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High resolution, quantitative reconstruction of erosion rates based on anatomical changes in exposed roots at Draix, Alpes de Haute-Provence — critical review of existing approaches and independent quality control of results

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ABSTRACT

Extensive areas of the French Alps are underlain by Jurassic black marls. Wherever these "terres noires" crop out they become subject to intense erosion, causing major sedimentation in regional reservoirs and river systems. In the badlands near Draix (Alpes de Haute-Provence, France), measured sediment rates were obtained at the plot scale by surface elevation change-based methods and at the catchment scale by monitoring sedimentation in dams. In this study, we use a dendrogeomorphic approach based on anatomical changes in exposed roots of Pinus sylvestris L. to accurately quantify continuous denudation rates. A total of 123 cross sections (75 from buried and 48 from exposed roots of 23 trees) were sampled in the Moulin basin. The size and position of roots at the time of exposure was determined via anatomical variations in the annual growth rings of roots. In cross sections of buried roots, a sharp reduction of earlywood tracheid lumen area – a growth signature which has traditionally been used to determine the moment of root denudation - was observed as soon as erosion reduced soil cover to \leq 3 cm. As a consequence, estimates of eroded soil thickness had to be adjusted to take account of this bias. Bias-adjusted, averaged, medium-term erosion rates derived from exposed roots vary between 6 and 7 mm y^{-1} at Moulin basin depending on the importance accorded to the uplift of roots after exposure. Values are significantly correlated to slope angle and match with erosion rates derived from monitored iron stakes (5.7 mm y⁻¹) or measurements of sediment yield in retention dams (4.7 mm y^{-1}) at the outlet of the Moulin basin. Besides demonstrating that the interpretation of anatomical signatures in tree roots to erosion have to be revised, this paper also shows that dendrogeomorphic analyses of roots are indeed a powerful tool for the quantification of minimal rates of soil erosion in environments where measurements of past activity are not available.

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1. Introduction

The Black Marls formations, or *terres noires* in French, of the Southern French Alps cover a surface of more than 3500 km² which is highly susceptible to weathering and erosion (Antoine et al., 1995; Descroix and Olivry, 2002). The Mediterranean climate of the middle Durance River with repeated frost in winter and high intensity rainfalls in summer has resulted in the formation of badland morphologies with scarce vegetation and erosion rates that are amongst the highest in the world (Walling, 1988) at around 10 mm y⁻¹ (Descroix and Olivry, 2002); Descroix and Mathys, 2003). These average values were obtained from

several years of monitoring activity and based on measurements that can be divided into two different categories: (i) devices measuring changes in surface level such as profilometers (Descroix, 1998), graduated needles driven into the soil (Olivry and Hoorelbeck, 1990), or successive, high accuracy digital elevation models (DEMs; Raclot et al., 2005; Puech et al., 2009); and (ii) those measuring erosion and sediment transport to the outlet of plots or catchments (for a detailed review see Descroix and Mathys, 2003).

In this paper, bioindicators are used to quantify multidecadal erosion rates in the marly badlands of Draix (Alpes de Haute-Provence, France). The study is based on (i) a dendrogeomorphic analysis of anatomical growth reactions in exposed tree roots, (ii) high resolution, quantitative reconstruction of erosion rates, and (iii) a calibration (accuracy assessment) of reconstructed rates with instrumental measurements. The purpose of dendrogeomorphology is

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to characterize and reconstruct geomorphic processes in space and time (Stoffel and Bollschweiler, 2009; Stoffel et al., 2010). The approach, first elucitated by Alestalo (1971) and further developed by Shroder (1980) and Braam et al. (1987) takes advantage of the fact that trees growing in temperate climates form yearly increment rings that can be used to precisely date external disturbances.

