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QUANTIFYING SOIL EROSION FROM HIKING TRAIL IN A PROTECTED NATURAL AREA IN THE SPANISH PYRENEES

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ABSTRACT

Recreational activities may impose adverse impacts on the environment of natural landscapes and protected areas owing to persistent tourist influx. Here, we use a dendrogeomorphic approach to estimate soil erosion induced by hikers at trails in the Ordesa and Monte Perdido National Park (north-eastern Spain). For the first time, exposed roots of *Pinus uncinata* Ramond ex DC and *Fagus sylvatica* L. were used on the Iberian Peninsula to reconstruct the timing and amount of soil erosion induced by hikers based on dendrogeomorphology. In addition, we propose a new characterization of ground microtopography using a microtopographic profile gauge and validate results of this approach with 3D point clouds derived from terrestrial laser scanning. Determination of the first year of root exposure was based on the analysis of changes in roots, at both the macroscopic and tissue levels. Analysis shows that a distinctive footprint is observable at macroscopic and microscopic scales following initial exposure and thus confirms results of previous work realized with roots of other tree species (e.g. *Pinus sylvestris* L.). Our results also indicate that a characterization of erosion based on microtopographic profiles can replace terrestrial laser scanning measurements, which are often difficult to obtain in remote areas. Estimates of soil erosion ranged between 3·1 ± 1·5 and 8·9 ± 4·3 mm y^{-1} (or 52·7 ± 25·5 to 151·3 ± 73·1 t ha^{-1} y^{-1}). The approach deployed here could help improve management of and access to natural protected areas and thus reduce the potentially negative impacts of recreational activities on these sensitive environments. Copyright © 2017 John Wiley & Sons, Ltd.

KEY WORDS: soil erosion; protected natural areas; dendrogeomorphology; *Fagus sylvatica* L.; *Pinus uncinata* Ramond ex DC

INTRODUCTION

The demand for lands dedicated to outdoor recreational uses has increased greatly since the second half of the 20th century (Toy & Hadley, 1987). Trails aimed at supporting recreational activities, such as hiking, biking and wildlife observation, on the one hand, can favour the protection of natural areas by concentrating visitor traffic to spatially restricted corridors (Symmonds *et al*., 2000; Wimpey & Marion, 2010; Marion *et al*., 2016). On the other hand, however, and in view of increasing recreational uses together with sometimes poorly designed and badly maintained trails, significant stresses on the environment of protected natural areas can be observed as well (Marion & Leung, 2001). For example, trails aligned perpendicularly to contour lines and/or trails exceeding slope angles of 10% are commonly considered to favour trail degradation (Leung & Marion, 1996; Farrell & Marion, 2002; Nepal, 2003). In addition, the intensity of trail use (Deluca *et al*., 1998; Dixon *et al*., 2004) and, more specifically, the type of use (e.g. intense uses such as horse and all-terrain vehicle access versus light uses such as hiking) are other factors influencing soil loss (Olive & Marion, 2009).

Long-term recreational uses may lead to soil compaction, muddiness, erosion and/or trail widening (Deluca *et al*., 1998; Chatterjea, 2007; Özcan *et al*., 2013), which in turn may significantly impact hydrophysical variables such as macroporosity, porosity, void ratio and saturated hydraulic conductivity but also favour an increase of bulk density (Sutherland *et al*., 2001). Soil compaction due to recreational trampling will also facilitate overland flow erosion (Hanson *et al*., 2004; Li *et al*., 2005; Pelfini & Santilli, 2006; Torn *et al*., 2009; Ramos-Scharron *et al*., 2014). The magnitude of these processes and associated impacts will depend on the intensity, frequency and timing of the disturbance, as well as on environmental conditions of the site under study (Torn *et al*., 2006).

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Recently, awareness of the negative impacts of soil erosion has been on the rise. In addition, recognition of the important role of this geomorphic process as an important factor in the alteration and degradation of natural protected areas has become a major topic of research (Wolf *et al.*, 2009; Wijitkosum, 2012). In this regard, an improved understanding of long-term erosion rates is critically needed, not only to obtain more detailed and reliable assessments and enhanced understanding of the underlying processes and potential issues but also to guide the development of effective management strategies in these sensitive environments (Bochet *et al.*, 2010; Dotterweich, 2013).

So far, most quantitative assessments of trail erosion mainly focused on the measurement of incision depths using a rigid bar, so as to obtain changes in cross-sectional area (CSA) and incision at fixed intervals (Cole, 1983; Hammitt & Cole, 1998; Yoda & Watanabe, 2000). Approaches using a variable CSA rely on the same principle but aim at reducing measurement time without sacrificing accuracy. To this end, measurements are taken at characteristic locations of the trail surface (Olive & Marion, 2009). Alternatively, one can also measure maximum trail incision along perpendicular transects (Dixon *et al.*, 2004; Hawes *et al.*, 2006; Marion *et al.*, 2006). A last possible approach consists of topographic surveys of soil erosion at recreational trails with differential GPS (Tomczyk & Ewertowski, 2013) or terrestrial laser scanning (TLS) (Ballesteros-Cánovas *et al.*, 2015; Bodoque *et al.*, 2015).

Dendrogeomorphology – that is, the study aimed at unravelling past geomorphic process activity in growth rings in trees and roots (Alestalo, 1971; Stoffel & Bollschweiler, 2008; Stoffel & Corona, 2014) – represents an alternative approach that has been used widely in the past to document and quantify erosion rates (LaMarche, 1961, 1968; Carrara & Carroll, 1979; Bodoque *et al.*, 2005; Stoffel *et al.*, 2013; Ballesteros-Cánovas *et al.*, 2017). As roots occur frequently on slopes, dendrogeomorphology can be used to obtain erosion rates over larger surfaces and are, in addition, representative in space and time, thus enabling estimation of soil erosion with (sub-)annual precision and with reasonable spatial resolution (Stoffel *et al.*, 2013). These facts represent a clear advantage of dendrogeomorphology over other conventional methods of direct and indirect erosion estimates, as the latter are often lacking the combination of spatial and temporal representativeness, primarily as a result of the economic costs of installations and their management over the lifetime of the equipment (Bodoque *et al.*, 2011). In addition, and as a further advantage, exposed roots also allow erosion rates to be obtained for large areas, provided that exposed roots are in fact present from tree species with good dendrochronological characteristics (Grissino-Mayer, 1993) and provided that available trees are located in homogeneous units in terms of their response to erosion (Bodoque *et al.*, 2011).

The standard dendrogeomorphic method used to estimate sheet erosion rates is based on the determination of the height of the exposed part of the root measured *in situ* (E_x) and is then contrasted with the time elapsed (in years) since the first exposure to the present day (LaMarche, 1961; Bodoque *et al.*, 2005). The ratio between these two parameters is used to calculate an erosion rate in millimetres per year. Much research has been carried out so far to accurately establish the first year of exposure. Thus, changes in the root caused by exposure have been analysed at the macroscopic level (Carrara & Carroll, 1979) or at the tissue or cell level (Fayle, 1968; Hitz *et al.*, 2008; Rubiales *et al.*, 2008; Corona *et al.*, 2011).

