Penetration resistance (b)	None
Infiltration capacity (b)	Very high
Organic matter (c)	Very low
Slope gradient (c)	From 15° to 36°
Texture of the soil/substratum (c)	Sand–loamy sand
Structure of the soil/substratum (a)	Structureless
Predominant erosional feature	Sandy slopes eroded by sheet erosion

Table 2
Characteristics of the studied HRU/ERU. n is the number of sample points.

Descriptive statistics ($n = 29$)	Slope (degrees)	Aspect (degrees)	Texture		
			% sand	% silt	% clay
Average	23.8	209.9	88.9	6.3	5.0
Standard deviation	8.3	82.9	7.3	4.2	3.7
Range	7–36	5–360	72–95	2.8–17.8	2.2–10.28

due to soil denudation, have been described as markers for accurately determining the first year of exposure (Carrara and Carroll, 1979; Gärtner et al., 2001; Gärtner, 2003; Bodoque et al., 2005; Hitz et al., 2008a,b; Rubiales et al., 2008). More recently, Corona et al. (2011) demonstrated that roots do not react with root anatomical responses in the moment they are exposed. They proved that there are anatomical effects when erosion reduces the soil cover over the root to approximately 3 cm.

Twenty-nine samples of exposed roots from 29 different trees were taken across the study site. This number of samples was conditioned by the number of exposed roots that met the requirements established for sampling. Of the total, three samples corresponded to *Pinus sylvestris* L. and the rest to *P. pinaster*. Roots were cut with a handsaw into sizes approximately 15 cm length. Afterward, two disk samples of about 2 cm wide were extracted from each sample. In all cases samples were obtained from roots that were following the steepest slope direction, in order to ensure that the estimated height of the removed soil layer was due to sheet erosion (Gärtner, 2007). They were taken only from exposed roots that were placed more than 1.5 m from the trunk, to avoid upward migration related to ongoing growth of the stem. Furthermore, roots close to the stem often show an asymmetric growth pattern with wider rings on the topside as a result of mechanical stresses exerted by the stem (Mattheck and Breloer, 1992; Gärtner, 2007).

A detailed description was made at each sampling point of the spatial and morphological characteristics of the surroundings. The following information was collected: i) geographical location (UTM coordinates); ii) altitude (m.a.s.l.); iii) aspect (sexagesimal degrees); iv) local (root) slope expressed (degrees); v) distance of the root section from the tree trunk (m) and vi) vertical distances between the upper part of the root and the soil surface (mm). To these purposes, a measuring tape was used. Additionally, soil samples were taken to verify that all the locations sampled belonged to the same HRU/ERU in terms of textural characteristics, content of organic matter, permeability and cohesiveness.

3.2. Sample preparation

Sections of the sampled roots were left to dry in the open air for 2 months. They were then processed for macro- and microscopic analysis, according to the protocol suggested by Gärtner et al. (2001). Two slices with an approximate thickness of 1.5 cm were obtained from the initial section. The slices were then sanded and polished with sandpaper (up to 400 grit) in order to facilitate recognition of the tree-rings. One of the sections was used for macroscopic assessment of the yearly growth pattern. The other was prepared for an analysis of anatomical variations. The samples were softened by soaking in different mixtures of water and alcohol because the sectioning procedure was hindered by an abundance of resin in the xylem of some of the samples. Cross-sections of approximately 1 cm wide and 20 μm thick were obtained along the radial direction with a sliding microtome. Staining with safranin was carried out as described by Schweingruber (1990), using a citrus oil clearing agent (Histoclear) as a dissolvent. After the staining procedure, sections were embedded on a hardening epoxy (Eukit) and dried at room temperature.

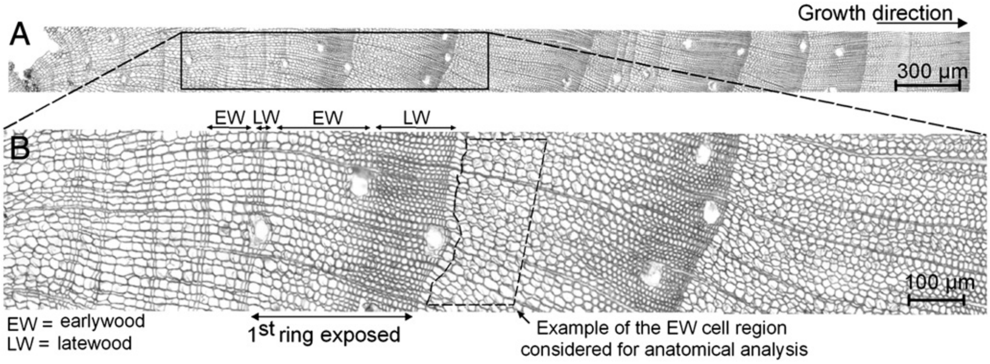

Fig. 3. Microscopic image of one of the samples analyzed. A) Cross-section of an exposed root of *P. pinaster*. B) Area within the EW (earlywood) considered for the anatomical analysis.

3.3. Wood anatomical analysis

Samples were observed under optical microscopy and photographed with a digital imaging system (LEICA DFC420). Microscopic images were analyzed at 50× magnification using WinCell PRO Version 5.6c software with a precision of 1 µm in the measurements.