In the past, studies using dendrogeomorphic methods primarily focused on the stem and only to a lesser extent on roots. Traditionally, sprouting of adventitious roots was used to infer deposition events associated with flooding (Martens, 1993; Nakamura et al., 1995) or debris flows (Strunk, 1989, 1991, 1997). The classical procedure implemented to determine erosion rates over timescales of hundreds to thousands of years was, in contrast, based on the ratio between the minimum depth of erosion - obtained from the reconstructed root diameter at the moment of denudation - and the time (i.e., number of growth rings) passed since root exposure (Eardley and Viavant, 1967; LaMarche, 1968; Dunne et al., 1978; McAuliffe et al., 2006). Carrara and Carroll (1979) added the idea of dating scars and changes in ringgrowth patterns (from concentric to eccentric) of exposed roots and declared this to be the first year of exposure. Morneau and Payette (1998) analyzed trampling scars on exposed roots to access information about caribou (Rangifer tarandus L.) activity in boreal forests. Sprouting of adventitious roots and scars were also applied for the quantification of gully (Vanderkerckhove et al., 2001; Malik, 2008), sheet (Bodogue et al., 2005), meander bank (Malik, 2006), or shore (Fantucci, 2007) erosion. All of these analyses concentrated on variations in ring width or structural changes in roots at a macroscopic level.

More recently, microscopic approaches and equations have been introduced, determining the year of exposure based on changes in (i) the anatomical structure of tracheids in conifer roots (Gärtner et al., 2001; Rubiales et al., 2008) and in (ii) the formation of vessels in roots of broadleaved trees (Hitz et al., 2008a,b). However, while yielding promising results, the microscopic approaches and proposed equations (Gärtner, 2007) — to date — have neither been tested for consistency nor checked for accuracy against other systematically measured rates of erosion at the same sites.

Therefore, the goals of this paper are (i) to check the reliability of wood-anatomical signatures in tree roots for dendrogeomorphic reconstructions of erosion rates, (ii) to test the equations traditionally used in erosion rate reconstructions, and (iii) to create the basis for a quick and accurate assessment of longer term erosion rates on large surfaces. For this purpose, we compare dendrogeomorphic erosion rates derived from microscopic analyses of root in *Pinus sylvestris* L. with iron stake measurements of changes in soil surface levels and through a quantification of sediment yield at the outlet of the basin.

2. Study site

The present study was conducted in the Draix Erosional Research Basins (Southern French Alps) where intense marly degradation has been monitored by Cemagref since 1982 (Mathys et al., 2003). Fieldwork was carried out in the experimental catchment of Moulin (approximately 8 ha), one of the five basins monitored by Cemagref. This catchment is located in Draix (44°8' N., 6°20'E.), 13 km North-East of the town of Digne, Alpes de Haute-Provence (Fig. 1) and consists of Jurassic marine black marls (Bajocian, Bathonian and Callovo-Oxfordian units) characterized by dense layering including a detrital and a carbonated phase. The carbonate content varies from 20 to 80% of the total volume. The detrital phases comprises mainly silt with a small proportion of clayey materials (Antoine et al., 1995). These formations are capped by fairly resistant limestones controlling topography in the area and forming elongated monoclinal ridges with elevations of up to 2000 m asl (Oostwoud Wijdenes and Ergenzinger, 1998). The marly formations of the Moulin basin are very sensitive to weathering and erosion (Antoine et al., 1995), which has resulted in characteristic badlands topography with short, steep, and highly dissected slopes.



Fig. 1. The Moulin basin (8 ha) is located near the town of Digne (Alpes de Haute-Provence, France) (A). In this marly catchment, the forested patches are scarce and isolated trees (*Pinus sylvestris L*.) frequently exhibit roots exposed by erosion (B).

Located at the interface of Alpine and Mediterranean climate systems, the study area receives mean annual rainfalls (1984-2004) of 900 mm and has an average of 200 days y^{-1} without rain and only 5 days y^{-1} with rainfalls >30 mm. Summers are dry with short, yet severe storms; and maximum precipitation occurs in April-May and September-October (Richard and Mathys, 1999). Mean annual temperature is 9.8 °C with warm summers (28 °C in July) and mild winters, but an average of 115 freeze and thaw cycles occur between November and April (Rovéra and Robert, 2005). Snow is usual but does not form a semipermanent cover.

