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Sheet erosion rates determined by using dendrogeomorphological analysis of exposed tree roots: Two examples from Central Spain

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Abstract

This paper describes the determination of sheet erosion rates by using dendrogeomorphological methods on exposed tree roots. Two sites on the northern slope of the Guadarrama Mountains, Central Spain, were studied: a popular trail in a Scots pine forest (Senda Schmidt, Valsaín) growing on granites and gneisses, and an open holm-oak forest on granitic slopes (Monterrubio). These sites were selected because they showed high denudation morphologies due to accelerated soil-erosion processes caused by human influence (trampling by continuous trekking and overgrazing), resulting in exposed roots. The method applied is based on the morphological pattern of roots, defined by the growth-ring series of the sampled roots. In order to confirm the validity of the criteria used and to make the estimations of erosion more accurate, several anatomical indicators of exposed and non-exposed *Pinus sylvestris* roots were characterized.

The study entailed a statistical analysis of exposure time and erosion depth. The influence of environmental factors affecting the variation in velocity of the erosion processes was also examined.

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With a significance level of 95%, the mean erosion rates were in the range of 1.7–2.6 mm/year (29–44 t/ha/year) on Senda Schmidt over the last 101 years, and 1.1–1.8 mm/year (19–31 t/ha/year) in Monterrubio over the last 42 years. Using a multifactor analysis of variance, we observed a change in the erosion rates as a function of position on the path along Senda Schmidt. In Monterrubio, however, we reached no significant conclusions, apart from an inverse relationship between erosion and slope gradient that was difficult to interpret.

Climate conditions in Senda Schmidt and the accuracy of dating Scots pine indicate that the evaluation on *P. sylvestris* roots is fairly reliable, which is not the case for oak roots. Although this paper is based on the application of an existing method, its novelty lies in being the first attempt in Spain to estimate 'accelerated' sheet erosion rates (due to recreational activities and overgrazing) using dendrogeomorphological techniques, supplemented by anatomical indicators for *P. sylvestris*.

Keywords: Tree ring; Tree root; Rill–interrill erosion; Dendrogeomorphology; Sierra de Guadarrama (Spain)

1. Introduction

At present, soil degradation is one of the most widespread environmental problems that occurs worldwide (Bridges et al., 2001). The combination of various factors (geomorphological, climatic and geographical, together with human activity), may favour erosive agents, which may considerably increase the risk of soil loss (Kirkby and Morgan, 1980). Bearing this in mind, there is a need to study techniques for evaluating both erosion and restoration processes of affected terrain (de Boodt and Gabriels, 1980; Schwertmann et al., 1989; Olson et al., 1994; Agassi, 1996; Morgan et al., 1998). This need arises from difficulties stemming from the complexity and multifactorial nature of hydric (sheet) erosion.

There are various methods of studying sheet erosion, ranging from prediction to direct measurements (Bryan, 1990; Toy et al., 2002). All methods involve certain characteristics and a series of biases. The advantage of dendrogeomorphological analysis of exposed roots over other erosion measurement techniques is that rates of erosion within the territory, as well as their variations, can be determined for both spatial and temporal points of view.

The study of a complete series of tree rings reveals information of both a chronological and environmental nature. Even though dendrochronology had already been used to characterize geomorphological processes in the 1960s, it was Alestalo who introduced the term 'dendrogeomorphology' in 1971. This is a subdiscipline of dendrochronology that uses different characteristic sequences of tree rings and other measures as indicators to characterize geomorphological processes from a spatial and temporal standpoint. The method is based on determining how active geomorphological processes affecting tree growth are reflected in the variation of width measurements of growth rings and in its morphology. Various dendrogeomorphological methods, their application areas and numerous bibliographical references can be consulted—for example, in LaMarche (1963, 1968), Carrara and Carroll (1979), Shroder (1980), Yamaguchi (1983), Shroder and Butler (1987), Butler (1987), Heikkinen (1994), Danzer (1996), Gärtner et al. (2001),