Less attention has, by contrast, been paid to the precise determination of E_x. The age of exposed roots has been related to the height of the root's central growth axis above the ground surface (McAuliffe *et al.*, 2006), or combined with the measurement of the minimum depth of soil erosion derived from the reconstructed root diameter at the moment of denudation (Danzer, 1996). The estimate of E_x was then corrected considering ongoing secondary growth (Corona *et al.*, 2011). However, these methodological approaches did not necessarily consider the importance of soil microtopography to obtain reliable erosion rates. More recently, variability in ground surface microtopography has been included in dendrogeomorphic research, both to improve the reliability of sheet erosion rates and to determinate uncertainty in the estimates. To address this issue, the combined use of TLS and Geographic Information Systems has been shown to represent a highly precise and valuable tool (Ballesteros-Cánovas *et al.*, 2015; Bodoque *et al.*, 2015). Nevertheless, the use of TLS may not be feasible in difficult conditions such as natural protected areas in steep mountain environments, as these regions are often difficult to access, even more so with heavy and large TLS equipment.

Accordingly, this paper aims at assessing soil erosion from recreation (hiking) trail in a Spanish mountainous natural protected area. To this end, we tested the suitability of new tree species (*Fagus sylvatica* L. and *Pinus uncinata* Ramond ex DC) for dendrogeomorphic dating and applied, for the first time in dendrogeomorphology, a microtopographic profile gauge (i.e. a device used to measure the lowering and/or accretion of soil) to characterize ground microtropography.

MATERIAL AND METHODS

Study Site

The study presented here was conducted in the Ordesa and Monte Perdido National Park (OMPNP) in the Central Spanish Pyrenees. The altitude of the National Park ranges between 700 and 3,355 m asl, although the study sites selected along the Faja Pelay trail were between 1,330 and 1,980 m asl (Figure 1).

Lithology comprises mainly calcareous substrates, such as limestones, sandstones, marls and flysch-type sediments (from the Eocene period) (Ríos *et al.*, 1989). Climate is defined as continental, but with a clear oro-mediterranean influence. Total annual precipitation is 1,735 mm (measured at the Góriz Station at 2,200 m asl; 42°40′N, 0°02′E) and shows high inter-annual variation. Rainfall shows two peaks

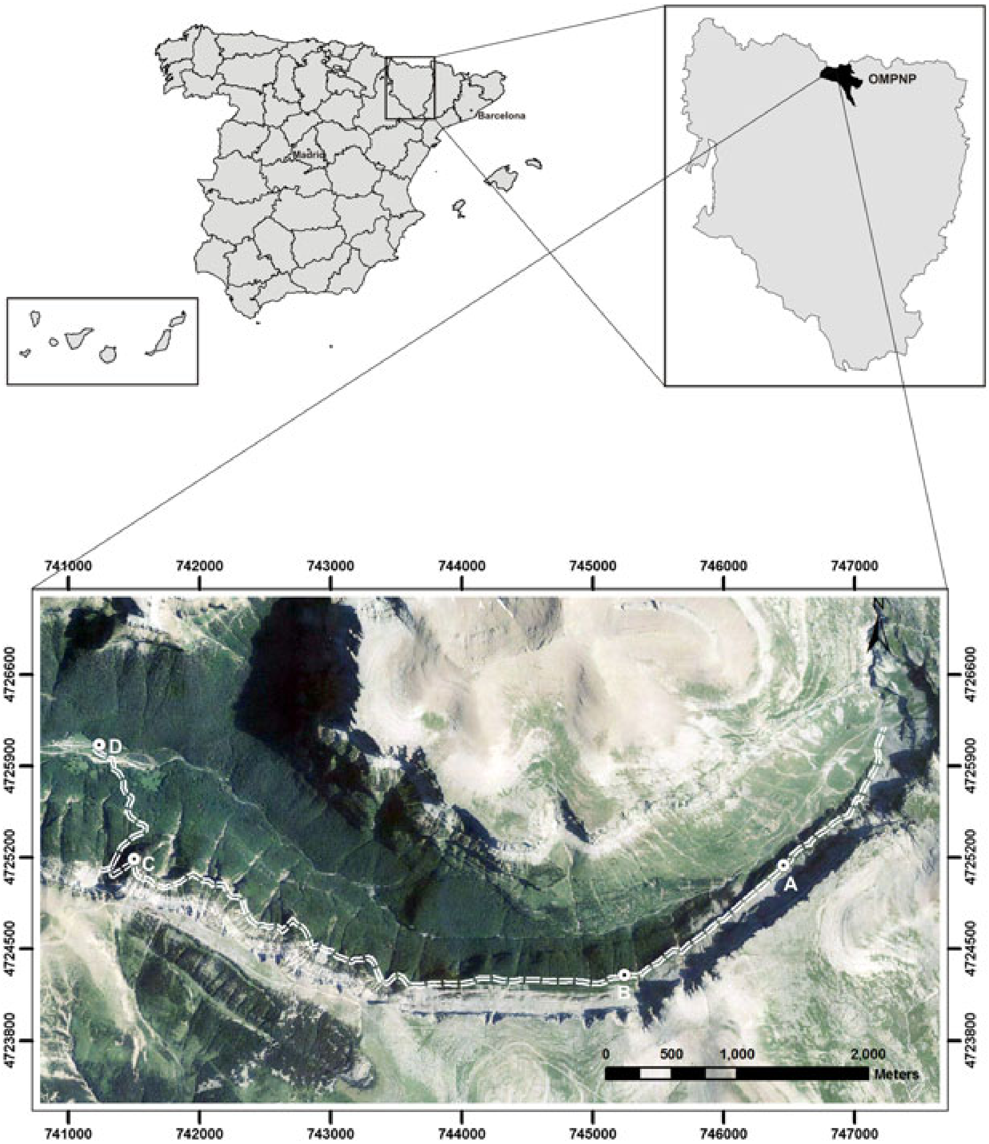

Figure 1. Location of the study area within the Ordesa and Monte Perdido National Park. The orthophoto shows the trail in which exposed roots were sampled and denotes the different study sites indicated as zones A (1,760–1,830 m asl), B (1,830–1,940 m asl), C (1,940–1,980 m asl) and D (1,980–1,330 m asl). Sites were selected based on their edaphic characteristics and level of stoniness. Coordinate system used is ETRS89, UTM zone 30N. [Colour figure can be viewed at wileyonlinelibrary.com]

in autumn and spring (32% and 30% of the annual sum, respectively), and snow precipitation is higher in spring than in winter. Mean annual temperature is about 5°C; the lowest monthly temperature is −2°C recorded in February, and the highest is 13°C recorded in July (Balcells & Gil-Pelegrín, 1992).