Freeze-thaw cycles are the key driver of black marl degradation, complemented by an interplay of wetting and drying phases (Antoine et al., 1995). The ice is the main factor responsible for the marl degradation because it acts to open cracks, increases soil porosity, weakens the stability of agreggates and enables the penetration of carbonate dissolution (Clotet et al., 1988). Similarly, water seepage may totally disintegrate marls platelets (Antoine et al., 1995). These platelets then form a silty overlayer with a particle size close to that of the original sediment. As a result, at the end of winter, a loose detrital layer made with thicknesses ranging from 5-10 cm made of locally produced clasts or colluvial material dispersed in a silt-clay matrix, usually covers a more or less fragmented regolith (10-50 cm) laying on the marly bedrock (Maguaire et al., 2002); and rills have mostly disappeared. In addition, in the absence of runoff in winter, marl platelets fall as a result of gravity and form stocks at the bottom of slopes, ready to be evacuated by the first runoff event (Rovéra et al., 1999). Saturation of the weathered layer, by melting snow for example, may cause solifluxion on more gentle slopes and small landslides and mudflows on steeper slopes (Corona et al., 2002; Rovéra and Robert, 2005). As a consequence, high sediment loads are normally transported by the first major spring rainfall and resulting floods. In summer and early autumn, severe storms provide material by concentrated runoff on the slopes. Headwater erosion in basin streambeds is also responsible for sediment destabilization on slopes.

These combined processes maintain bare slopes, where woody vegetation is generally scarce, and tree cover restricted to 15% of the total surface in the case of the Moulin basin. At interfluves and on more stable slopes, trees are more abundant and stands mostly consist of Scots pine (Pinus sylvestris L.) and Austrian black pine (Pinus nigra Arn. ssp. nigra). Almost all trees at Draix show the typical symptoms of tree stress and a partial exposure of lateral roots.

3. Material and methods

3.1. Methods of erosion reconstruction

For a high resolution and accurate quantification of the erosion rate, two parameters are needed: the number of rings since exposure (*NRex*) and the thickness of the eroded soil layer (E_r) since the

Hypothesis 2



Fig. 2. Schematic view (cross section) of root exposure illustrating the parameters used for the calculation of erosion rates with hypotheses H1 (relative uplift of the root axis relative to the subsequent growth after exposure) and H2 (stability of the root axis).

exposure. When a root loses its edaphic cover, a series of anatomical changes will occur in its growth rings of roots because of the effect of exposure itself (e.g., variations in edaphic temperature and humidity, reduction in pressure of soil cover) and because of the mechanical stress (e.g., abrasion) that the root undergoes when exposed. Gärtner et al. (2001) defined reduced cell lumen area in earlywood tracheids by about 50% – a distinct sign of exposure in conifer roots. However, in the case of continuous and progressive denudation such as on marly slopes, we can assume that a reduction of tracheid cell lumen area will occur as soon as the soil covering the root is reduced to a few centimeters. If true, this bias (ε) would need to be quantified to avoid misinterpretation of the year of denudation and a subsequent underestimation of mean annual erosion rates since exposure.

The thickness of the eroded layer is derived from the height of the exposed part of the root measured in the field (E_x) that clearly depends on the stability of the root axis. Two hypotheses were tested; the first one (H1), illustrated in Fig. 2, assumes that the radial growth pressure exerted by the root is lower than the mechanical impedance of the soil, i.e., its reaction to deformation by the root. As all samples

are still in contact with the soil, the subsequent growth of the root (Gr1, Gr2) on both sides of the root axis after exposure will cause a relative vertical uplift of the root axis; and E_{r1} (i.e., Er according to H1) must be adjusted to avoid overestimation of the erosion rates as follows (Fig. 2):

$$E_{r1} = E_{x} - (Gr1 + Gr2) + (B1 + B2)/2 + \varepsilon$$
(H1)

With:

B1, B2: thickness of bark on the upper/lower side of the root ε : bias

The second hypothesis (H2) assumes stability of the root axis through time. The relative uplift of the root center from the growth increment of the lower part is balanced by the positive diageotropism — the ability of some roots to adjust their curvature as a response to environmental changes (e.g., temperature, aeration, moisture and mechanical impedance) — that bends the root upward (Coutts, 1989;