The anatomical parameters analyzed were those which are good indicators of the occurrence of the first year of exposure according to literature (Rubiales et al., 2008). These were: a) ring width, b) latewood (LW) percentage and c) cell lumen area of tracheids. The occurrence of resin ducts (RD) was also assessed. Analysis of this parameter was based on visual observation and direct counting of the ducts on digital images. The area analyzed for RD was defined by the width of the microscopic image (0.8 cm), the total length of earlywood (EW) and percentage of LW. Measurements were taken perpendicular to the growth ring. The cell sizes of the lumen of the axial tracheids were determined from measurements through on averaging of 2000 cells contained in a mean area of 0.6 mm^2 of the early earlywood (EE), representing the first part of EW (Fig. 3). This is considered to be the best tree ring layer for environmental proxy (Ballesteros et al., 2010b).

3.3.1. Statistical analysis

Prior to the statistical analysis, anatomical parameters were described by visual examination of the microscopic images to give a qualitative approximation of the first year of anatomical responses due to soil erosion. The anatomical parameters used as indicators for this purpose (see Rubiales et al., 2008) were: i) a reduction in the lumen area of early-earlywood (EE) tracheids and ii) a notable increase in both the width of the whole ring and the percentage of LW. In order to guarantee their validity, a statistical approach based on this preliminary assessment was implemented using a two-sample comparison test. All the parameters considered in the analysis were compared and pre/post tree rings –established with respect to the first year in which anatomical changes occurred– were defined as input data. For this purpose the non-parametric Mann–Whitney Wilcoxon test (Sprent and Smeeton, 2001) was applied. Analysis was based on considering the neighboring five rings formed before and after the first ring that responded to soil denudation in terms of anatomical changes.

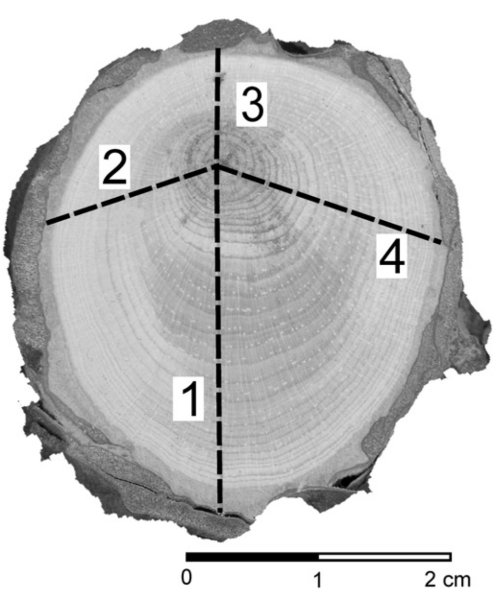

Fig. 4. Scanned image of a sample in which the radii where ring widths were measured are marked.

3.4. Dendrochronological dating of growth ring series

The dendrochronological principle of cross-dating (Fritts, 1976) was applied, with the aim of improving precision for dating both the first year of response to soil erosion (previously estimated using anatomical criteria; see Section 3.2) and subsequent rings denoting characteristic features of exposure. This also made it possible to identify the existence of discontinuous or multiple rings, which would imply an increase in the dating reliability. To this end, sections of exposed roots were sanded and polished with sandpaper (up to 400 grit) in order to visualize each growth ring properly. In each section, four or five radii were marked along the directions that showed the highest variability regarding measurements of the width of the growth rings (Fig. 4). Growth rings of each radius were measured to an accuracy of 0.01 mm using a LINTAB measuring device coupled to a stereomicroscope and TSAPW in software. It was not possible to apply statistical cross-dating techniques because of the limited growth ring series available. Therefore, both the presence of discontinuous or multiple rings and dating of the series were determined by visual analysis of overlapping graphs.

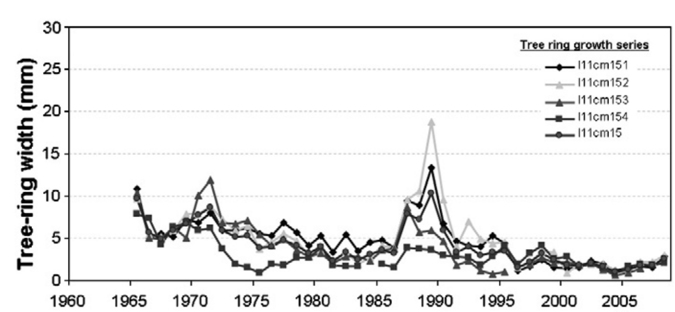

Fig. 5. Growth ring series for one of the samples analyzed. The sudden increase in width measurements is as a result of exposure.

Table 3
Two-sample comparison tests for homogeneous groups: N (non-exposed rings) and E (exposed rings) for each sample of wood analyzed. The codes a and b are referred to the homogenous groups, whereas values in italic indicate a statistically insignificant difference at the 95% confidence level.