The distribution of local vegetation is determined by topography and aspect. On northern slopes comprised between 1,500 and 1,700 m asl, woodland formations are dominated by *F. sylvatica* L. and *Abies alba* Mill. and thus poor in herbaceous plants. By contrast, the *Fagus–Abies* community contains a shrub layer dominated by *Buxus sempervirens* L. At higher elevations, up to 2,000 m asl, *P. uncinata* Ramond ex DC dominates and eventually even colonizes cliffs. *P. uncinata* Ramond ex DC represents the only tree species adapted to the low winter temperatures and significant snow cover in this area and has an undergrowth of *Rhododendron ferrugineum* L. and *Vaccinium myrtillus* L. (Camarero & Gutierrez, 1999).

The number of visitors to the OMPNP exceeds 600,000 per year on average according to the Spanish Ministry of Agriculture and Fisheries, Food and Environment, making OMPNP the sixth most visited national park in Spain. These numbers are for the entire national park; disaggregated statistics reporting on the number of hikers, which in fact use each of the available trails, does not exist.

Sampling of Exposed Roots and Characterization of Ground Microtopography

The field sampling for the study described in this paper was conducted at the Faja Pelay trail. The investigated trail was divided into five zones, which are hereafter referred to as A-stony part, A-without stoniness, B, C and D (see Figure 1 for details). Characterization of ground microtopography can be a critical factor to be considered, as it allows obtaining accurate erosion rates using dendrogeomorphic techniques (Stoffel *et al*., 2013; Ballesteros-Cánovas *et al*., 2015; Bodoque *et al*., 2015). In that sense, and given the difficulties of TLS portability in mountainous areas, we propose an alternative method based on the use of microtopographic profile gauges (Benito *et al*., 1992; Desir & Marin, 2007; Figure 2B and C). The gauges were in fact used to obtain ground surface profiles, from which E_x was estimated once the threshold distance (*TD*) was determined. *TD* is here defined as the distance between the root and the sediment knickpoint, from which the profile defines the lowered of ground surface because of sheet erosion (Bodoque *et al*., 2015). For this purpose, a microtopographic profile gauge was placed perpendicularly to the exposed root, and levelled horizontally for all measurements in such a way that different datasets could be compared. The profile obtained was then drawn on a graph paper to allow inference of the amount of eroded soil along the profile and with sub-millimetre precision.

Where terrain allowed access with the TLS (this was only possible at zone D; Figure 1), microtopographic profiles were obtained with a microtopographic profile gauge, and results were subsequently compared with those gathered with the TLS, so as to check reliability of the new method. The TLS used in this study was a Leica Scan Station 2, as it can measure up to 50,000 pts per second with a 1-mm precision (Figure 2D). To cover the entire surface of interest, we used at least two different TLS positions to avoid shadow zones. Different positions were merged by using a minimum of four high-definition surveying targets, which were positioned to cover the area and height range. The selected locations were identified and scanned with a spatial resolution of 1 mm. Survey control was facilitated by the CYCLONE software, allowing for a visualization of point cloud data in the field.

Text files obtained from the TLS were then transferred to ARCGIS 10.1, and a digital elevation model (DEM) was derived with a cell size precision of 3 mm, using the Spatial Analysis Toolbox and the inverse distance weighting as interpolation methods. We then use the Create Profile tool offered by 3D Analysis of ARCGIS to extract perpendicular cross sections from the DEM with an approximate length of 150 cm. The resulting microtopographic information was thereafter used to determine the sedimentation and/or scour erosion knickpoint in the profile, and to consequently perform measurement of eroded soil at specific distances so as to consider exclusively sheet erosion. This distance needs to be taken into account as ground surface is lowered irregularly as a result of erosion and consequently may result either in an overestimation or underestimation of real

Figure 2. Sampling stages: (A) illustration of exposed roots as observed along the trail; (B) measurements of soil microtopography using a microtopographic profile gauge; (C) acquisition of microtopographic profiles to estimate E_x; (D) characterization of soil microtopography using a terrestrial laser scanning; (E) sampling of an exposed root with a handsaw; (F) cross-sectional view of one of the exposed roots sampled. For details, see text. [Colour figure can be viewed at wileyonlinelibrary.com]

erosion rates (Ballesteros-Cánovas *et al*., 2015; Bodoque *et al*., 2015). Subsequently, the perpendicular cross sections were exported to a spreadsheet file format, in order to statistically compare the TLS profiles with those obtained from microprofiling.

Following the procedure described in Bodoque *et al*. (2005), we sampled 39 sections of exposed *P. uncinata* Ramond ex DC and *F. sylvatica* L. roots. In addition, we also sampled a small subset of buried roots at different soil depths (max. 10-cm depth) so as to check for the observed bias related to root response under thin soil layer (Corona *et al*., 2011). Finally, we sampled soil in the vicinity of each sampled root to characterize edaphic properties.

Determination of the Timing of Root Exposure

Sections of the sampled roots were air dried for 2 months. Thereafter, two slices with an approximate thickness of 1·5 cm each were obtained from the initial section. The slices were sanded and polished with sandpaper (up to 400 grit) to facilitate recognition of growth rings. Determination of the first year of exposure was performed with both macroscopic and microscopic analyses. With regard to the first approach, we used the increase in latewood percentage and larger growth-ring widths as erosion indicators, as these parameters have been described to occur in response to stress induced by exposure (i.e. abrasion, variations in edaphic temperature and humidity, and reduction in soil cover pressure, among other factors). This change in growth behaviour has already been contrasted statistically in previous work and was demonstrated to represent first footprints of exposure in tree-ring records of *Pinus sylvestris* L. and *Pinus pinaster* Ait. (Bodoque *et al*., 2005; Rubiales *et al*., 2008; Bodoque *et al*., 2011; Bodoque *et al*., 2015).

After polishing, all cross sections were scanned with a minimum resolution of 2,800 dpi using an Epson-Perfection V700 Photo, which allowed accurate visualization of the cores containing sections with particularly thin rings. Measurements were then performed with WinDENDRO. On each cross section, different radii were marked along the directions that showed the highest variability in growth-ring widths. In a next analytical step, visual cross-dating procedures were applied; these were intended to improve dating precision for the first year of response to soil erosion and to correctly date subsequent rings; this step also included denoting characteristic features related to exposure (Stoffel *et al*., 2012). This step also made it possible to identify the existence of discontinuous or multiple rings, which further helped to increase dating reliability. However, and as usual with roots, it was not possible to apply statistical cross-dating techniques because of the limited number of growth-ring series available and the limited agreement between roots (Fritts, 1976; Bodoque *et al*., 2005; Corona *et al*., 2011; Lopez Saez *et al*., 2011).