Table 1

Characteristics of exi	posed roots and en	osion rates determine	d from wood	anatomical ch	nanges according	to both hy	pothesis I	H1 and H2.
						,		

N° of tree	N° of root	ID of cross	Topographic	Age (years)	Slope (°)	E_{x} (mm)	E _{r1} (mm)	E _{r2} (mm)	Year of	Duration of	Erosion rate 1	Erosion rate 2
		section	conditions						exposure	exposure (Nrex)	$(E_{ra}1. mm y^{-1})$	$(E_{ra}2. mm y^{-1})$
1	1.1	1.1.1	Gully slope	38	22	77	63	66	1996	13	7.2	7.4
1	1.1	1.1.2	Gully slope	36	22	95	77	90	1993	16	6.7	7.5
1	1.1	1.1.3	Gully slope	33	22	85	63	85	1995	14	6.6	8.2
2	2.1	2.1.1	Gully slope	28	34	68	61	61	1988	21	4.3	4.3
3	3.1	3.1.1	Gully slope	28	40	78	71	71	1991	18	5.6	5.6
4	4.1	4.1.1	Gully slope	32	41	170	160	160	1986	23	8.3	8.3
5	5.1	5.1.1	Gully slope	29	39	150	136	136	1987	22	7.6	7.5
6	6.1	6.1.1	Interfluve slope	36	5	62	58	54	1991	18	4.9	4.7
7	7.1	7.1.1	Interfluve slope	37	6	90	50	85	1984	25	3.2	4.6
8	8.1	8.1.1	Interfluve slope	23	5	77	38	77	1992	17	5.2	6.3
8	8.1	8.1.2	Interfluve slope	31	6	67	48	62	1994	15	5.2	6.1
9	9.1	9.1.1	Interfluve slope	34	4	73	53	66	1993	16	5.2	6.0
10	10.1	10.1.1	Interfluve slope	46	13	135	101	118	1971	38	3.4	3.9
10	10.1	10.1.2	Interfluve slope	45	13	70	51	59	1995	14	5.8	6.4
11	11.1	11.1.1	Gully slope	44	38	91	65	89	1990	19	5.0	6.3
11	11.1	11.1.2	Gully slope	32	50	156	128	151	1990	19	8.3	9.5
11	11.1	11.1.3	Gully slope	33	54	165	120	155	1990	19	7.9	9.7
11	11.1	11.1.4	Gully slope	31	40	96	62	90	1993	16	5.8	7.5
11	11.1	11.1.5	Gully slope	24	50	141	109	132	1992	17	8.2	9.5
11	11.1	11.1.6	Gully slope	25	52	172	145	165	1987	22	8.0	8.9
11	11.1	11.1.7	Gully slope	17	50	95	75	87	1998	11	9.5	10.6
12	12.1	12.1.1	Gully slope	40	26	133	101	120	1987	22	6.0	6.8
12	12.1	12.1.2	Gully slope	29	25	176	150	165	1988	21	8.6	9.3
12	12.1	12.1.3	Gully slope	23	32	141	123	133	1988	21	7.3	7.8
13	13.1	13.1.1	Gully slope	60	31	52	46	47	1998	11	6.9	7.0
13	13.1	13.1.2	Gully slope	65	38	262	224	250	1965	44	5.8	6.4
13	13.1	13.1.3	Gully slope	57	41	266	236	248	1976	33	8.1	8.4
14	14.1	14.1.1	Gully slope	63	48	71	48	61	1995	14	5.6	6.5
14	14.1	14.1.2	Gully slope	61	41	108	77	101	1997	12	8.9	10.9
14	14.1	14.1.3	Gully slope	44	18	148	99	148	1973	36	3.6	4.9
14	14.1	14.1.4	Gully slope	53	27	140	105	134	1981	28	4.8	5.9
15	15.1	15.1.1	Gully slope	45	26	104	44	99	1973	36	2.1	3.6
15	15.1	15.1.2	Gully slope	46	16	83	45	71	1975	34	2.2	3.0
15	15.1	15.1.3	Gully slope	47	24	79	36	79	1973	36	1.8	3.0
15	15.1	15.1.4	Gully slope	48	28	75	35	71	1975	34	1.9	3.0
16	16.1	16.1.1	Gully slope	46	27	34	17	34	1997	12	3.9	5.3
16	16.1	16.1.2	Gully slope	20	32	68	43	68	1995	14	5.2	7.0
16	16.1	16.1.4	Gully slope	18	29	47	17	45	2000	9	4.7	7.5
16	16.1	16.1.5	Gully slope	18	31	51	22	48	1997	12	4.3	6.5
17	17.1	17.1.1	Interfluve slope	18	6	32	12	20	1995	14	3.0	4.2
17	17.2	17.2.1	Gully slope	20	40	53	37	16	1999	10	6.7	8.0
18	18.1	18.1.1	Gully slope	32	43	88	77	11	1999	10	10.7	11.4
18	18.2	18.2.1	Gully slope	49	35	48	39	9	2004	5	13.8	15.0
19	19.1	19.1.5	Interfluve slope	19	9	52	42	10	1997	12	6.0	6.6
20	20.1	20.1.1	Interfluve slope	62	10	90	31	59	1975	34	1.8	2.8
20	20.1	20.1.2	Interfluve slope	62	10	35	12	23	1993	16	2.6	3.4
21	21.1	21.1.1	Gully slope	12	47	58	34	24	2003	6	10.7	13.2
23	23.1	23.1.1	Gully slope	45	40	185	119	66	1975	34	4.4	5.9
			Average	37	29	102	75	88	1989	20	5.9	6.9
			•									