Sample code	Lumen area (μm^2)				Percentage of latewood				Width of the growth rings (mm)			
M1	N	864.62 (a)	E	333.31 (b)	N	14.46 (a)	E	45.53 (b)	N	*4.06* (a)	E	*6.71* (a)
M2	N	2314.99 (a)	E	854.97 (b)	N	13.34 (a)	E	28.93 (b)	N	*7.04* (a)	E	*11.05* (a)
M4	N	1501.10 (a)	E	778.23 (b)	N	*21.41* (a)	E	*46.05* (a)	N	*1.02* (a)	E	*2.05* (a)
M5	N	1333.28 (a)	E	556.64 (b)	N	*22.15* (a)	E	*35.39* (a)	N	*1.78* (a)	E	*2.89* (a)
M7	N	1720.88 (a)	E	421.90 (b)	N	23.79 (a)	E	52.11 (b)	N	1.36 (a)	E	5.53 (b)
M8	N	1085.42 (a)	E	631.81 (b)	N	*21.37* (a)	E	*29.32* (a)	N	*2.30* (a)	E	*3.36* (a)
M9	N	709.78 (a)	E	284.74 (b)	N	41.10 (a)	E	78.45 (b)	N	*0.70* (a)	E	*1.67* (a)
M10	N	2004.10 (a)	E	921.78 (b)	N	17.74 (a)	E	31.11 (b)	N	0.82 (a)	E	3.81 (b)
M13	N	2159.90 (a)	E	328.32 (b)	N	*22.16* (a)	E	*34.32* (a)	N	*0.95* (a)	E	*2.22* (a)
M14	N	966.84 (a)	E	280.99 (b)	N	24.38 (a)	E	44.43 (b)	N	1.46 (a)	E	2.72 (b)
M15	N	1772.59 (a)	E	769.40 (b)	N	*23.20* (a)	E	*37.21* (a)	N	0.67 (a)	E	2.73 (b)
M17	N	1095.24 (a)	E	297.03 (b)	N	*24.42* (a)	E	*39.41* (a)	N	*0.63* (a)	E	*0.75* (a)
M21	N	2006.25 (a)	E	1129.25 (b)	N	*37.37* (a)	E	*48.43* (a)	N	1.56 (a)	E	3.63 (b)
M22	N	1549.37 (a)	E	1014.24 (b)	N	16.95 (a)	E	34.75 (b)	N	1.31 (a)	E	3.04 (b)
M23	N	770.87 (a)	E	207.93 (b)	N	26.06 (a)	E	49.94 (b)	N	*0.85* (a)	E	*0.81* (a)
M24	N	1386.16 (a)	E	563,32 (b)	N	*7.54* (a)	E	*12.67* (a)	N	*1.17* (a)	E	*1.72* (a)
M27	N	1874.55 (a)	E	1031.33 (b)	N	23.15 (a)	E	41.23 (b)	N	*1.96* (a)	E	*3.18* (a)
M31	N	*573.62* (a)	E	*543.4* (a)	N	*29.22* (a)	E	*40.35* (a)	N	0.86 (a)	E	2.15 (b)
M32	N	1615.94 (a)	E	501.22 (b)	N	17.12 (a)	E	35.58 (b)	N	0.55 (a)	E	2.27 (b)
M35	N	1459.93 (a)	E	706.98 (b)	N	*10.29* (a)	E	*14.05* (a)	N	*0.66* (a)	E	*1.04* (a)
M36	N	1106.6 (a)	E	455.317 (b)	N	*44.21* (a)	E	*54.04* (a)	N	*0.26* (a)	E	*0.19* (a)
M38	N	1237.97 (a)	E	457.55 (b)	N	*20.56* (a)	E	*24.37* (a)	N	*6.58* (a)	E	*5.54* (a)
M39	N	881.95 (a)	E	330.65 (b)	N	*7.51* (a)	E	*36.57* (a)	N	9.47 (a)	E	3.04 (b)
M41	N	1688.55 (a)	E	803.45(b)	N	*26.10* (a)	E	*38.90* (a)	N	3.53 (a)	E	16.15 (b)
M42	N	501.50 (a)	E	307.14 (b)	N	*13.76* (a)	E	*26.06* (a)	N	3.93 (a)	E	17.11 (b)
M45	N	501.50 (a)	E	307.14 (b)	N	24.04 (a)	E	42.43 (b)	N	1.34 (a)	E	0.95 (b)
M46	N	261.67 (a)	E	140.75 (b)	N	26.45 (a)	E	43.84 (b)	N	*5.51* (a)	E	*4.28* (a)
M47	N	502.45 (a)	E	192.77 (b)	N	*30.35* (a)	E	*39.11* (a)	N	*3.98* (a)	E	*3.66* (a)
M48	N	374.66 (a)	E	153.41 (b)	N	22.24 (a)	E	36.09 (b)	N	*4.13* (a)	E	*2.85* (a)

3.5. Estimation of sheet erosion rates

To quantify sheet erosion rates, the following parameters are required: i) the number of rings since exposure took place (NR_{ex}) and ii) the thickness of the eroded soil layer once the exposure has occurred (E_x). Additionally, because sheet erosion implies a continuous and progressive denudation, some anatomical parameters undergo changes before the root is exposed (Corona et al., 2011) (e.g., tracheid cell lumen is reduced when the soil covering is reduced to a few centimeters). Therefore, the evaluation of mean annual erosion rates will be underestimated if this bias (ε) is not taken into account (Corona et al., 2011). As a result of the soil characteristics (i.e., very low bulk density) of the study site, ongoing secondary root growth was not considered. Under this premise, the estimation of soil erosion rate (E_r; mm y^{-1}) is given by:

$$E_r = \frac{E_x + \varepsilon}{NR_{ex}}. \quad (1)$$

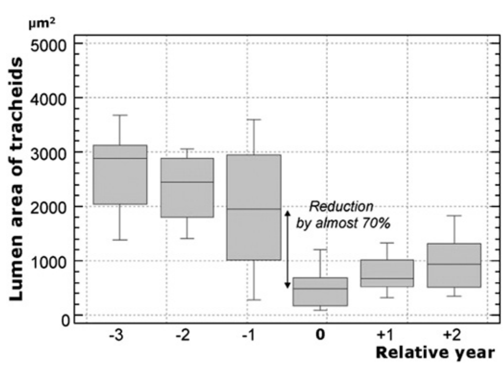

Fig. 6. Box plot showing changes of EE (early earlywood) tracheids in the lumen area as a result of exposure. The first year of exposure is year zero. Negative X values refer to non-exposed tree-rings. In contrast, positive values are linked to exposed tree-rings.