As the species from which the roots were sampled have not been analysed before, we performed an anatomical characterization of the exposed roots sampled. Samples of exposed roots were also compared with cross sections of deeply buried roots lacking the impact and thus evidence of exposure. This analytical step intended to demonstrate that the macroscopic patterns of exposure described in previous work (and for other species) are also applicable to *F. sylvatica* L. and *P. uncinata* Ramond ex DC. A subset of cross sections was then selected for the preparation of microsections and thus for wood anatomical analysis. Cross sections were cut with a depth of ~25 μm, stained with safranine and fixed with Eukitt. Microscopic measurements were realized using a Leica Application Suite v3 2.0 image analyser coupled to a Leica DFC420 camera on live images of the microsections. Slides were observed under ×125 and ×250 magnification.

Estimation of Erosion Rates

Quantification of sheet erosion rates was based on (i) the number of years since exposure (NR_{ex}) and (ii) the thickness of the soil layer eroded since initial exposure (E_x). With regard to the second parameter, the possible overestimation of E_x, as reported by Corona *et al*. (2011), was corrected, and we thus consider that secondary root growth after exposure can occur in both the upper and lower parts of the root. Moreover, some anatomical parameters have been described to undergo changes before the root is exposed (e.g. tracheid lumen starts to drop as soon as the soil covering is less than a few centimetres thick; Corona *et al*., 2011). Therefore, the evaluation of mean annual erosion rates will be underestimated if this bias (ε) is not taken into account (Corona *et al*., 2011). Based on the premises stated earlier, the annual erosion rate (E_{ra}) was reconstructed as follows (Corona *et al*., 2011):

$$E_{ra} = \frac{E_x - (G_{r1} - G_{r2}) + \left(\frac{B_1 + B_2}{2}\right) + \mathcal{E}}{NR_{ex}}$$

Where: E_{ra} is the annual erosion rate (mm y^{-1}); E_x (mm) is the average thickness of the eroded soil layer extracted from ground microtopography profiles; G_{r1} and G_{r2} (mm) represent secondary (subsequent) growth on the upper/lower side of the root after exposure; B_1 and B_2 (mm) represent bark thickness on the upper/lower side of the root; $\mathcal{E}$ is the bias defined as the minimum thickness of soil below which roots start to modify their cell anatomy; and NR_{ex} is the number of rings formed since the time of exposure.

The transformation of dendrogeomorphic erosion rates to t ha^{-1} y^{-1} units was made by estimating bulk density from pedo-transfer functions defined by Rawls *et al*. (1982), which in turn depend on soil texture. The resulting value was then revised owing to the fact that soil compaction occurs along the hiking trails. To this end, we used values obtained from the literature for soils with textures similar to the soils existing at the study sites (Bodoque *et al*., 2005).

Statistical Analysis

Reliability of the perpendicular microtopographic profiles was then checked by comparing results with those of the

DEM derived from TLS data. To this end, linear correlation existing between the two datasets was estimated by applying the Pearson product–moment correlation coefficient. Statistical significance of the correlations was determined at the 95% confidence level. With respect to *TD* and factors involved in soil erosion, we looked at whether statistically significant differences exist between the various sampling zones considered. For this purpose, the Kruskal–Wallis test (i.e. a non-parametric statistical test adopted to compare more than two groups) was used at the 95% confidence level (p-value $< 0{\cdot}05$). If the p-value obtained was such that the H0 hypothesis (i.e. the mean ranks of the groups are the same) had to be rejected, we concluded that at least one group (i.e. sampling zones A, B, C and/or D) was different from the others. To identify which samples were responsible for the rejection of H0, we applied Dunn's multiple comparison procedure.

Regarding the null hypothesis (H0), we analysed effect sizes to assess strength of relationship between the investigated variables. To this end, we calculated the epsilon-squared (E_R^2) estimate of effect size, which depends on the value H obtained in the Kruskal–Wallis test and the total number (n) of observations (Grissom & Kim, 2012). Additionally, a *post-hoc* test using the Mann–Whitney U-test (i.e. a non-parametric statistical test used to compare two groups) with continuity correction was performed in case that a given variable showed a significant effect (i.e. at the 95% confidence level) of a site on the values after application of the Kruskal–Wallis test. In addition, Z-scores of the Mann–Whitney U-test were used together with the total number of observations to estimate effect size (Grissom & Kim, 2012).

RESULTS

Analysis of Ground Microtopography

All profiles analysed showed concave shapes on either side of the exposed root. Concavity ends at the point where morphology is determined by the receding ground surface caused by sheet erosion. This fact enabled definition of the *TD* factor, which indicates in fact the position at which E_x should be measured (Figure 3).

The *TD* values are characterized by differing values for each of the sampled zones and exhibit high dispersion