Polacek et al., 2006) and by adventitious roots anchored in the soil. In this case, the overestimation in E_x will only result from the subsequent growth of the upper part of the root since exposure and E_{r2} is calculated as follows (Fig. 2):

$$E_{r2} = E_{x} - (Gr1) + (B1 + B2)/2 + \varepsilon$$
(H2)

In both cases, E_r is divided by the number of rings formed since the year of exposure (*NRex*) to calculate the annual erosion rate E_{ra} :

$$\mathbf{E}_{\mathrm{ra}} = \mathbf{E}_{\mathrm{r}} / \mathrm{NRex} \tag{1}$$

3.2. Sampling strategy and growth-ring analysis

At the study site, 123 cross sections have been taken from 25 different roots from 23 trees, at a minimum distance of 50 cm from the stem basis. This distance has been chosen as (i) stem movement induced by ongoing growth tends to pull roots upwards (Stokes and Berthier, 2000) and as (ii) roots close to the stem basis and growing near the soil surface often experience bending stress resulting from stem displacement (Watson, 2000) and therefore exhibit asymmetric growth structures in cross sections. Before cutting cross sections, a detailed documentation of the position of the exposed roots with respect to the present soil surface was made and data recorded on topography, altitude, aspect, distance of the root section from the tree trunk, hillside slope, and slope All samples chosen for analysis were still in contact with the soil. The vertical distances between the upper part of the root and the soil surface during sampling (E_x) were determined with a depth gauge (see Fig. 2). The sawing of roots was carried out in summer and autumn 2009.

P. sylvestris displaying exposed roots located in topographic conditions similar to monitored sites were of special interest for the comparison. Two slope classes were selected for the sampling of exposed roots: 0-15° corresponding to interfluve slopes and 15-45° corresponding to gully slopes. The thalweg and the steepest slope segments were not sampled because comparison with measurement series from monitored sites would not have been possible in these cases (see below). Furthermore, in order to assess parameter ε , i.e., the maximum depth at which anatomical changes may occur (Fig. 2), 11 partly exposed roots from 9 different trees were excavated. Cross sections of the buried portions of the roots were every systematically sawn from 2 to 10 cm so as to obtain samples from intact roots in soils with different soil cover thickness. A total of 75 buried cross sections were sampled, representing burial depths of samples ranging from -1 to -135 mm.

All specimens were cut into cross sections about 2 cm thick and air-dried for ~30 day; they were prepared for macroscopic analysis (i.e., sanded sequentially with 60, 80, 320, and 600 grit-sanding belts) before growth-ring width was measured on four radii per cross section using a LINTAB measurement device. The resulting growth curves were cross dated per root to assure correct dating of samples.