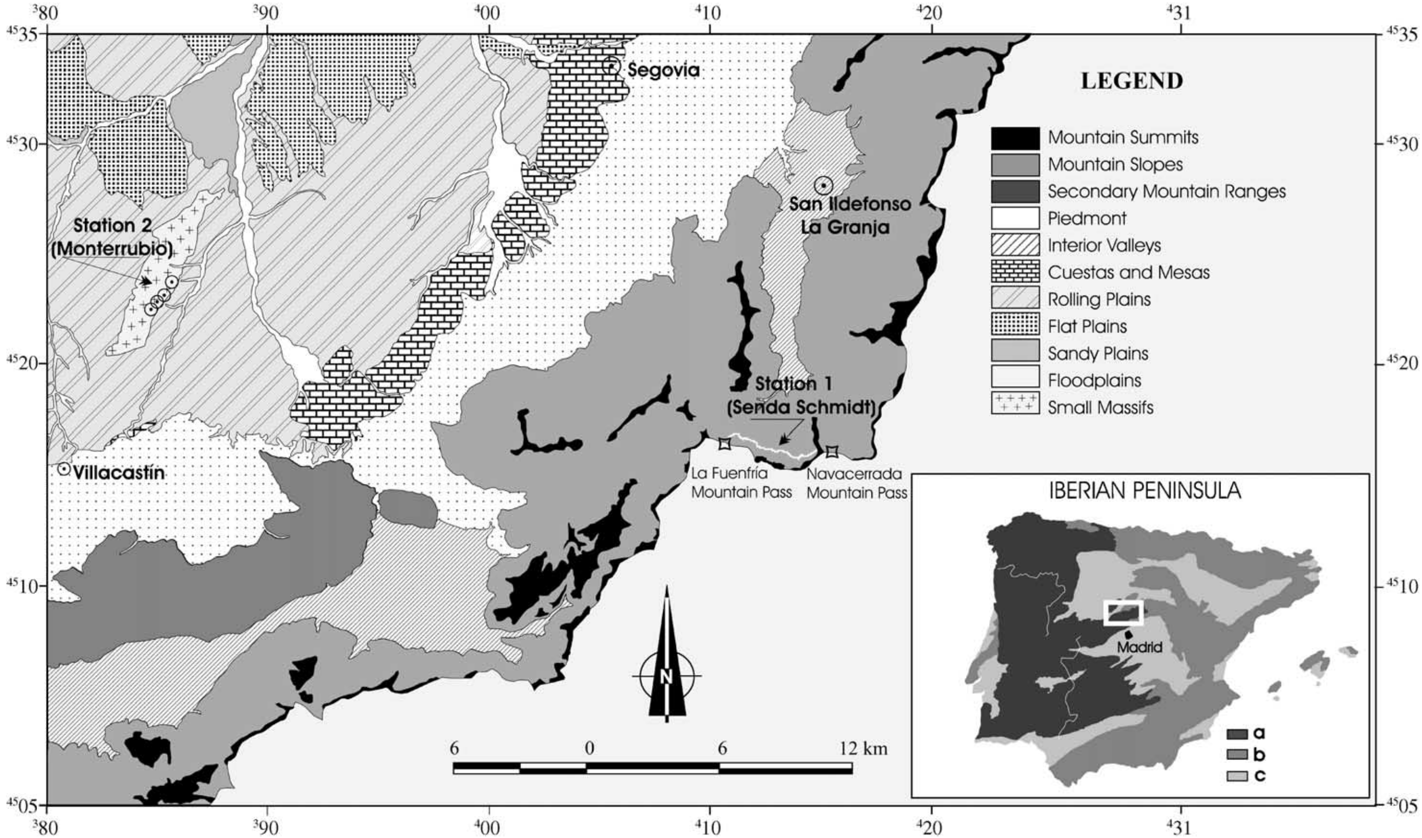

Fig. 1. Location of the two stations studied in the geomorphological context of the northern slope of the Sierra de Guadarrama, in the centre of the Iberian Peninsula: (a), Iberian Massif; (b) Alpine Belts; (c) Cenozoic Basins. The coordinates refer to zone 30T, Projection UTM, Hayford ellipsoid.

and Vanderkerckhove et al. (2001). The majority of dendrogeomorphological studies have focused on the characterization of the tree trunk. Only to a lesser extent have roots been used. In general, work on roots has been based on determining the age of adventitious roots in order to date the deposition events that are associated with processes such as flooding (Martens, 1993; Nakamura et al., 1995) and mass movements (Strunk, 1989, 1991, 1997).

The procedure used to determine rates of erosion from exposed roots is based on the change in the ring-growth pattern (from concentric to eccentric) when the root is exposed. The quotient defined by the vertical distance between the upper part of the root and the present ground surface, and the temporal interval during which the root has been exposed, offers an estimate of the erosion rate in mm/year (LaMarche, 1963, 1968; Eardley and Viavant, 1967; Carrara and Carroll, 1979; McCord, 1987; Danzer, 1996).

In addition to the change from a concentric pattern to an eccentric one, reaction wood develops, and there are also changes in the anatomical structure of the rings. As Gärtner et al. (2001) state, when a root loses its edaphic cover in a continuous and progressive manner, a series of anatomical changes occur due both to the effects of exposure (for example, variations in temperature, reduction in pressure of soil cover, light incidence, etc.) and to the mechanical stress that the root undergoes when it is exposed. In fact, it is the characterization of the changes that take place in the microscopic structure of the root (for example, width of the growth ring, number of cells per ring, percentage of latewood, diameter of cellular light in earlywood), which allows the first year of exposure to be precisely determined.

Fig. 2. Exposed *P. sylvestris* roots in the Senda Schmidt (Valsaín, Segovia).

This article describes the use of this technique at two locations on the northern slope of the Sierra de Guadarrama (Spanish Central System) (Fig. 1), in the province of Segovia: on a popular trail in a Scots pine forest (Senda Schmidt, Valsaín), and in an open holm-oak forest situated on hillsides, in the municipal area of Monterrubio. In both cases, accelerated soil erosion has occurred as a result of human activity. The 'accelerated' denudation of the two locations selected has exposed a large number of roots on the surface (Fig. 2), which has enabled experimentation with the technique described above.

Therefore, the objectives of this paper are: first, to validate dendrogeomorphological methods for exposed roots; second, to estimate the sheet erosion rates in two specific sites in Central Spain; and third, to determine the influence of environmental factors on the calculated rates. This work represents the first attempt in Spain to estimate 'accelerated' sheet erosion rates (due to recreational activities and overgrazing) using dendrogeomorphological techniques, supplemented by anatomical indicators. Previously, Vanderkerckhove et al. (2001) had developed, in south-eastern Spain, a dendrogeomorphological evaluation method for erosion rates in gullies.

2. Study areas

2.1. Senda Schmidt

The first sample area is a trail called 'Senda Schmidt', in the 'Montes de Valsaín' (Fig. 1). This is one of the most popular trails in the Sierra de Guadarrama. Although it has been used heavily since the 1970s (for trekking and mountain biking), recreational activities started here in the late nineteenth century. Geomorphologically, the Senda Schmidt is situated on mountain slopes (see Fig. 1) that developed mainly on substrata of coarse-grained monzogranite porphyry, with a small section, near the Fuenfría Mountain Pass, that developed on augen gneisses. In certain sectors of the trail, coverings of colluvium deposits are present. The trail rises from 1780 m to 1870 m above sea level. The general aspect of the hillside is north and its average slope is 23°.

The climate is mid-latitude, temperate, mesothermic (Csbk'3j according to Köppen), of a Mediterranean continental type (due to its distance from the coast), with mountain influence. The average annual temperature is 6 °C and the average rainfall is about 1400 mm/year, concentrated during the months of October to May, but with every month of the year recording precipitation.

The soil type is a mixture of lythic, umbric and dystric leptosols, of a sandy loam texture. The vegetation is dominated by *Pinus sylvestris*, with an accompanying undergrowth of creeping juniper (*Juniperus communis* ssp. *alpina*), black padded brushwood (*Cytisus oromediterraneus*) and Spanish bluebell (*Adenocarpus hispanicus*).

2.2. Monterrubio holm-oak forest

The second location (Fig. 1) is an open holm-oak forest on a hillside, which has traditionally suffered from intense overgrazing. This has resulted in the almost complete disappearance of herbaceous covering, so that erosion has been accelerated and the A soil horizon is missing.

The hillside generally has a linear profile and its altitude ranges from 970 to 1040 m above sea level. Its general aspect is towards the southeast and its average slope is 14°. This general configuration is modified only locally by the presence of deep gullies. The substratum of these hillsides is made up of biotite monzogranites. The soils, of a sandy–clay–loam texture, are thin (dystric cambisols) and are frequently inexistent or barely developed (lythic leptosols).

The climate of the holm-oak forest is also temperate, mid-latitude, mesothermic (Csbk'3j according to Köppen), of a Mediterranean continental type, with a large water deficit in the summer period and frequent frost cycles in the winter period (an average of 53 days of frost per year). Average rainfall is 450 mm a year and the average annual temperature is 11–12 °C.