A statistical inference method was implemented to characterize the erosive process. To this end, a preliminary analysis was carried out to determine whether the population from which the samples came followed a normal distribution. This consisted of taking measurements to test for significant deviations from normal distribution (i.e., standardized kurtosis and standardized skewness) and application of the Shapiro–Wilk test, based on comparison of the quantiles of normal fitted distribution with quantiles of the data. 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. Finally, a 95% confidence interval was determined for the population mean of the sheet erosion rates estimated at the study site.

In order to establish whether estimated erosion rates were to some degree determined by the morphometric parameters considered in sampling (i.e., slope and hillside aspect), Pearson's coefficient was applied to determine the degree of correlation between each variable and the calculated erosion rate. A linear correlation between each pair of variables was also tested for significance. This analysis was complemented with an ANOVA analysis (Fisher's least significant difference—LSD method) to determine whether some of the morphometric factors had a significant effect on the dependent variable.

Table 4
Percentage of samples that, within the three main anatomical parameters considered as main indicators of root exposure, defined statistically significant differences between tree rings denoting exposure and those formed under the protection of the soil.

Anatomical parameters denoting root exposure by erosion	Lumen area in EE (μm^2)	Percentage of latewood	Width of the growth rings (mm)
Percentage of samples which show statistically significant differences	97%	45%	44%

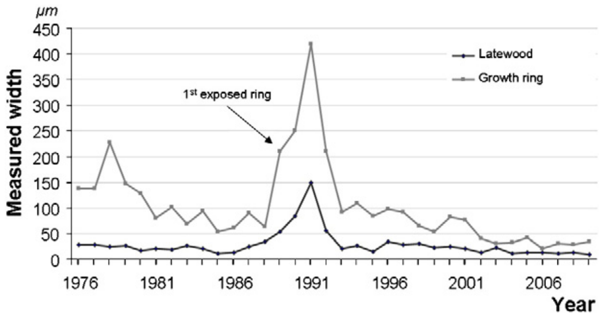

Fig. 7. Plot showing an example of changes in latewood and growth rings as a response to exposure.

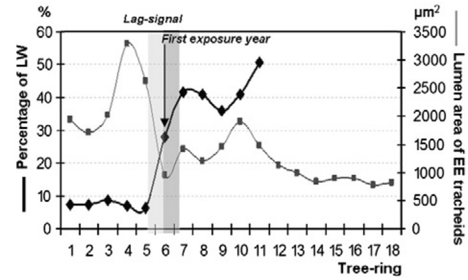

Fig. 8. Lag in the anatomical signal denoting the first year of exposure based on the consideration of two parameters: percentage of LW (latewood) and lumen area of EE (early earlywood) tracheids.

4. Results

4.1. Dendrochronological dating of tree-ring series

A visual assessment of the analyzed roots showed that exposure was mostly marked by a perceptible increase in width rings (Fig. 5). Discontinuous tree-ring formation due to cambium damage as a consequence of exposure was more common in outer rings. In fact, in some cases these rings had been completely destroyed after exposure took place. In addition, in 66% of the samples discontinuous inner rings were also present. In this regard, there was no overlap between samples, except for the year 1996, which produced the highest matches (six discontinuous growth rings in four of the samples analyzed). The presence of double or multiple rings can be considered almost anecdotal because these were detected in just one root sample. The age of the samples analyzed ranged from a minimum of 7 years to a maximum of 44 years, with a mean value of 29.16 ± 9.43.

Table 5
Obtained erosion rates and values of the parameters taken into account at each sampled point. NR_{ex}: Number of rings since exposure took place. E_x: Thickness of the eroded soil layer once the exposure have occurred.

Sample code	Slope (°)	Aspect (°)	Year of exposure	$E_x+\varepsilon$ (mm)	NR_{ex}	Erosion rate (mm y^{-1})
M1	21	360	1998	72	10	7.2
M2	7	220	2002	58	6	9.7
M4	18	150	2005	56	3	18.7
M5	27	318	1997	69	11	6.3
M7	9	115	1989	53	19	2.8
M8	30	154	1995	78	13	6.0
M9	25	270	1988	61	20	3.1
M10	23	130	1993	59	15	3.9
M13	18	302	1991	61	17	3.6
M14	26	231	1987	78	21	3.7
M15	14	5	1987	51	21	2.4
M17	28	20	1999	48	9	5.3
M21	22	332	1981	68	27	2.5
M22	15	200	1999	50	9	5.6
M23	34	304	1999	68	9	7.6
M24	36	230	1997	63	11	5.7
M27	34	232	2002	56	6	9.3
M31	31	204	1997	55	11	5.0
M32	32	208	1997	61	11	5.5
M35	18	196	1981	59	27	2.2
M36	10	142	1968	65	40	1.6
M38	33	190	1983	52	25	2.1
M39	23	280	2004	49	4	12.3
M41	34	184	2001	53	7	7.6
M42	34	271	2002	52	6	8.7
M45	17	208	2002	45	6	7.5
M46	16	235	1982	54	26	2.1
M47	17	180	1988	67	20	3.4
M48	23	125	1999	53	9	5.9

4.2. Wood anatomical analysis and statistical assessment of data

Almost all the analyzed exposed tree-roots showed important changes in the selected anatomical parameters once exposure had occurred. This can be interpreted as a consequence of both the effects of exposure (e.g., variations in temperature, reduction in pressure of the soil cover, and light incidence) and the mechanical stress that the roots underwent when they lost their soil cover. As a consequence, most of the tree-rings showed considerable growth, which was especially noticeable in the first rings formed after exposure. Latewood was clearly distinguishable since it had several rows of thick-walled tracheids. In addition, there was a notable reduction in the lumen area of EE tracheids once root exposure took place. In this regard, the results obtained from the comparison procedure (Tables 3 and 4) make evident that all the samples analyzed except one showed a statistically significant reduction (Fig. 6).