Cross sections were then prepared for microscopic analysis. We therefore prepared small cubes from the cross sections (max. 2×4 cm) and cut microsections with a Reichert sliding microtome (thickness of cuts ~15 µm). The micro sections were then treated with sodium hypochlorite solution (NaOCl), deionized water, and solvable safranin before they were dehydrated with alcohol and xylol as described by Schweingruber (1978). In a final step, the microsections were put on slides, embedded in Canada balsam, and dried at 60 °C for 24 h.



Fig. 3. Evolution of the mean lumen area of earlywood tracheids in 11 sections (15.1.1 to 15.1.11) of root R15 (15.1.1-15.1.5: exposed sections; 15.1.6-15.1.11: buried sections). Arrows in years 1973, 1975 and 2005 indicate a sharp reduction of mean lumen area of earlywood tracheids.



Fig. 4. Evolution of the mean lumen area of earlywood tracheids in 30 sections of root R16 (16.1.1-16.1.5: exposed sections; 16.1.6-16.1.30: buried sections). Arrows in years 1995, 1997, 1999, 2000 and 2002 indicate a sharp reduction of mean lumen area of earlywood tracheids.

Microsections were then observed and photographed with a digital imaging system under optical microscopy. Measurements of the cell lumen area in earlywood tracheids were performed with the semiautomated WinCELL2005 software. Following Rubiales et al. (2008), cell lumen area was determined through an averaging of 12 cells' measurements per growth ring.

3.3. Comparison of dendrogeomorphic data with erosion measurements

The reliability of dendrogeomorphic approaches was tested by comparing reconstructed growth-ring data with denudation rates measured with a network of marking stakes (Hennessy et al., 1986). A total of 46 marking iron stakes were monitored at yearly intervals since February 2002 on interfluves (11) and on bare slopes (35) with gradients varying from 6° to 45° (Table 1). For technical reasons, steep slopes (>45°) and thalwegs were not sampled, as (i) iron stakes would likely have perturbed sedimentary transit and as (ii) they would probably have been dislodged by concentrated runoff, mudflows, or cryoejection on the steepest slopes (Rovéra et al., 1999; Descroix and Mathys, 2003). In the thalwegs, (iii) they would have been swept away by floods with high sediment load (Oostwoud Wijdenes and Ergenzinger, 1998). Several 5- to 10-m-long transects at 1-m intervals were installed parallel to the fall line on the gully slopes with 25-cm-long (Ø 6 mm) stakes driven 20 cm into the ground. The distance from the top of the stake to ground level was monitored using a 0.02 mm resolution depth gauge, yielding a 7-year average denudation rate (2002-2009) for each stake. To compare both methods, three linear regression models ErS1, ErS2 and ErS3 involving slope (S) and erosion rate (Er) were derived from the reconstructed dendrogeomorphic data (ErS1, ErS2) and the monitoring of denudation rates (ErS3).

4. Results

4.1. Anatomical changes in buried sections

The evolution of cell lumen area in earlywood tracheids is exemplified with roots R15 and R16 in Figs. 3 and 4, respectively. In the buried part of R15, two different patterns can be discerned. For the samples located between -1 mm (15.1.5) and -25 mm (15.1.6) under the current soil surface, cell lumen area decreased in 1975 and 2005, respectively. Between -51 mm (15.1.7) and -99 mm (15.1.11), in contrast, wood anatomy of roots does not exhibit any marked reductions. In R16 (Fig. 4), all buried sections located at vertical distances \leq 33 mm under the current soil surface show a distinct reduction in cell lumen area in earlywood tracheids at different positions of root R16 near the soil surface (-1 to -33 mm), showing that cell lumen area drastically drops to <60% in 2002 as compared to the average of the 3 years preceding the 2002 event. Growth reduction is much smaller in the samples that were located between -33 and -51 mm under the soil surface (about -40%). For all samples covered by >33 mm of sediment, no significant variations in 2002 could be detected for cell lumen area. Table 2 illustrates that the threshold exemplified for root R16 in Fig. 5 can be found in the whole data set and that 24 of the 27 cross sections located in the colluvial layer at vertical depths ranging from -1 to -30 mm show a significant and persistent decrease in cell lumen area. For samples covered with more sediment, growth reductions appear to be exceptional and could only be observed in one cross section (16.1.19).