The dominant vegetation is almost exclusively an open holm-oak forest (*Quercus ilex* ssp. *ballota*). This forest lacks practically any bushy or herbaceous strata (if we except the sporadic presence of *Juniperus oxycedrus*, *J. communis*, *Cistus laurifolius*, *Lavandula stoechas* ssp. *pedunculata* and *Thymus mastichina*). All of this is probably due to a combination of natural causes (high slope angles with gullies) and human activity (overgrazing and selective clearing fires).

3. Methodology

3.1. Field sampling

The sampling of exposed roots at both locations was carried out during August 2001. Before cutting each section, a detailed description was made of the spatial and morphological characteristics of the surroundings of the root and these details were kept on file. The following information was collected: geographical location (UTM coordinates); altitude; aspect in sexagesimal degrees, both for the hillside and for the specific root location ('local aspect'); texture of the soil in the sampling area; distance of the root section to the tree trunk; and hillside slope and slope of the specific root location (both expressed in degrees). Finally, the vertical distance between the upper part of the root and the present soil surface was measured, taking measurements on both ends of the root section in order to determine maximum, minimum and average amounts.

A total of 36 *P. sylvestris* specimens that were uniformly distributed along the trail were sampled, as well as 32 *Q. ilex* specimens. However, given the difficulty of recognizing the *Q. ilex* rings, samples valid for later statistical treatment were obtained from only 18 holm-oak trees. For each tree, the aim was to find an exposed root with a diameter of more than 5 cm. The roots were cut with a hand saw into sections of approximately 15 cm long. In all cases, samples were taken from roots that were orientated along the direction of the maximum slope of the hillside. This orientation provides the best denudation values, as in all other cases the root tends to act as a small 'dam', retaining sediments on one side and remaining bare on the other. Furthermore, sections were obtained only from exposed roots that were farther than 1.5 m from the trunk, as at lesser distances exposure could be related to tree growth (Carrara and Carroll, 1979).

Finally, samples were taken from the soils surrounding the cut roots, with the aim of determining their texture and bulk density, the latter being an essential piece of data to transform mm/year erosion rates to t/ha/year, and thereby to allow its comparison with other data obtained from the bibliography.

3.2. Preparation and dendrogeomorphological analysis of the samples

3.2.1. Dendrochronological analysis

Sections of the sampled roots were left to dry in open air over 2 months. Later, two slices were obtained from the initial section, each slice measuring approximately 1.5 cm thick. This process was used to improve the perpendicularity in the cut. They were later polished. In the samples of *P. sylvestris*, the yearly growth pattern of the rings, and their transformation from concentric to eccentric, could be seen clearly (Fig. 3a). This was not the case in the samples of *Q. ilex*, which had to be dyed with 10% methyl blue in order to improve their visibility (Fig. 3b).

Along with the change in the ring growth pattern, another indicator used to date the exposure time was the formation of reaction wood when the root is exposed. In *P. sylvestris* this is clearly evident, whereas in *Q. ilex* it was not observed. Thus, as a response to the stress mechanism to which *P. sylvestris* is subjected, reaction wood is formed. This mechanism, affecting conifers, is called 'compression'. In the zone in which it appears, the rings grow thicker and the roots show eccentric sections (Mattheck and Breloer, 1996) (Fig. 3a).

Next, one slice of each sample was scanned at a resolution of 1200 dpi in order to study the annual growth pattern of the rings. Then, the number of rings that showed eccentric growth was counted. This served as a bio-indicator to determine when the root had lost the upper part of its bark, and accurately estimated when erosion led to the soil surface being at the same level as the position of the root. As only living roots were sampled, it is probable that the last growth ring corresponds to the year in which sampling took place.

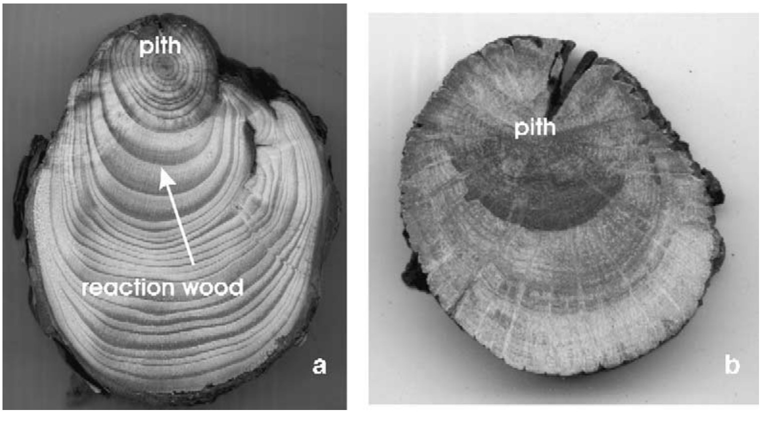

Fig. 3. Polished sections of the exposed roots of: (a) *P. sylvestris*, from Senda Schmidt. Note the eccentricity and presence of reaction wood after exposure. (b) *Q. ilex*, from the holm-oak forests in Monterrubio.

This way, each of the rings forming the annual growth series can be synchronized simply by counting. However, the dating of the ring series by visual examination alone can introduce a degree of uncertainty into the datings, as the series might show false rings, missing rings, etc. If the prerequisites that define the principle of cross-dating are observed (Stokes and Smiley, 1968), errors present in the series can be detected, as these will exhibit growth patterns—ring-width measurements—that can be correlated statistically. Using the CATRAS software (Computer Aided Tree Ring Analysis System; Aniol, 1983), the ring widths were measured to an accuracy of 0.01 mm. Because of the short length of the series available, only those with a size corresponding to 24 years or more were used for subsequent analysis. As a consequence, of the initial 34 annual growth series, a total of 7 were rejected. Next, the COFECHA program (Holmes, 1983; Holmes et al., 1986; Grissino-Mayer, 2001) was used to assess the quality of the measurements, and also to determine the degree of certainty in the synchronized series.

On the other hand, in the *Q. ilex* samples the previous analysis was not undertaken. We assume that the sheet erosion assessment shows a certain degree of uncertainty, given that in zones with semi-arid climates, which the Monterrubio location approximates, the holm-oak tends to form false rings when intense rainfall occur after a prolonged dry period. It also has irregular growth that is characterized by rings that are not very clear (Bichart, 1982; Ferrés, 1985). In the same way, false rings and multi-seried medullar circles make it difficult to interpret the growth pattern of this species and to determine age (Loissant and Rapp, 1971; Susmel et al., 1976; Ferrés, 1985).

3.2.2. Anatomical analysis

For the study of growth-pattern variations in the anatomical structure of roots submitted to mechanical erosion, seven samples were analysed from different *P. sylvestris* specimens (taken from trees representative of the entire trail). At the same time, they were compared with two sample cores of roots from trees situated on a slope that was not experiencing the impact of continuous trampling by hikers. This analysis was not carried out in the exposed root samples of the holm-oak (*Q. ilex*) because the characteristics of its wood make the interpretation of the annual growth pattern of this species very difficult (Gené et al., 1993).