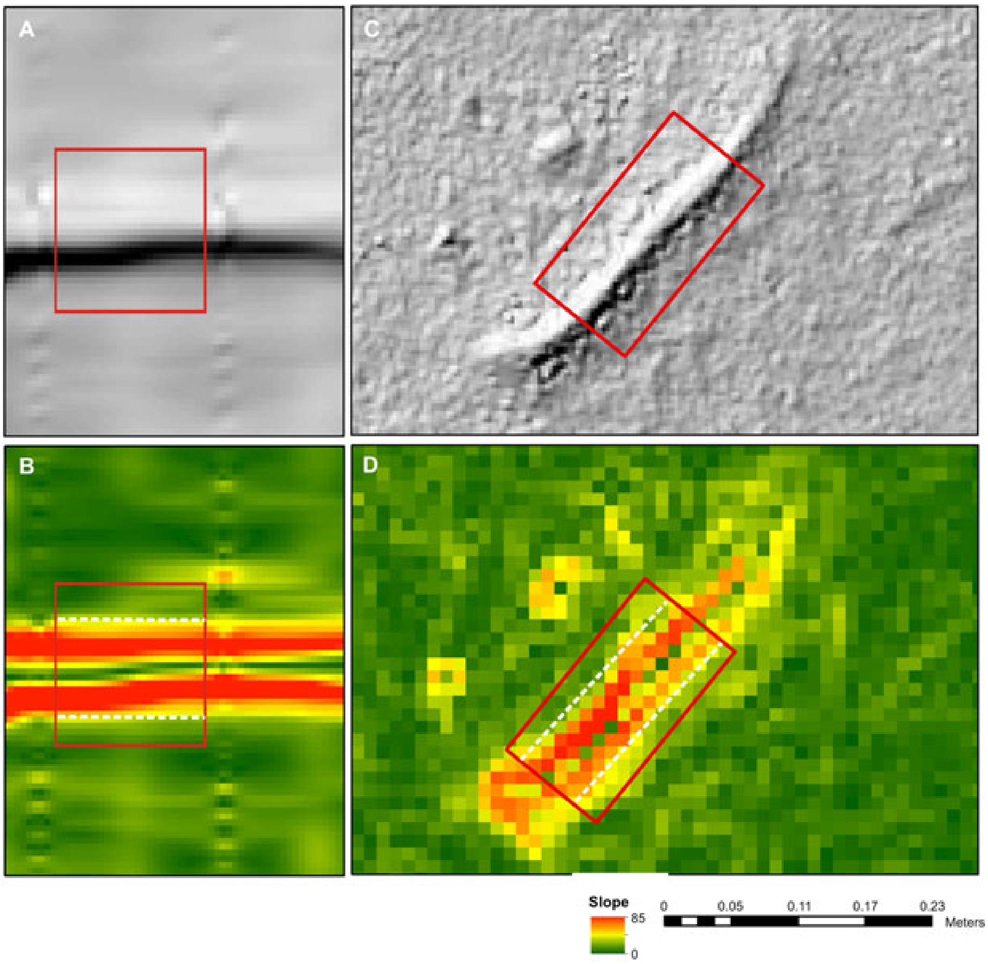

Figure 3. (A) Hillshade model obtained by means of microtopographic profiles at zone B and (B) raster of slopes derived from the hillshade model (Figure 1); (C) hillshade model obtained from terrestrial laser scanning at zone D and (D) resulting raster of slopes. Slopes are expressed in sexagesimal degrees. In plots B and D, dashed lines indicate the *TD* at which E_x has to be measured. [Colour figure can be viewed at wileyonlinelibrary.com]

(Table I). Interestingly, average *TD* values estimated at zone C of the trail were statistically different from the other sampling zones (*p*-value = 0·029, E_R^2=0.26, Kruskal–Wallis test). Average *TD* values at zone A were 4·1 ± 3·5 mm, and the surfaces of the same zone of the trail, but with increased stoniness, showed similar average values (4·2 ± 3·0 mm). At zone B, average *TD* values were 6·8 ± 4·2 mm. Zone C is characterized by the highest *TD* values reaching 40·0 ± 15·8 mm on average. Finally, at zone D, estimated average TD values were 8·6 ± 5·8 mm.

Concerning the degree of similarity of soil microtopography obtained with a microtopographic profile gauge and TLS, Pearson's correlation coefficients ranged between 0·51 and 0·71, meaning that similarity between the approaches indeed is statistically significant at the 95% confidence level (*p*-value <0·0001).

Timing of Root Exposure

Among the five zones studied, zone A presented the most recently exposed roots. In the segments of the trail lacking stoniness, the first year of exposure was dated to between 1996 and 2008. Root exposure in the same zone of the trail, but with soil stoniness [i.e. soils in which the coarsest soil fraction (rock fragments) is predominant], was dated to between 1995 and 2006. By contrast, the oldest signs of root exposure were found in zone C where dendrogeomorphic reconstructions yielded dates between 1967 and 2007. In zones B and D, the first year of exposure occurred between 1980 and 2002 and 1988 and 2012, respectively (Table II).

With regard to anatomical analysis, the first time of exposure can be seen in the form of characteristic anatomical changes. In *P. uncinata* Ramond ex DC, a gradual reduction of cell lumen occurs in earlywood tracheids after exposure, reaching a magnitude of reduction of about 40%. Root rings experience an abrupt increase in ring width, which is the result of an increase in both tracheid number and size. Furthermore, a gradual increase in cell wall thickness is discernible, more noticeable in latewood tracheids; at the same time, we observe a gradual decrease in the lumina of latewood cells.

Table I. Morphometric data of the profiles used for the sampling of exposed roots

	Sample code	Root diameter (mm)	Profile aspect	Threshold distance, *TD* (mm)	Profile aspect	Threshold distance, *TD* (mm)
Zone A	MA-01	28	E	4·0	W	1·1
	MA-02	28	E	4·7	W	4·4
	MA-03	17	E	1·3	W	0·2
	MA-04	27	E	0·4	W	nd
	MA-05	37	E	7·7	W	nd
	MA-06	18	E	0·3	W	0·2
	MA-07	18	E	4·2	W	4·3
	MA-08	17	E	9·0	W	1·2
	MA-09	26	S	3·4	N	nd
Zone A (stony part)	MA-10	18	nd	0·9	W	0·7
	MA-11	15	E	3·0	W	nd
	MA-12	16	E	nd	W	1·6
	MA-13	25	E	1·5	nd	nd
	MA-14	30	S	2·0	N	2·0
	MA-15	28	S	nd	N	0·8
	MA-16	26	nd	nd	W	3·5
	MA-17	27	E	nd	W	0·6
	MA-18	24	E	0·81	nd	nd
Zone B	MB-01	26	E	2·1	nd	nd
	MB-02	30	E	2·4	W	2·2
	MB-03	20	E	1·2	W	1·8
	MB-04	32	E	5·1	nd	nd
	MB-05	30	E	2·5	nd	nd
	MB-06	45	E	2·1	nd	nd
Zone C	MC-01	20	E	0·1	nd	nd
	MC-02	30	E	0·1	W	0·3
	MC-03	20	E	0·2	W	0·3
Zone D	MD-01	32	E	1·1	W	0·5
	MD-02	32	E	1·9	W	4·9
	MD-03	40	E	2·3	W	2·8
	MD-04	55	E	4·5	nd	nd
	MD-05	43	E	4·0	W	1·0
	MD-06	45	E	3·9	W	2·8
	MD-07	50	E	0·5	W	0·6
	MD-08	25	E	1·7	W	1·3
	MD-09	30	E	3·7	nd	nd

Aspect of profiles corresponds to the perpendicular direction with respect to the north direction of roots.

Table II. Sheet erosion rates considering secondary growth and ground microtopography

	Sample code	Year of exposure	G_{r1} (mm)	G_{r2} (mm)	Profile aspects	E_x (mm)	Erosion rate (mm y^{-1})	Profile aspects	E_x (mm)	Erosion rate (mm y^{-1})
Zone A	MA-01	2005	8	15	E	5·9	0·8	W	1·4	5·0
	MA-02	2006	5	17	E	8·5	9·1	W	8·0	8·9
	MA-03	2005	6	8	E	2·4	9·3	W	2·5	7·3
	MA-04	1996	5	15	E	5·1	3·1	W	nd	nd
	MA-05	2004	11	19	E	17·7	5·6	W	nd	nd
	MA-06	2008	3	9	E	0·2	16·2	W	2·6	19·5
	MA-07	2007	3	8	E	10·9	10·5	W	10·6	10·3
	MA-08	2005	5	3	E	18·2	7·2	W	10·3	10·3
	MA-09	2002	5	18	S	2·5	5·2	N	nd	5·7
Zone A (stoniness)	MA-10	2000	nd	8	nd	0·3	5·3	W	2·7	nd
	MA-11	2003	nd	8	E	3·9	6·9	W	nd	5·7
	MA-12	2006	nd	10	E	nd	11·0	W	18·0	7·3
	MA-13	1995	nd	20	E	10·5	3·2	nd	nd	9·1
	MA-14	2002	4	15	S	5·8	5·9	N	3·8	nd
	MA-15	2001	3	3	S	nd	nd	N	2·0	5·8
	MA-16	2002	3	10	nd	nd	nd	W	8·4	4·9
	MA-17	2002	4	10	E	nd	7·6	W	4·8	6·0
	MA-18	2003	nd	12	E	2·6	7·2	nd	nd	5·2
Zone B	MB-01	1996	2	12	E	5·5	4·0	nd	nd	nd
	MB-02	1998	nd	15	E	5·4	4·6	W	9·3	5·6
	MB-03	1994	3	10	E	6·4	1·4	W	2·6	1·5
	MB-04	1993	5	10	E	13·7	3·3	nd	nd	nd
	MB-05	1980	nd	22	E	11·4	1·9	nd	nd	nd
	MB-06	1994	15	15	E	3·2	2·5	nd	nd	nd
Zone C	MC-01	1996	20	10	E	23·3	7·7	nd	nd	nd
	MC-02	1998	30	18	E	42·3	3·2	W	38·4	2·8
	MC-03	2007	20	7	E	54·6	14·0	W	22·6	13·7
Zone D	MD-01	1991	3	20	E	5·9	2·5	W	2·6	2·8
	MD-02	1991	3	20	E	5·6	2·9	W	6·6	2·6
	MD-03	1988	nd	35	E	7·6	2·3	W	7·4	2·4
	MD-04	2004	nd	25	E	11·3	7·1	nd	nd	nd
	MD-05	2012	3	nd	E	8·0	nd	W	3·3	nd
	MD-06	1997	nd	15	E	20·0	3·76	W	7·1	3·7
	MD-07	1998	3	3	E	1·8	4·28	W	3·8	3·9
	MD-08	2002	5	5	E	4·6	4·89	W	5·9	5·3
	MD-09	2003	nd	15	E	7·6	2·54	nd	nd	nd