4.2. Erosion rates determined from exposed roots and stake monitoring

The wood anatomical structure of the exposed root 16.1.4 is shown in Fig. 6 for the years 1992–2005. This sample was taken on an interfluve (Fig. 6A, B) and shows thin cell walls and large cell lumens in earlywood tracheids until 1998. From 1999 onward, growth rings show a more stem-like wood structure, with very distinct latewood and cell lumen area of earlywood tracheids being reduced to about 50% (Fig. 6C, D). Based on its position on the interfluves and the present soil surface, we infer that the growth ring of 1999 was formed at the time when the root was located in the colluvial layer at a vertical depth of -13 mm below the soil surface.

Similar reductions in cell lumen area as that described above are observed for all exposed roots chosen for analysis between 1971 and 2004 (mean: 1989) and can be seen, e.g., in some exposed parts of root R15 (15.1.1, 15.1.3 and 15.1.4; Fig. 3) and between 1995 and 2000 in root R16 (16.1.1 to 16.1.5; Fig. 4). The height of the exposed part of roots as measured in the field (E_x) varies between 32 and 266 mm. According to hypothesis H1, this height was corrected to take into account the relative uplift of the root axis related to root growth after exposure and bias-adjusted ($\epsilon = 30$ mm). The resulting erosion rates, E_{ra1} , range between 1.8 and 13.8 mm y⁻¹ (mean: 5.9 ± 2.6 mm y⁻¹; Table 1). Erosion rates range from 1.8 to 5.2 mm y⁻¹ (mean: 4.1 ± 1.5 mm y⁻¹) on the interfluves and vary between 2.2 and 13.8 mm y⁻¹ (mean: 6.3 ± 2.7 mm y⁻¹) on gully slopes.

According to hypothesis H2 (i.e., stability of the root axis), the height correction factor needed to account for changes as root denudation is much lower and results in bias-adjusted erosion rates E_{ra2} ranging from 2.8 to 15.0 mm y⁻¹ (mean: 6.9 ± 2.6 mm y⁻¹). The resulting average erosion rate for interfluves is 5.0 ± 1.4 mm y⁻¹ and reaches 7.4 ± 2.7 mm y⁻¹ on the gully slopes. Without bias-adjustment (not presented here), E_{ra1} and E_{ra2} ranges between 0.75 and 7.8 mm y⁻¹ (mean: 4 ± 2.1 mm y⁻¹, 2.4 ± 1.1 mm y⁻¹ on the interfluves, 4.5 ± 2.1 mm y⁻¹ on the slopes) and between 0.8 and 8.4 mm y⁻¹ (mean: 4.4 ± 2.2 mm y⁻¹, 2.9 ± 1.3 mm y⁻¹ on the interfluves, 4.9 ± 2.2 mm y⁻¹ on the slopes), respectively.

The mean ablation rate obtained with annual monitoring of 46 iron stakes between 2002 and 2009 is $5.7 \pm 2.3 \text{ mm y}^{-1}$ (Table 3). On the interfluves, erosion rates E_{ra3} range from 2.6 and 5.1 mm y⁻¹ (mean: $4.1 \pm 1.6 \text{ mm y}^{-1}$). On the slopes, the average erosion rate is 6.2 mm y⁻¹, but values locally exceed 10 mm.



Fig. 5. Mean lumen area of earlywood tracheids of root R16 in A.D. 2002 as compared to the three previous years.