The study of the samples' anatomical structure was first attempted by cutting a thin slice with a microtome. However, the abundance of resin in the samples, as well as the heterogeneity to resistance of the cut, made it impossible to obtain good sections. Consequently, the method that was finally used consisted of softening the samples, with a mixture of glycerine and alcohol following the protocol proposed by Barefoot and Hankins (1982). This treatment is effective when the woods are sufficiently permeable. The method consists of saturating the sample in water. Next, it is submerged in a solution of alcohol and glycerine in a ratio of 1 : 1. This solution sufficiently lubricates and softens most woods so later treatments are not needed. Later, cuts were made with a knife to obtain usable samples.

The analysis was carried out via observation by reflection in a binocular magnifying glass and in a microscope with the light reflected against a dark background. Measurements were made with the image analyser on digital photographs of the following parameters: width of the growth ring; number of cells per ring; percentage of latewood and diameter of cellular light in earlywood. The measurements taken were carried out perpendicular to the growth ring and always from the zone that gave more growth. For the

Table 1
Measurements of the parameters sampled and evaluated on Senda Schmidt (*P. sylvestris*)

Sample number	Situation (X-UTM)	Hillside aspect (degrees, clockwise from north)	Local (root) aspect (degrees, clockwise from north)	Height from ground—max / min (mm)	Hillside slope (°)	Local (root) slope (°)	Approximate age of exposure (years)*	Approximate age of root (years)*	Maximum erosion rate (mm/year)	Minimum erosion rate (mm/year)	Average erosion rate (mm/year)
1	412 233	260	260	42/29	13	18	12	25	3.5	2.4	3.0
3	412 169	222	212	94/77	24	12	42	64	2.2	1.8	2.0
4	412 042	205	331	62/51	24	5	55	80	1.1	0.9	1.0
5	411 929	222	231	84/39	28	22	10	63	8.4	3.9	6.1
6	411 528	208	172	58/31	24	10	20	65	2.9	1.5	2.2
7	411 428	222	175	48/40	24	10	7	65	6.9	5.7	6.3
8	411 410	241	248	56/56	18	10	33	60	1.7	1.7	1.7
9	411 354	185	168	76/44	17	5	50	116	1.5	0.9	1.2
10	411 332	154	154	181/105	18	4	101	134	1.8	1.6	1.7
11	414 680	318	318	94/46	18	26	24	42	3.9	1.9	2.9
13	414 350	327	327	92/54	27	6	30	43	3.0	1.8	2.4
14	414 341	341	22	73/67	26	7	26	80	2.8	0.9	2.7
15	414 240	1	1	144/71	23	8	24	95	6.0	3.9	4.5
16	414 161	19	340	61/53	21	8	46	90	1.5	1.3	1.2
17	414 109	344	332	80/72	17	14	34	70	5.7	2.4	2.2
18	414 053	347	285	100/89	12	7	28	47	3.6	1.7	3.4
19	412 620	41	11	84/61	23	8	67	114	1.3	0.9	1.1
20	412 392	29	24	52/35	19	8	27	58	1.9	1.6	1.7
21	413 993	335	292	84/82	18	12	10	75	8.4	8.2	8.3
22	413 580	30	38	51/41	14	8	73	73	0.7	0.6	0.6
23	413 619	25	99	109/74	21	4	57	118	1.9	1.3	1.6
24	413 868	26	224	79/74	24	7	29	61	2.7	2.6	2.6
25	413 979	316	253	102/59	17	4	9	31	11.3	6.6	8.9
26	412 170	42	42	67/43	24	13	43	102	1.6	1.0	1.3
27	414 604	319	273	61/56	16	6	27	87	2.3	2.1	2.2
28	414 020	330	330	66/35	18	7	67	113	1.0	0.5	0.7
29	412 746	15	54	74/49	25	13	33	92	2.2	1.5	1.8
30	412 847	339	318	64/59	17	11	76	106	0.8	0.8	0.8
31	413 094	353	44	61/54	25	6	18	111	3.4	3.0	3.2
32	413 127	13	23	83/46	24	3	60	102	1.4	0.8	1.1
33	413 198	9	9	42/36	17	9	31	68	1.4	1.2	1.3
34	413 366	10	54	84/73	18	9	28	109	3.0	2.6	2.6
35	413 389	14	14	84/73	18	8	62	102	1.4	1.2	1.3
36	413 521	74	36	66/44	21	12	43	70	1.5	1.2	1.2

*Age determined by simple ring counting, but not by cross-dating or determination of false or missing rings, thus age can only be considered to be approximate (Fritts, 1976).

Table 2
Measurements of the parameters sampled and evaluated on Monterrubio (*Q. ilex*)

Sample number	Hillside aspect (degrees, clockwise from north)	Local (root) aspect (degrees, clockwise from north)	Height from ground max/min (mm)	Hillside slope (°)	Local (root) slope (°)	Approximate age of exposure (years)*	Approximate age of root (years)*	Maximum erosion rate (mm/year)	Minimum erosion ate (mm/year)	Average erosion rate (mm/year)
1	124	130	81/52	7	12	40	61	2.0	1.3	1.6
2	176	176	76/72	9	13	42	. . .	1.8	1.7	1.7
3	160	160	31/22	14	13	. . .	. . .	. . .	. . .	. . .
4	168	147	33/30	18	13	. . .	. . .	. . .	. . .	. . .
5	158	158	33/28	16	17	. . .	. . .	. . .	. . .	. . .
6	114	252	72/66	4	8	19	44	3.8	3.5	3.6
7	104	72	42/33	8	7	. . .	. . .	. . .	. . .	. . .
8	116	159	60/58	9	11	30	. . .	2.0	1.9	1.9
9	116	158	33/32	9	8	28	. . .	1.2	1.1	1.1
10	116	106	55/52	9	11	23	48	2.4	2.3	2.3
11	106	188	51/32	9	0	29	34	1.8	1.1	1.4
12	98	131	20/17	17	13	35	. . .	0.6	0.5	0.5
13	176	137	40/28	17	17	. . .	. . .	. . .	. . .	. . .
14	196	196	21/21	19	18	. . .	. . .	. . .	. . .	. . .
15	184	211	48/32	20	21	. . .	. . .	. . .	. . .	. . .
16	207	264	39/25	21	12	. . .	. . .	. . .	. . .	. . .
17	175	175	35/30	19	18	24	. . .	1.5	1.2	1.3
18	175	175	35/30	19	18	. . .	. . .	. . .	. . .	. . .
19	181	106	31/11	18	15	19	. . .	1.6	0.6	1.1
20	170	170	15/12	20	20	19	. . .	0.8	0.6	0.7
21	195	223	49/38	18	12	30	. . .	1.6	1.3	1.4
22	144	133	30/8	15	13	28	. . .	2.0	2.0	2.0
23	180	194	33/29	10	3	21	40	1.4	0.2	0.8
24	200	200	25/21	11	9	18	. . .	. . .	. . .	. . .
25	194	194	33/29	19	8	. . .	. . .	. . .	. . .	. . .
26	213	213	31/19	21	22	27	47	1.1	0.7	0.9
27	167	120	30/14	22	23	. . .	. . .	. . .	. . .	. . .
28	184	111	32/21	19	15	12	. . .	2.7	. . .	2.7
29	206	166	27/22	17	12	. . .	. . .	. . .	. . .	. . .
30	222	188	20/18	13	12	. . .	. . .	. . .	. . .	. . .
31	166	136	15/13	9	8	. . .	. . .	. . .	. . .	. . .
32	137	93	52/21	11	7	0	. . .	2.6	1.0	1.8