In the case of *F. sylvatica* L., an abrupt increase in ring width can be found and is related to an increase in both the number of vessels and tracheids. It is worth noting that exposure also induces the formation of much clearer ring boundaries, and a shift from semi-ring porous to semi-diffuse porous growth-ring structures. The related decrease in vessel size is in the order of about 30%. In addition, we note an increase in fibres in latewood tissues and an increase of fibre wall thickness (Figure 4).

Estimation of Erosion Rates

Table II shows the results of the dendrogeomorphic erosion rate analysis. The five zones selected for analyses were very similar with respect to E_x, at a confidence level of 95%, with the exception of zone C (E_x = 36·2 ± 13·5 mm) for which E_x showed statistically significant differences as compared with that of the other sampling areas (p-value = 0·007, E_R^2=0.27, Kruskal–Wallis test). Much smaller E_x values are found in the most stony portions of zones A and D, where average E_x values are 6·2 ± 4·9 and 6·8 ± 4·2 mm, respectively. In that portion of zone A lacking stoniness, E_x shows average values of 7·6 ± 5·5 mm, whereas average E_x values in zone B are 7·2 ± 3·9 mm.

Erosion rates were then corrected for ongoing secondary growth on either side of the root after exposure. With respect to the upper side of the root, estimated erosion values exhibited significant divergences between zone C and the other sampling areas (p-value = 0·012, E_R^2=0.49, Kruskal–Wallis test) and again showed the highest values with 23·3 ± 5·8 mm. By contrast, the lowest values, in the order of 3·4 ± 0·9 and 3·5 ± 0·6 mm, respectively, were observed in zone D and the stony segment of zone A. In zone B, the average was estimated to 6·2 ± 5·2 mm. At the lower side of the root, we could not find significant differences of values between the zones (p-value = 0·347, E_R^2=0.12, Kruskal–Wallis test). Here, the smallest values were found in the stony segment of zone A (i.e. 10·7 ± 4·8 mm). In all other areas, values showed high similarity and defined a value range comprised between 11·7 and 17·3 mm.

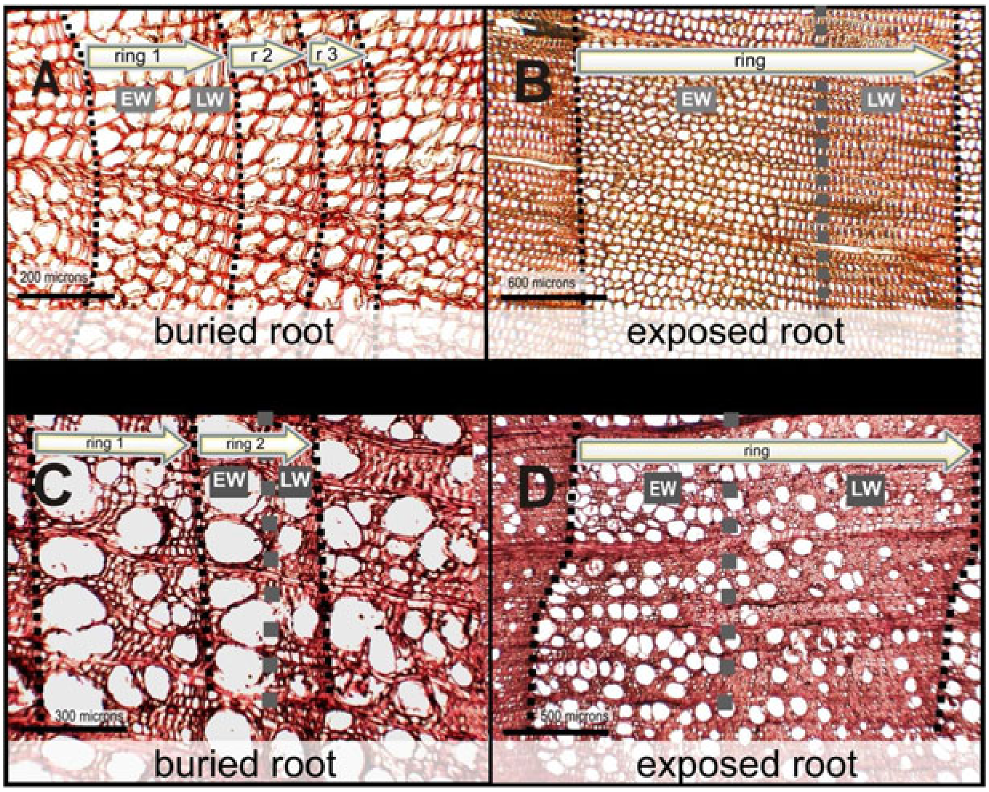

Figure 4. Wood anatomy of *Pinus uncinata* Ramond ex DC roots: (A) anatomy of buried roots (200 μm); (B) anatomy of an exposed wood (500 μm). Wood anatomy from roots of *Fagus sylvatica* L.: (C) anatomy of a buried root (500 μm); (D) anatomy of exposed wood (500 μm). [Colour figure can be viewed at wileyonlinelibrary.com]