The percentage of LW increased due to exposure in all cases. Nevertheless, such increases were significant in only 45% of the studied images. This is because this factor frequently gave values one or two years after exposure that were similar to values denoting non-exposure (Fig. 7). In six cases, a lag of one increment ring was observed between the response presented by the EE tracheid lumen area and the percentage of LW as a result of exposure. The width of growth rings showed more erratic behavior. Thus, 72.4% of tree-ring samples denoting exposure were characterized by much larger widths than non-exposed tree-rings (Fig. 7). However, statistically significant differences in the LW percentage were observed in only 44% of the samples. In contrast, a reduction in tree-ring width as a result of exposure was observed in 27.6% of the samples.

4.3. Estimates of sheet erosion rates and data analysis

A preliminary statistical analysis regarding sheet erosion rates (Table 5) indicated that neither standardized skewness nor standardized kurtosis values (3.45 and 5.01 respectively) were within the range expected for a normal distribution. Furthermore, the Shapiro–Wilk test rejected the hypothesis that the sample came from a normal distribution with 95% confidence as the p-value was less than 0.05. After the logarithmic transformation and the subsequent antilogarithmic conversion, a range of erosion rate between 6.2 and 8.8 mm y^{-1} (125.2 and 177.8 t ha^{-1} y^{-1} for a bulk density of 2.02 g cm^{-3}) was determined at 95% confidence level. These rates were obtained from data provided by 17 of the 29 samples analyzed. Erosion rates from the remaining 12 samples were not representative of erosion intensity in the study area. In addition, there was no evidence that a statistically significant correlation existed among the variables (in all cases the p-value was >0.05). Analysis of variance (ANOVA) was used to determine the factors that have a significant influence on the estimated erosion rates. The probability values obtained at a 95% confidence level indicate that none of the factors considered can explain the results.

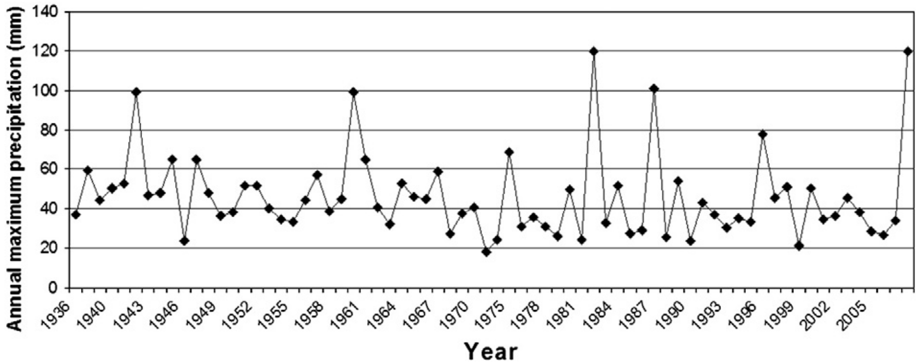

Fig. 9. Annual daily maximum precipitation time series for the study site.

5. Discussion

The interrelationships among bedrock, topography, soil and vegetation reflect a common hydrological and erosive response within each HRU/ERU (Lucía et al., 2010). Therefore, a significant advance in this field is that the erosion rates obtained at each HRU/ERU through the dendrogeomorphology technique can be transferred to similar HRUs/ERUs. For example, the same erosion rates can be expected in slopes with conditions similar to those in the Central and Eastern Iberian Peninsula, where gullies on slopes with silica sand are common. Thus, HRUs/ERUs are used for storage and transmission of information on how these landforms react to erosion. Finally, understanding the processes and rates by linking HRU/ERU and dendrogeomorphology can allow extension of the knowledge obtained in the study area to others.

It can be considered that estimated erosion rates are highly accurate, because tree-ring series were cross-dated. An analysis of discontinuous and multiple rings made it possible to determine the age of the roots, as well as the specific year in which the first exposure ring was formed.

The methodological approach to characterize soil erosion has been developed and applied widely since the 1960s (LaMarche, 1968; Dunne et al., 1978; Carrara and Carroll, 1979; Bodoque et al., 2005; McAuliffe et al., 2006; Chartier et al., 2009). Gärtner (2007) proposed an improved equation for estimating erosion rates, in which the height of eroded soil depends on the intensity of the erosive process and ongoing secondary root growth. Subsequently, Corona et al. (2011) showed that anatomical response due to hydric erosion occurs prior to the root's exposure. Therefore, it can be considered that most of the available erosion rates obtained by means of dendrogeomorphogical analysis of exposed tree roots are underestimated, because this adjustment has not been taken into account. Regarding secondary root growth, the root migrates upward since growth occurs in the entire section. It should be pointed out, however, that the soil that housed the root system of the trees sampled was very loose. In fact, tests carried out with a pocket penetrometer did not report any measure of unconfined compressive soil strength. Therefore, the process of upward migration of the root due to growth in its upper part was ruled out, since the pressure exerted by the root in the lower part of the soil was sufficient to permit the root to penetrate downward. Accordingly, we did not take into account ongoing secondary root growth to estimate erosion rates. However, it has to be outlined that a minimal upward migration can not be excluded completely, because some expansion to both sides occurs as the root grows; therefore a minimal upward migration can take place.