Dotted lines indicate that no data is available.
*Age determined by simple ring counting, but not by cross-dating, or determination of false or missing rings, thus age can only be considered to be approximate (Fritts, 1976).

'diameter of cellular light in earlywood' parameter, the measurements were carried out for 12 cells, taken randomly from earlywood.

3.3. Data analysis

The fact that the two sampled areas (Senda Schmidt and Monterrubio) have distinct physiographical characteristics has facilitated analysis of the influence (via statistical tools) of the environmental factors that control the erosive process (slope, aspect, soil texture, etc.).

Using the COFECHA program, the annual growth series were filtered with a cubic spline function for a period of 15 years, each one of them being divided into 12-year segments with an overlap of 6 years. In addition, an autoregression model was applied to the series to eliminate autocorrelation, and also a logarithmic transformation, with the purpose of making the series as centred and unskewed as possible.

The main part of this analysis has been based on a statistical method using data from the time of exposure and depth of erosion (Tables 1 and 2). In order to demonstrate that the population from which samples come follows a normal distribution, the Kolmogorov–Smirnov statistic and the measures of shape (standardized kurtosis and standardized skewness) were used. Where those variables did not adjust to a normal distribution, a logarithmic transformation was made from the data, and the distribution resulted in a log-normal type. Next, a descriptive statistical analysis was carried out.

A correlation matrix was done by applying Pearson's correlation coefficient, which determined the degree of correlation between each of the variables examined in this study and the average denudation rate variable. Also, the linear correlation between each pair of variables was tested for significance. Due to the fact that the statistical significance of the 'aspect' variables (in the 'hillside aspect' and 'local aspect' variables) did not correspond to their physical significance, the degree of the relationship was quantified again on the basis of the data of average erosion rates and the corresponding orientations of each sample point using Spearman's rank correlation coefficient. On the basis of the results obtained in the previous analyses, adjustment functions were created with the variables that best modelled the erosion rates.

This analysis was complemented with a multifactorial analysis of variance (Fisher's least significant difference—LSD method), with the aim of determining which of the factors studied had a significant statistical effect on the dependent variable. An analysis of variance (Fisher's LSD method) was also performed for the four variables considered in the anatomical analysis (width of the growth ring, number of cells per ring, percentage of latewood and diameter of cellular light in earlywood). To accomplish this analysis, two groups of measurements were defined: the first consisted of the series concentric (not-exposed rings) and the second to the series of exposed rings.

4. Results

4.1. Assessment of the quality of cross-dating

As a result of the statistical validation analysis of the synchronized series carried out with the COFECHA program, it can be concluded that none of the series presented a correlation value above the critical one (0.67) in any of their segments. Moreover, neither is there an improvement in the correlation values when a 10-year lag on either side of the dated position is applied, except in one series, which may be coincidental. Therefore, from a statistical viewpoint, the degree of accuracy in the synchronized series cannot be determined.

4.2. Descriptive statistical analysis

A preliminary statistical analysis of Senda Schmidt established that the population from which the sample was taken did not form a normal distribution (Table 3). The estimate of the logarithmic transformed variable average value enabled the average value of the erosion rate in the Senda Schmidt to be obtained via statistical inference and at a 95% confidence level. This was done for the exposure period of the sampled roots (101 years), resulting in values of 1.7–2.6 mm/year.

In the case of Monterrubio, the descriptive statistical analysis carried out for the 'average erosion rate' variable shows that the population from which the sample comes follows a normal distribution (Table 4). Nevertheless, a logarithmic transformation of the measurements was also done in order to derive a more exact conclusion. At the 95% significance level, the average value of the 'erosion rate' variable was found to vary from 1.1 to 1.8 mm/year interval, for the exposure period of 42 years.

4.3. Analysis of the degree of correlation between the variables used in the study

In the case of the Senda Schmidt, at a 95% confidence level, there is no evidence that a statistically significant correlation exists among the variables (in all cases, the P value >0.05). An analysis of the correlation of the variables was also carried out for the Monterrubio area. A significant correlation, with a 95% level of significance, was obtained between the variables 'log (average erosion rate)' and 'hillside slope'. Using Spearman's coefficient, the lack of a significant lineal correlation was also established between

Table 3
Values of statistical parameters applied to the maximum, minimum and average data samples obtained in the Senda Schmidt (*P. sylvestris*)

Statistical measurements	Maximum erosion rate (mm/year)	Minimum erosion rate (mm/year)	Average erosion rate[1] (mm/year)
Mean	2.9	2.0	2.6
Median	2.2	1.6	2.1
Geometric mean	2.3	1.6	2.1
Maximum value	11.3	6.6	8.9
Minimum value	0.7	0.5	0.6
Range	10.6	6.1	8.3
Variance	6.0	2.3	4.1
Standard deviation	2.5	1.5	2.0
Standardized skewness	4.8	4.2	4.5
Standardized kurtosis	4.6	3.3	3.9

[1]Estimated Kolmogorov–Smirnov statistic = 0.21; approximate P value at 99% confidence level is <0.01.

Table 4
Values of statistical parameters applied to the maximum, minimum and average data samples obtained in Monterrubio (*Q. ilex*)

Statistical measurements	Maximum erosion rate (mm/year)	Minimum erosion rate (mm/year)	Average erosion rate[1] (mm/year)
Mean	1.8	1.3	1.6
Median	1.7	1.2	1.4
Geometric mean	1.6	1.3	1.4
Maximum value	3.8	3.5	3.6
Minimum value	0.6	0.2	0.5
Range	3.2	3.3	3.1
Variance	0.6	0.6	0.6
Standard deviation	0.8	0.8	0.8
Standardized skewness	1.6	2.2	2.0
Standardized kurtosis	1.5	2.0	1.5

[1]Estimated Kolmogorov–Smirnov statistic = 0.12; approximate P value at 90% or higher confidence level is >0.10.