The resulting average erosion rates showed a statistically significant site effect on erosion rates (at p-value $< 0{\cdot}0001$, $E_R^2{=}0.51,$ Kruskal–Wallis test). In zone A (stony part), reconstructed erosion rates were significantly higher ($6{\cdot}5 \pm 1{\cdot}9$ mm y^{-1}) than in zones B and D [i.e. $3{\cdot}1 \pm 1{\cdot}5$ and $3{\cdot}6 \pm 1{\cdot}4$ mm y^{-1}, respectively; p-value $< 0{\cdot}002$, $r^2(\eta^2) = 0{\cdot}50$, Mann–Whitney U-test and p-value $< 0{\cdot}0001$, $r^2(\eta^2) = 0{\cdot}49$, Mann–Whitney U-test, respectively]. The same conclusion can be drawn between zone A (without stoniness; i.e. $8{\cdot}9 \pm 5{\cdot}4$ mm y^{-1}) and zones B and D [p-value $< 0{\cdot}0001$, $r^2(\eta^2) = 0{\cdot}52$, Mann–Whitney U-test and p-value $< 0{\cdot}0001$, $r^2(\eta^2) = 0{\cdot}56$, Mann–Whitney U-test, respectively]. However, we could not find any statistically significant differences between zone A (stony part) and zone C [i.e. $8{\cdot}3 \pm 5{\cdot}3$ mm y$^{-1;}$ p-value $= 0{\cdot}677$, $r^2(\eta^2) = 0{\cdot}009$, Mann–Whitney U-test] nor between zone A (without stoniness) and zone C [p-value $= 0{\cdot}793$, $r^2(\eta^2) = 0{\cdot}003$, Mann–Whitney U-test]. In addition, we did not observe any significant changes between sites B and C [p-value $= 0{\cdot}092$, $r^2(\eta^2) = 0{\cdot}22$, Mann–Whitney U-test], sites B and D [p-value $= 0{\cdot}393$, $r^2(\eta^2) = 0{\cdot}03$, Mann–Whitney U-test] or sites C and D [p-value $= 0{\cdot}087$, $r^2(\eta^2) = 0{\cdot}15$, Mann–Whitney U-test].

Assuming an average bulk density of $1{\cdot}7$ g cm^{-3} for the loamy-sand and loam soils present at the study site, eroded volumes are $151{\cdot}3 \pm 73{\cdot}1$ t ha^{-1} y^{-1} (zone A lacking stoniness), $110{\cdot}5 \pm 32{\cdot}3$ t ha^{-1} y^{-1} (zone A, with marked stoniness), $52{\cdot}7 \pm 25{\cdot}5$ t ha^{-1} y^{-1} (zone B), $141{\cdot}1 \pm 91{\cdot}8$ t ha^{-1} y^{-1} (zone C) and $61{\cdot}2 \pm 23{\cdot}8$ t ha^{-1} y^{-1} (zone D).

DISCUSSION

In this study, we quantified soil loss from recreational trail in natural protected areas in mountain regions. We did not apply the approaches that are more commonly used to study soil erosion in recreational trails, such as CSA, variable CSA, maximum incision to the trail or topographic surveys, but focused on alternative, innovative techniques instead. This choice was motivated by the fact that conventional approaches are difficult to apply in mountainous areas owing to heavy equipment, difficult to be transported in such environments, which would limit the number of transects that can be realized and, therefore, also the spatiotemporal representativeness of soil erosion rates (Jewel & Hammitt, 2000). In addition, it seems rather uncertain to be in a position to fulfil all of the assumptions of approaches based on CSA in these mountainous areas; by way of example, one first issue is the analysis itself, which needs to be conducted cyclically. In addition, it also seems quite challenging to be certain of the horizontal position and that the same height above the fixed points can be guaranteed, as soil creep tends to play a role in such environments (Tomczyk & Ewertowski, 2013).

Other direct approaches aimed at the documentation of soil loss are also hampered by some limitations and cannot be applied easily in natural mountainous environments with high conservational values. In that sense, the use of gerlach troughs (Novara *et al*., 2011), water collectors (Desir & Marin, 2007) or gauging stations (Zheng & Chen, 2015) may not be suitable as they can further increase visual vulnerability of the landscape. A similar reasoning can also be applied to models aiming at estimating soil erosion (Morgan *et al*., 1999), inasmuch as they need gauges located in the field to enable their calibration and validation (Ciampalini *et al*., 2012).

The study deployed here was based on a dendrogeomorphic reconstruction of erosion rates in the OMPNP, Central Spanish Pyrenees, and demonstrated the importance of a proper and detailed characterization of ground microtopography, as this will allow reliable reconstruction and estimation of erosion rates with annual resolution. In addition, this study also was the first to use exposed roots of *F. sylvatica* L. and *P. uncinata* Ramond ex DC as bioindicators of soil erosion. Owing to the successful use of these species in the current study, these widespread species can be used in future work aiming at the documentation of soil erosion rates.

Our findings are in line with recent studies by Stoffel *et al*. (2013), Bodoque *et al*. (2015) or Ballesteros-Cánovas *et al*. (2015) and underline the importance of proper ground microtopography. At the same time, they also demonstrate the potential and applicability of tree roots for a successful acquisition of reliable erosion rates in the field. Although we identify certain differences between the DEM derived from TLS and microtopographic profiles, sometimes even in the order of up to 50% of the variance of the measurements, we would like to stress that the accuracy of the approach deployed here is still similar overall than that obtained with TLS alone (~mm). Consequently, we concluded that the accuracy of the DEM could be improved further by using more microtopographic profiles for each root. By proofing, the adequacy of results and the potential of microtopographic profiles, this study also opens doors to follow-up research, in particular in high mountain areas, where the use of TLS has so far been difficult. The use of *TD* values as an indicator of the distance at which ground surface is no longer modifying as a consequence of radial and axial growth pressures exerted by the root (Misra *et al*., 1986; Clark *et al*., 1999) has been illustrated as well. We conclude that this distance value should be used in future work when it comes to the definition of the point at which E_x shall be measured.

The *TD* values obtained in this study ranged from 4·1 ± 2·5 to 40·1 ± 15·7 mm and were thus significantly lower than those reported by Bodoque *et al*. (2015) in a sandy gully in central Spain (6–190·7 mm). These differences are related to differences in soil mechanics properties of both study sites. In the gullies studied by Bodoque *et al*. (2015), soils around the root systems were very loose, whereas the soils at the level of the trail investigated here is very much compacted as a result of continuous trampling, such that soil shear stress is significantly higher in the latter case. Likewise, differences in *TD* values between the different sampling areas along the trail could be due to two factors: (i) the capacity of roots to modify ground surface partially depends on their diameter. Hence, the lower *TD* values in zone C occur at a site where root diameters were smallest (Table I); (ii) soil mechanic characteristics along the trail. By way of example, we observe the lowest *TD* values in zone A as higher internal friction (due to stoniness) implies a higher shear stress at this site and, therefore, a lower capacity to deform ground surface by root pressure.