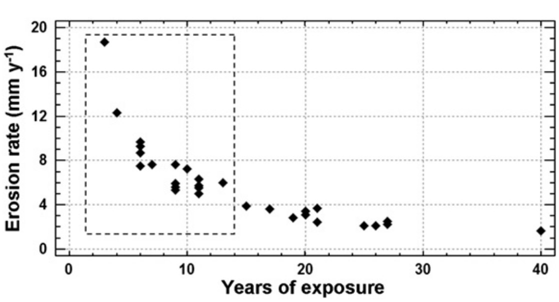

Fig. 10. Chart relating erosion rates and years of exposure of the exposed roots. Erosion rates inside the square are those used in the statistical analysis. The separation of the erosion rates in two populations was verified using the Mann–Whitney' non parametric test. The result obtained defined a p-value <0.05, indicating statistically significant differences between the medians of the two groups with a 95% confidence level.

Soil loss data were obtained by applying wood anatomical analysis to the quantification of soil erosion rates using partly exposed living roots from *P. pinaster* and *P. sylvestris*. A more precise determination of the first year of exposure was obtained from this analysis, which also avoided bias in erosion estimation because it was based on a quantitative assessment with statistical criteria. The two species studied showed analogous anatomical growth patterns due to exposure. Moreover, these were similar to other patterns observed in softwood species (Fayle, 1968; Gärtner et al., 2001; Gärtner, 2003; Hitz et al., 2006, 2008a). In this regard, the use of *P. pinaster* roots as a dendrogeomorphologic indicator for estimating sheet erosion rates is one of the major contributions of this research, as this Mediterranean pine is widely distributed in disturbed environments throughout SW Europe and the Iberian Peninsula.

Because exposure is a response to a continual lowering of the soil surface, a characteristic anatomical pattern is noticeable in the tree-ring record (Gärtner, 2003). Latewood tracheids become thick-walled, making it easier to differentiate ring boundaries. Likewise, the lumen area of EE tracheids almost always decreases when continuous denudation affects buried roots. However, other factors, such as RD occurrence, which has been reported to be a valuable dendroecological factor (Rigling et al., 2003), are not always present at the same time as exposure. As a consequence, this does not seem to be a relevant feature for characterizing the erosive process (Rubiales et al., 2008). This is in agreement with observations of *Pinus* sp. made by Stoffel (2008) and Ballesteros et al. (2010a) for other geomorphic processes.

An interesting finding derived from the anatomical analysis is that it was possible to establish the season in which the first year of anatomical response predominantly occurred. It was observed that the increase in the percentage of latewood as a response to soil denudation took place a year in advance with respect to the decrease in the lumen area of EE tracheids (Fig. 8). This lag was recognized in 20.7% of the samples. This circumstance may have implications from a hydrological point of view, since it can be hypothesized that the more intense erosive activity will take place in the warm season as a result of more frequent convective storms (Gayà, 2009).

The estimated mean erosion rates (6.2–8.8 mm y^{-1}; 125.2–177.8 t ha^{-1} y^{-1}) are lower than those estimated for the same area by other direct methods. Erosion rates estimated using erosion pins for short divides existing within the catchment of the same gullies were between 9 and 16 mm y^{-1} for a period of two hydrological years (Lucía; results unpublished). However, the data for the divides may not be representative as the length of the measurement was not long and because high magnitude and low frequency precipitation events were included within that two-year hydrological period.

The estimated erosion rates in the study area occurred in a period where there have not been changes in the annual daily maximum precipitation patterns at the nearest rain gage (Fig. 9). The above results suggest that the roots with a higher number of rings indicating anatomical response to soil denudation (those with a higher diameter and largely devoid of soil cover) led to significant underestimation of erosion rates, probably because roots protected soil against erosion. In contrast, slightly uncovered roots with few tree-rings denoting exposure offered much more realistic erosion rates. As shown in Fig. 10, roots with less than 15 years of exposure give more representative erosion rates (6.2–8.8 mm y^{-1}). Longer exposure substantially reduced erosion rates to 2.2–3.3 mm y^{-1}.

6. Conclusions

This paper describes the first attempt in Spain to estimate sheet erosion rates using dendrogeomorphological and anatomical indicators for *P. pinaster*. Analysis of exposed roots based on this approach make it possible to quantify a type of erosion process in a singular geomorphic environment. This demonstrates the utility of dendrogeomorphology in studies of medium term sheet erosion dynamics, which constitutes a great advantage over common measuring devices which require costly installations in order to produce data. Study findings revealed a site with important soil erosion activity, with estimated soil loss within the range 6.2–8.8 mm y^{-1}. The intense erosion processes on the regional slopes were initiated by ancient quarrying. The fact that all the samples were taken within the same HRU/ERU asserts that the estimated rates are representative of the study site. However, the main contribution of this paper is methodological. The combined use of Hydrologic/Erosion Units and dendrogeomorphological analysis has given information about how a homogeneous area reacts to natural processes. Although it is impossible to monitor active geomorphic processes everywhere, areas with a homogeneous hydrologic and erosion response can be identified and delineated, making information from selected areas useful. Such information could be extrapolated to areas with similar characteristics.

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References

Alestalo, J., 1971. Dendrochronological interpretation of geomorphic processes. Fennia 105, 1–139.

Ballesteros, J.A., Stoffel, M., Bodoque, J.M., Bollschweiler, M., Hitz, O., Díez-Herrero, A., 2010a. Changes in wood anatomy in tree rings of *Pinus pinaster* Ait. following wounding by flash floods. Tree Ring Res. 66, 93–103.

Ballesteros, J.A., Stoffel, M., Bollschweiler, M., Bodoque, J.M., Díez-Herrero, A., 2010b. Flash-flood impacts cause changes in wood anatomy of *Alnus glutinosa*. *Fraxinus angustifolia* and *Quercus pyrenaica*. Tree Physiol. 30, 773–781.