'hillside aspect' and 'local aspect' against the 'log (average erosion rate)', at a 95% confidence level.

4.4. Development of adjustment models between those variables that give a significant correlation

For Monterrubio, the relationship was measured between the logarithm of estimated average erosion rates and the 'hillside slope' variable. As a result, the mathematical function that best adjusts to the values of the bi-dimensional variable is a linear function. In this case, the determining coefficient (R^2) is equal to 22%, where the correlation coefficient is equal to -0.47. Likewise, the standard error of the residuals is equal to 0.45, whereas its average absolute value is 0.33.

4.5. Analysis of variance of the environmental factors

The multifactorial analysis of variance enables those factors to be determined that significantly influence the logarithm of average erosion rate. In view of the probability values obtained for the Senda Schmidt, at a 95% confidence level, only the 'situation in the trail' variable contributed significantly to explain the result measurements. Therefore, a multiple comparison analysis was performed for the levels that were defined in the 'situation in the trail' factor, which enabled the comparison in pairs of level means. The results of this analysis show that there are significant differences between the average erosion rates in the first 800 m of the Senda Schmidt trail nearest the Navacerrada Mountain Pass and the rest of the trail (Table 5).

4.6. Analysis of variance of the variables considered in the anatomical analysis

Results from the analysis of variance verified the existence of a statistically significant difference between the two groups of measurements (Table 6). The statistical analysis

Table 5
Multiple comparisons of 'average erosion rates' after log transformation as a function of the location within Senda Schmidt (*P. sylvestris*)

Location (X-UTM)	No. Samples	Erosion rate		Homogeneous groups
		Average	Standard deviation	
2 (413094–413868)	7	1.93	1.22	a
1 (411332–413094)	15	2.33	1.18	a
3 (413868–414680)	12	3.59	1.22	b
Contrast			Difference	± Limits
1–2			1.21*	0.42
1–3			− 1.54*	0.52
2–3			− 1.86*	

*Indicates a statistically significant difference.

leads to the conclusion that the changes in annual growth are indicators of erosive phases, whereas the percentage of latewood and the diameter of cellular light in earlywood are indicators of change in most cases. The results obtained verify that the anatomical changes produced by having the roots of *P. sylvestris* exposed allow the determination of the first year of exposure. This also coincides with the first year of exposure determined by morphological criteria, with a range of difference that in no case exceeded ± 3%.

Of all the parameters studied, the one that offered the clearest indication of exposure was the measurement of the ring's width, both in the number of cells per ring and in the overall size. In fact, we noted an increase of up to 10 times the average value of the ring's width due to exposure at a point corresponding to the traumatic disappearance of the secondary meristem (cambium). Conversely, the 'diameter of cellular light in earlywood' parameter is the inverse of the preceding parameter—there is an abrupt drop in cell size. Subsequently, once the disturbance has been overcome, the sizes tend to stabilize (Fig. 4). Another variable that responds clearly in the first year of exposure is the percentage of latewood (Table 6), which shows a significant increase (Figs. 5 and 6).

5. Discussion

The determination of the first year of root exposure is essential for obtaining sheet erosion rates. In this respect, it has to be emphasized that tissue death of the upper part of the root is basically due to trampling and cattle browsing, and not to the exposure itself. In Senda Schmidt, the massive and continuous influx of visitors makes it seem that not much time passed between the first exposure and the disappearance of the bark. In Monterrubio, it is assumed that intensive grazing implies that the animals start browsing on the roots as soon as they are exposed (see also Vandekerckhove et al., 2001, pp. 136–137).

The analysis of anatomical changes that take place in the roots as a response to exposure allows the first year of exposure to be determined with precision (Gärtner et al., 2001). For this study, the definition of the first year of exposure on the basis of his criterion is accurate to + 1–3 years, bearing in mind what is defined as the start of eccentricity in the ring growth patterns. This difference could be caused by the time the samples took to shed their bark once exposed. The method also includes a potential margin

Table 6

Comparison matrix of groups N (non-exposed rings) and E (exposed rings) for each sample of wood analysed (I to VII)

ID samples	Tree-ring series	Groups	Width of the growth ring (mm)		Number of cells per ring		Percentage of latewood		Diameter of cellular light in earlywood (μm)	
			Average	Homogeneous groups	Average	Homogeneous groups	Average	Homogeneous groups	Average	Homogeneous groups
I	43	N	0.184	a	5.85	a	2.28	a	37.13	a
	17	E	1.288	b	33.76	b	45.06	b	21.94	b
	40	P	0.211	a	5.58	a	1.81	a	24.19	b
II	40	N	0.314	a	5.57	a	8.17	a	51.40	a
	26	E	0.878	b	27.23	b	58.24	b	22.00	b
III	73	N	0.181	a	4.33	a	4.28	a	39.83	a
	27	E	0.986	b	21.33	b	44.11	b	24.02	b
IV	42	N	0.344	a	8.57	a	*29.45*	a	*37.58*	a
	26	E	1.283	b	33.50	b	*30.92*	a	*34.88*	a
V	33	N	0.555	a	12.24	a	*39.88*	a	*25.08*	a
	20	E	1.471	b	32.3	b	*44.97*	a	*23.79*	a
VI	46	N	0.215	a	5.08	a	5.11	a	53.65	a
	41	E	0.612	b	13.19	b	31.63	b	35.52	b
VII	26	N	0.794	a	7.61	a	*23.60*	a	68.48	a
	21	E	1.992	b	21.05	b	*30.06*	a	42.02	b

Samples are of *P. sylvestris*. Values in italics indicate that this pair does not show a statistically significant difference at the 95% confidence level. For sample I, another group has been defined subsequent to E, called P (post-exposed rings).