In this study, the first year of exposure was estimated by analysing the macroscopic footprint observed in the tree-ring series after exposure. In *P. sylvestris* L. and *P. pinaster* Ait., roots have been demonstrated to exhibit a sharp increase in root-ring widths following exposure, as well as an increase in the percentage of latewood tracheids (Bodoque *et al*., 2005, 2011). The reaction in the conifer species used here was very similar to the changes observed in other *Pinus* species in the past. In the case of *F. sylvatica* L., we can confirm similarities in reactions and patterns between this species and other deciduous species described in the literature (Fayle, 1968; Hitz *et al*., 2008; Rubiales *et al*., 2008). The newly introduced species thus seems suitable for dendrogeomorphic reconstructions of erosion rates and can be used in future work.

Erosion rates in the Spanish Pyrenees ranged between 3·01 ± 1·54 and 8·9 ± 4·3 mm y^{-1} and are therefore similar to values reconstructed for a popular hiking trail in central Spain (0·70 to 9·75 mm y^{-1}; Bodoque *et al*., 2005) but larger than the rates estimated by Pelfini & Santilli (2006) for two trails in the Italian Alps (0·4 to 7·1 mm y^{-1}). At the same time, however, the results obtained here are significantly lower than those obtained in other mountain areas and by using CSA, variable CSA, maximum incision to the trail, or topographic surveys. For example, Yoda & Watanabe (2000) measured incision values of up to 110 mm y^{-1} in a national park in northern Japan and in the cross section where erosion was most active. Tomczyk & Ewertowski (2013) estimated mean values for the deepening of cross sections to between 16 and 25 mm y^{-1} in two protected natural areas of Poland. These differences are first explained by the fact that the site investigated here is much drier than the Japanese site, but also because the dendrogeomorphic approach conducted here focused on sheet erosion, whereas the other studies also characterized erosive processes such as gully erosion and side-wall collapse erosion.

In terms of edaphic properties, the soils examined in this study at different trail segments show similar characteristics, and a predominance of loamy and loamy-sand soils (Figure 5). Furthermore, we also observe close similarities in the percentage of organic matter. Therefore, the edaphic configuration of the soil should not be seen as a decisive element when it comes to explain variability in estimated

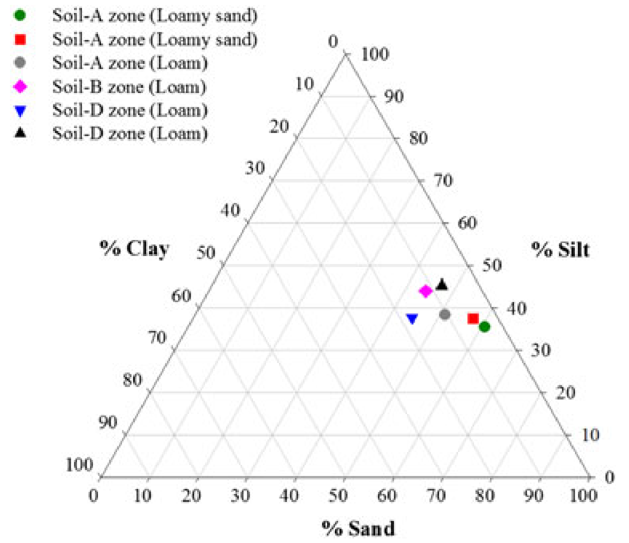

Figure 5. Textural classification of soil samples taken along the trail. [Colour figure can be viewed at wileyonlinelibrary.com]

erosion rates. By contrast, we realize that surface stone cover can be considered as a natural soil surface stabilizer (Poesen *et al*., 1999), thereby limiting soil losses. This assertion has been analysed in the stony segment of zone A of the trail. In fact, the segment of zone A lacking stoniness showed erosion rates that were 27% higher than those observed in the segments with stoniness. Likewise, we realize that erosion rates are not controlled by precipitation, as we do not find any trend in the available time series (Figure 6). We also do not observe any consistent relation between the number of visitors per year and their decreasing number with increasing distances from the starting point of the trail (although a majority of hikers only visit the first zones assessed in this study).

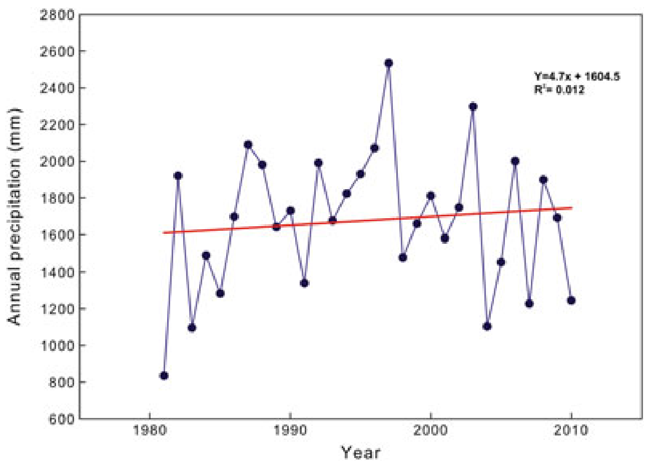

Figure 6. Representative precipitation time series corresponding to the study site. According to the Mann–Kendall trend test at a 95% significance level (p-value = 0·724), we cannot identify any significant trend between precipitation and erosion rates. Red line corresponds to the linear trend of precipitation data. [Colour figure can be viewed at wileyonlinelibrary.com]

Our study does not evaluate trail widening, which has important ecological and aesthetic implications (Wimpey & Marion, 2010). However, it demonstrates that the use of the trail by hikers has been intense over the last decades (and in particular in the part of zone A without stoniness). Results also provide prime information on soil degradation in areas that are highly transited and can thus be used when it comes to changes and/or the improvement of management of the recreational use of natural areas in highly vulnerable mountain regions. In that sense, dendrogeomorphology can indeed assist managers and planning in their evaluation of objectives and in the study of trail conditions, by providing spatially resolved data on the variability of erosion rates. Managers could thus take advantage of this source of data and include conclusions into the design of trail maintenance and the evaluation of visitor management or resource protection actions.

CONCLUSIONS

In this study, soil erosion has been assessed in space and time along a popular trail in the Central Spanish Pyrenees by using a combination of dendrogeomorphic analyses of exposed roots and via a detailed characterization of ground microtopography. A proper microtopographic characterization of roots and their immediate vicinity has been demonstrated to be a key factor to reliably estimate erosion rates, as it determinates where E_x has to be measured in the field. In this study, we have, for the first time, used a microtopographic profile gauge to determine erosion rates based on dendrogeomorphology. This methodological improvement is particularly useful in difficult and steep terrain, typical for mountain environments, where the use of conventional TLS is complicated owing to problems of portability. The methodological approach deployed here is also thought to enhance the characterization of locations and rates of erosion in natural protected areas in mountain environments, and to ultimately reduce the negative impact of erosion in these environments as a result of outdoor recreational activities. This information should be gathered at more sites and consequently used in the future to design the best management practices, which could ultimately prevent or, at least, reduce soil erosion, so that a more sustainable management of protected areas can be put into practice.

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