Beighley, R.E., Dunne, T., Melack, J.M., 2005. Understanding and modelling basin hydrology: interpreting the hydrogeological signature. Hydrol. Process. 19, 1333–1353.

Boardman, J., Parsons, A.J., Holland, R., 2003. Development of badlands and gullies in the Sneeuberg, Great Karoo, South Africa. Catena 50, 165–184.

Bodoque, J.M., Díez-Herrero, 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.

Bollschweiler, M., Stoffel, M., Schneuwly, Dominique, M., Bourqui, K., 2008. Traumatic resin ducts in *Larix decidua* stems impacted by debris flows. Tree Physiol. 28, 255–263.

Cammeraat, L.H., 2004. Scale dependent thresholds in hydrological and erosion response of a semi-arid catchment in southeast Spain. Agr. Ecosyst. Environ. 104, 317–332.

Carrara, P., Carroll, T., 1979. The determination of erosion rates from exposed tree roots in the Piceance Basin, Colorado. Earth Surf. Proc. Land. 4, 307–317.

Chartier, M.P., Rostagno, C.M., Roig, F.A., 2009. Soil erosion rates in rangelands of northeastern Patagonia: a dendrogeomorphological analysis using exposed shrub roots. Geomorphology 106, 344–351.

Corominas, J., Moya, J., 1999. Reconstructing recent landslide activity in relation to rainfall in the Llobregat River basin, Eastern Pyrenees, Spain. Geomorphology 30, 79–93.

Corona, C., Lopez-Saez, J., Rovéra, G., Stoffel, M., Astrade, L., Berger, F., 2011. High resolution, quantitative reconstruction of erosion rates based on anatomical changes in exposed roots at Draix, Alpes de Haute-Provence — critical review of existing approaches and independent quality control of results. Geomorphology 125, 433–444.

Dunne, T., Dietrich, W.E., Brunengo, J., 1978. Recent and past erosion rates in semi-arid Kenya. Z. Geomorph. 29, 130–140.

Fayle, D.F.C., 1968. Radial Growth in Tree Roots — Distribution, Timing, Anatomy. Technical Report No. 9. Faculty of Forestry, University of Toronto, Toronto.

Flügel, W.A., Märker, M., Moretti, S., Rodolfi, G., Staudenrausch, H., 1999. Soil erosion hazard assessment in the Mkomazi river catchment (KwaZulu/Natal — South Africa) by using aerial photo interpretation. Zentralbl. Geol. Palaeontol. 1, 641–653.

Fritts, H.C., 1976. Tree Rings and Climate. Academic Press, New York.

Gärtner, H., 2003. Holzanatomische Analyse diagnostischer Merkmale einer Freilegungsreaktion in Jahrringen von Koniferenwurzeln zur Rekonstruktion geomorphologischer Prozesse. Diss. Bot. 378, 1–118.

Gärtner, H., 2007. Tree roots—methodological review and new development in dating and quantifying erosive processes. Geomorphology 86, 243–251.

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, 81–91.

Gayà, M., 2009. Tornadoes and severe storms in Spain. Conference preprints of the 5th European Conference on Severe Storms, 12–16 October 2009, Landshut, Germany, pp. 323–325. http://www.essl.org/ECSS/2009/preprints/chapter10.pdf.

Godfrey, A., Everitt, B.L., Martin-Duque, J.F., 2008. Episodic sediment delivery and landscape connectivity in the Mancos Shale badlands and Fremont River system, Utah, USA. Geomorphology 102, 242–251.

Harvey, A.M., 2001. Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, Northwest England. Catena 42, 225–250.

Hitz, O., Gärtner, H., Monbaron, M., 2006. In: Heinrich, I., Gärtner, H., Monbaron, M., Schleser, G. (Eds.), Reconstruction of Erosion Rates in Swiss Mountain Torrents. TRACE — Tree Rings in Archaeology, Climatology and Ecology, 4. Forschungszentrum Jülich GmbH, Jülich, pp. 196–202.

Hitz, O.M., Gärtner, H., Heinrich, I., Monbaro, M., 2008a. Application of ash (*Fraxinus excelsior* L.) roots to determine erosion rates in mountain torrents. Catena 72, 248–258.

Hitz, O.M., Gärtner, H., Heinrich, I., Monbaron, M., 2008b. Wood anatomical changes in roots of European ash (*Fraxinus excelsior* L.) after exposure. Dendrochronologia 25, 145–152.

Kosmas, C., Dalanatos, N., Cammeraat, L.H., Chabart, M., Diamantopoulos, J., Farad, R., Gutiérrez, L., Jacob, A., Marques, H., Martínez-Fernández, J., Mizara, A., Moustakas, N., Nicolau, J.M., Oliveros, C., Pinna, G., Puddu, R., Puigdefábregas, J., Roxo, M., Simao, A., Stamou, G., Tomasi, N., Usai, D., Vacca, A., 1997. The effect of land use on runoff and soil erosion rates under Mediterranean conditions. Catena 29, 45–59.

LaMarche, V.C., 1968. Rates of slope degradation as determined from botanical evidence, White Mountains, California. US Geo. Surv. Prof. Paper 352-I, pp. 341–377.

Lindquist, R.C., 1980. Slope processes and forms at Bryce Canyon National Park. Ph.D. Thesis. University of Utah, United States.

Lucía, A., Vicente, F., Martín Moreno, C., Martín Duque, J.F., Sanz, M.A., de Andrés, C., Bodoque, J.M., 2008. Procesos geomorfológicos activos en cárcavas del borde del piedemonte norte de la Sierra de Guadarrama (Provincia de Segovia). Bol. RSEHN Secc. Geol. 102, 47–69.