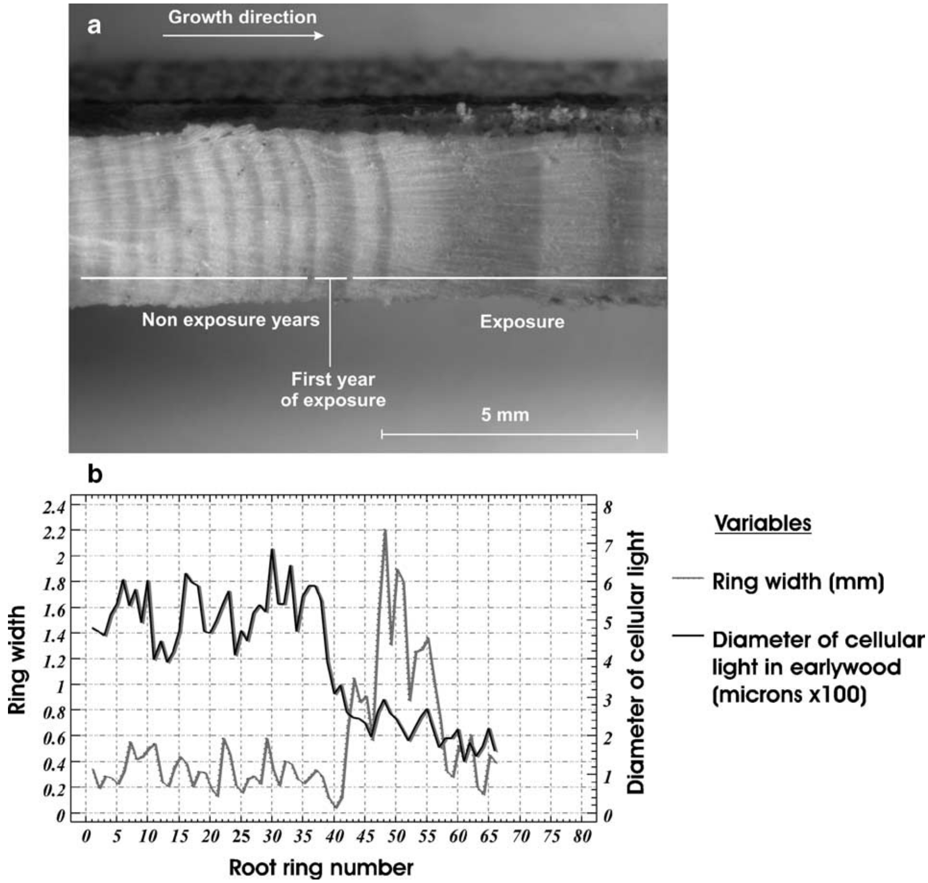

Fig. 4. (a) Change threshold in the ring-width measurement (*P. sylvestris*, Senda Schmidt). The discontinuous line indicates the first year of exposure; (b) Variation in time in the tree ring-width series, as well as the diameter of cellular light in earlywood.

of additional error, as it was not able to be determined if there were false rings or missing rings. In this respect, *Q. ilex* normally shows both false rings and missing rings, and therefore the results have a higher degree of uncertainty. This should be the result of the Mediterranean climate of the Monterrubio area, as well as the characteristics of holm-oak wood, with its tendency to produce false rings. In contrast, on Senda Schmidt it is less likely that the *P. sylvestris* trees would develop false rings or display missing rings because the adjacent Navacerrada rain gauge indicates an average annual rainfall of 1400 mm, with precipitation occurring in every month (Pérez Delgado, 2003). This suggests that the sample area is not subject to periods of drought. However, not all false and missing rings are climatically caused, and this may be especially true with roots. In fact, the cause of false and missing rings in roots should be studied. *P. sylvestris* can show rings with discontinuous annual growth. This anomaly can be due to: a delay or deficiency in growth hormones during the earlywood phase of development of the ring (Panshin and de Zeeuw,

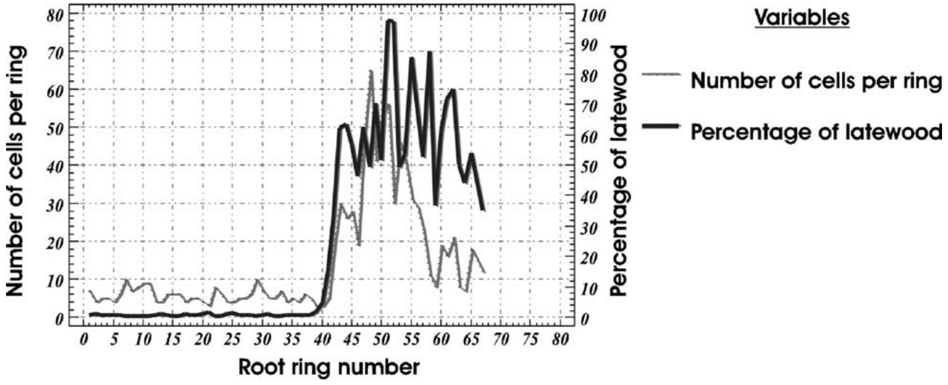

Fig. 5. Variation in the time of the number of cells per ring and of the latewood percentage (*P. sylvestris*, Senda Schmidt).

1970); to a lack of humidity in the soil; to competition for light and nutrients; or to the progressive reduction of the ring width as the age of the tree increases (Fritts, 1976). In some cases, disturbance may be caused by nearby rocks in the soil (Grissino-Mayer, 2002). This is the situation in the Senda Schmidt. In fact, both fragments of rock, as well as the actual rock substratum, outcrop in many areas.

According to Fritts (1976), the dendrochronological cross-dating technique should solve this problem. However, the application of the cross-dating technique in this study has been ineffective. There are several reasons that explain the lack of any significant correlation between the series, and, as a consequence, between each one of these with the master chronology. Some are statistical. Therefore, on the one hand, he use of a spline function with a 15-year period may conceal a large part of the environmental signal that determines the growth pattern in the ring series. On the other hand, the segmentation of the series in elements of less than 30 years may determine that correlation values are either low or implausible (Grissino-Mayer, 2001). Other reasons have to do with physiographical characteristics that exist in Spain, which cause the rings not to respond preferentially to one or more limiting factors. In reality, trees are not generally in such unfavourable conditions. Ring growth is the consequence of various factors that may be different in trees in close proximity (Fernández and Manrique, 1997). Finally, cross-dating of roots has a series of difficulties that are inherent to their anatomical and morphological structure (Krause and Eckstein, 1993). Furthermore, the variability of the ring-width measurements is not explained by the action of a major limiting factor, as it happens in dendroclimatology. It appears that there are various limiting factors involved in this study, which could explain a percentage of the statistically significant variation of the ‘ring width’ variable. Some of these factors show a spatial variability; therefore, their weight of influence as limiting factors is heterogeneous in the study areas. As a consequence, the mechanical stress that is associated with trampling—either from trekking or overgrazing—shows different intensity levels. Even temperature cannot be considered uniform, although the sampling has been carried out at a more or less uniform altitude—Senda Schmidt generally runs level along a north-facing hillside, but it also has zones with a south-facing aspect. All

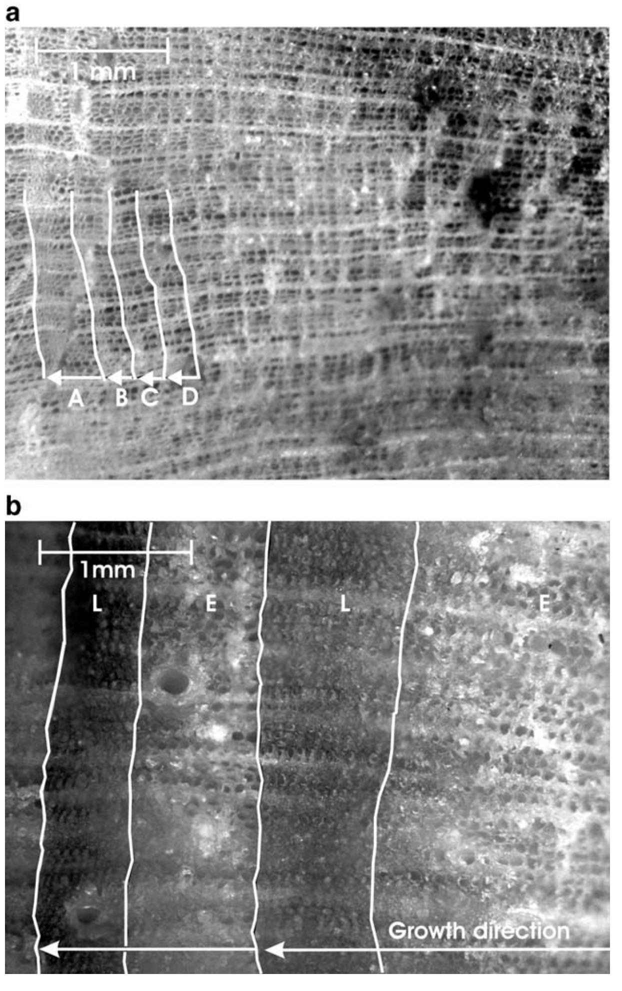

Fig. 6. (a) Cross-section of a *P. sylvestris* root in non-exposure conditions (A, B, C, D, represent growth rings). (b) Cross-section of a *P. sylvestris* root exposed by sheet erosion. Note the increasing growth ring width and the increasing percentage of latewood. L = latewood; E = earlywood.

of this hinders the establishment of statistically significant correlations among the existing series of ring-width measurements; and, as a result, cross-dating is not reliable.

The statistical treatment of the 'exposure time' and 'lowering depth' data has allowed, with a 95% level of confidence, average erosion rates for the two locations studied to be obtained: 1.7–2.6 mm/year, in the Senda Schmidt (for a period of 101 years of exposure) and 1.1–1.8 mm/year in Monterrubio (for a period of 42 years of exposure). The transformation of average erosion data from mm/year to t/ha/year via the consideration of the average density of eroded soils (1.7 t/m^3 in both cases), has determined average erosion rates for the Senda Schmidt that are far superior to those estimated by the Map of Erosive Classes in the Duero Watershed (López et al., 1987): 29–44 t/ha/year for Senda Schmidt, obtained from our analysis, compared with 0–5 t/ha/year for the Valsaín pine forest (where the Senda Schmidt is located) obtained from López et al. (1987). Furthermore, for the past 10 years of exposure, at a 95% significance level, the rates are found to be within the range of 102–170 t/ha/year. The explanation for such a high increase in these values is attributed to the intensive recreational use in a reduced area. The compaction caused by trampling produces decreased infiltration, increasing the erosive power of raindrop impact as well as surface runoff. In the Monterrubio area, the estimated average erosion rate obtained in this analysis, at a confidence level of 95%, is at an interval of 19–31 t/ha/year, compared with 25–50 t/ha/year in its surroundings, as obtained from López et al. (1987). The influence of different environmental factors in the erosion variable made up the second set of analyses and results. In the Senda Schmidt, the variance analysis carried out on the variable 'log (average erosion rate)' indicates that the factor 'location within the trail' is the only factor that has a statistically significant influence on the dependent variable. The analysis of multiple comparisons indicates that the erosion rates are significantly higher on the first 800 m of the trail closest to the Navacerrada Mountain Pass. This seems to indicate that a high percentage of visitors to Senda Schmidt make partial treks along this first part of the trail.

Contrarily, the conclusions derived from the dendrochronological analysis carried out on the samples of *Q. ilex* from Monterrubio, raise a series of doubts. This oak has a tendency to form false rings, resulting in great difficulty in correctly interpreting ring-growth patterns. Nevertheless, the attempt to calibrate its use as a bio-indicator of erosion rates was justified by the fact that the holm-oak forests occupy a large part of the Iberian Peninsula (ICONA, 1974, 1980).

In every case (for the Monterrubio holm-oak), the existence of an inverse lineal correlation ($R^2 = 22\%$; P value < 0.05) was determined between the variables 'log (average erosion rate)' and 'hillside slope'. Despite this, the result did not allow conclusions to be established, due to the following factors: first, the correlation coefficient is -0.47; second, the dependent variable only explains 22% of the existing erosion rates; third, only 18 of the 32 samples taken in the field were useful for statistical analysis; and fourth, there is a tendency of holm-oaks to form false rings.

6. Conclusions

The use of exposed roots as geomorphological indicators to quantify existing erosion in a given area could be especially useful for characterizing the influence of human activity in sheet erosion processes, as in the cases studied here. But not all the species allow dendrogeomorphological analyses. Whereas conifers show easily observable growth rings, this is not the case for broad-leaved trees. *Q. ilex*, for example, develops rings that are not very clear, and growth is irregular, making dying techniques and alcohol washes necessary. Also, the existence of false rings and interannular rings increases the difficulty of interpretation of these roots.

When the estimates are carried out based only on the analysis of the eccentricity pattern, they have a certain degree of uncertainty, as bark can be maintained on the top of the root after exposure, and therefore concentric rings can continue to grow. This is not the case in this study, given that the continuous presence of trekkers (in Senda Schmidt) and intensive grazing (in Monterrubio) makes the preservation of the bark over long periods of time improbable after its first exposure. For other situations, this shortcoming can be compensated for by determining, precisely, the first year of exposure by thin-section analysis of changes in the anatomical structure of the root. Again, this is feasible for Scots pine plants. Accordingly, all our data indicates that the evaluation on *P. sylvestris* roots is fairly reliable, but not for the oaks. However, as the root ages were determined by ring counting as the cross-dating principle was not feasible, the results can only be taken as approximate.

The novelty of this paper lies in the application of an existing method—the analysis of exposed roots—for determining sheet erosion rates in Central Spain. In addition, the analysis of anatomical indicators for *P. sylvestris* is achieved, which make estimations more accurate.

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