Lucía, A., Laronne, J.B., Martín-Duque, J.F., Sanz, M.A., 2010. Geomorphic dynamics of gullies developed in sandy slopes of Central Spain. *Barranca de los Pinos* experimental catchment. In: Egozi, R., Lekach, J. (Eds.), 4th International Seminar on Small Catchments Dynamics: Connectivity in Time and Space. IAHS, Israel, pp. 6–7.

Malik, I., 2008. Dating of small gully formation and establishing erosion rates in old gullies under forest by means of anatomical changes in exposed tree roots (Southern Poland). Geomorphology 93, 421–436.

Malik, M., Matyja, M., 2008. Bank erosion history of a mountain stream determined by means of anatomical changes in exposed tree roots over the last 100 years (Bílá Opava River — Czech Republic). Geomorphology 98, 126–142.

Märker, M., Moretti, S., Rodolfi, G., 2001. Assessment of water erosion processes and dynamics in semiarid regions of southern Africa (KwaZulu/Natal RSA; Swaziland) using the Erosion Response Units concept (ERU). Geogr. Fis. Din. Quat. 24, 71–83.

Mattheck, C., Breloer, H., 1992. Root cross-sections tell the load history. Allg. Forst Jagdztg. 163, 142–145.

McAuliffe, J.R., Scuderi, L.A., McFadden, L.D., 2006. Tree-ring record of hillslope erosion and valley floor dynamics: landscape responses to climate variation during the last 400 yr in the Colorado Plateau, northeastern Arizona. Global Planet. Change 50, 184–201.
Moreno, F., 1989. Zonas kársticas en la vertiente N de la Sierra de Guadarrama. Ph.D. Thesis, Universidad Complutense de Madrid, Spain.
Nichols, M.H., 2007. The Walnut Gulch experimental watershed — 50 years of watershed monitoring and research. In: de Graaff, J., Cameron, J., Sombatpanit, S., Pieri, C., Woodhill, J. (Eds.), Monitoring and Evaluation of Soil Conservation and Watershed Development Projects. World Assoc. of Soil and Water Cons, Bangkok, p. 496.
Osterkamp, W.R., Toy, T.J., 1997. Geomorphic considerations for erosion prediction. Environ. Geol. 29, 152–157.
Pelfini, M., Santilli, M., 2006. Dendrogeomorphological analyses on exposed roots along two mountain hiking trails in the Central Italian Alps. Geogr. Ann. A. 88, 223–236.
Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C., 2003. Gully erosion and environmental change: importance and research needs. Catena 50, 91–113.
Reid, L.M., Dewey, N.J., Lisle, T.E., Hilton, S., 2010. The incidence and role of gullies after logging in a coastal redwood forest. Geomorphology 117, 155–169.
Rey Benayas, J.M., Martins, A., Nicolau, J.M., Schulz, J.J., 2007. Abandonment of agricultural land: an overview of drivers and consequences. Perspect. Agr. Vet. Sci. Nutr. Nat. Resour. 57, 1–14.
Rigling, A., Brülhardt, H., Bräker, O.U., Forster, T., Schweingruber, F.H., 2003. Irrigation effect on tree growth and vertical resin duct production of *P. sylvestris* L. on dry sites in the Central Alps, Switzerland. Forest Ecol. Manage 175, 285–296.
Rubiales, J.M., Bodoque, J.M., Ballesteros, J.A., Díez-Herrero, A., 2008. Response of *P. sylvestris* roots to sheet-erosion exposure: an anatomical approach. Nat. Hazard. Earth Syst. 8, 223–231.
Schweingruber, F.H., 1990. Anatomie Europäischer Hölzer. Haupt, Bern.
Sidorchuk, A., Märker, M., Moretti, S., Rodolfi, G., 2003. Gully erosion modelling and landscape response in the Mbuluzi river catchment of Swaziland. Catena 50, 507–525.
Smith, H.G., 2008. Estimation of suspended sediment loads and delivery in an incised upland headwater catchment, south-eastern Australia. Hydrol. Process. 22, 3135–3148.
Sprent, P., Smeeton, N.C., 2001. Applied Nonparamentric Statistical Methods. Chapman & Hall/CRC, Boca Raton, London, New York, Washington, D.C.. 461 pp.
Stoffel, M., 2008. Dating past geomorphic processes with tangential rows of traumatic resin ducts. Dendrochronologia 26, 53–60.
Uhlenbrook, S., 2003. An empirical approach for delineating spatial units with the same dominating runoff generation processes. Phys. Chem. Earth 28, 297–303.
Valentín, C., Poesen, J., Li, Y., 2005. Gully erosion: impacts, factors and control. Catena 63, 132–153.
Vandekerckhove, L., Muys, B., Poesen, J., De Weerdt, B., Coppe, N., 2001. A method for dendrochronological assessment of medium-term gully erosion rates. Catena 45, 123–161.
Vicente, F., Sanz, M.A., Lucía, A., Martín-Duque, J.F., 2009. Evolución geomorfológica en tiempos históricos recientes de cárcavas del borde del piedemonte norte del Guadarrama. Estudio a partir de fuentes documentales. Bol. RSEHN Secc. Geol. 103, 49–64.
Wiles, G.C., Calkin, P.E., Jacoby, G.C., 1996. Tree-ring analysis and Quaternary geology: principles and recent applications. Geomorphology 16, 259–272.
Zielonka, T., Holeksa, J., Ciapala, S., 2008. A reconstruction of flood events using scarred trees in the Tatra Mountains, Poland. Dendrochronologia 26, 173–183.