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Table 2

Depth of the buried root sections and number of growth rings formed since earlywood cell area reduction.

section since earlywood cell area reductio 15 15.1 15.1.6 -25 5 15 15.1 15.1.7 -51 0 15 15.1 15.1.8 -65 0 15 15.1 15.1.9 -94 0 15 15.1 15.1.11 -99 0 16 16.1 16.1.7 -88 0 16 16.1 16.1.8 -85 0 16 16.1 16.1.8 -85 0 16 16.1 16.1.9 -87 0	
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N° of tree	N° of root	ID of cross section	Depth	Number of years since earlywood cell area reductior
23	23.1	23.1.4	-58	0
23	23.1	23.1.5	-125	0

4.3. Comparison of the models

The Student's *t*-test shows that erosion rates E_{ra1} and E_{ra2} obtained with dendrogeomorphic methods do not show significant differences from systematically monitored erosion rates E_{ra3} at a significance level of 95%. Table 4 displays average erosion rates for 10° slope classes. For both hypotheses H1 and H2, average erosion rates exhibit a positive relationship with slope angle. For H1, Er1 increases from an average of 4.1 mm y⁻¹ in slope class 0-10° to 8.7 mm y⁻¹ on slopes >40°. For H2, Er2 is on average 5 mm y⁻¹ in slope class 0-10° and 9.8 mm y⁻¹ on slopes >40°. Fig. 7 presents two linear regression models, ErS1 and ErS2, involving slope and erosion rate derived from:

$$E_{ra1} = 0.1 S + 3(ErS1)$$
 (2)

$$E_{ra2} = 0.11 \,\text{S} + 3.79 (\text{ErS2}) \tag{3}$$

where, E_{ra1} , E_{ra2} : Erosion rates in mm/y derived from H1 and H2, respectively; and S: slope in degrees.

The coefficients of correlation for both models are 0.62 and 0.65, respectively. They are significant at the 0.05 level. The root mean squared errors (RMSE) are 2.1 mm y^{-1} for ErS1 and 2.0 mm y^{-1} for ErS2.

The average erosion rate derived from stake monitoring is also positively correlated with slope angle. Er3 increases from an average of 2.2 mm y^{-1} for slope class 0-10° to 7.8 mm y^{-1} for slopes >40° (Table 4). The resulting linear regression model ErS3 was derived from the monitoring of iron stakes and given as follows (Fig. 7):

$$E_{ra3} = 0.11 \,\text{S} + 2.8(\text{ErS3}) \tag{4}$$

The coefficient of correlation of the model is 0.52 and the model is significant at the 0.05 level (RMSE 1.9 mm y^{-1}). For H1 and H2, obtained with dendrogeomorphic results, the slopes of the regression lines are close to that derived from the monitoring approach. Without bias-adjusting, the slopes are lower, 0.08 and 0.06, according to H1 and H2, respectively.

5. Discussion

5.1. Occurrence of anatomical changes in buried roots

In the study we present here, the wood anatomical reaction of roots subject to denudation was used to determine the timing of exposure and erosion rates in Black Marls formations of the Southern French Alps. For the first time, results obtained with dendrogeomorphic techniques have been checked for consistency and accuracy through a comparison of data with results obtained with systematic measurements of erosion rates with iron stakes.

The use of anatomical reactions of conifer roots in the assessment of exposure dates is not new, but has never been independently checked in the past for (i) reliability and (ii) accuracy of reconstructed erosion rates as well as for (iii) validity of basic assumptions (i.e., a change in cell structure corresponds to the year of exposure). In previous research (e.g., Gärtner et al., 2001; Gärtner, 2007), abrupt reductions of cell lumen area of earlywood tracheids were considered a reliable indicator for the determination of exposure dates of conifer



Fig. 6. Decrease of mean lumen area of earlywood tracheids in cross section 16.1.4: (A) overview of the root section; (B) detail of the section after sanding; (C) microsection; and (D) evolution of the mean lumen area of earlywood tracheids.

roots. The same indicator was used in this study, in marly badlands prone to continuous denudation.

However, in contrast to the assumption used in previous research, we based our analysis on a systematic and high resolution, quantitative assessment of changes in cell lumen area in exposed as well as buried roots sampled at various depths below the current soil surface. Data clearly demonstrate that the reduction in

cell lumen area of earlywood tracheids starts to occur as soon as roots approach the soil surface and the remaining soil cover is reduced to <30 mm. At the study site, soils close to surface level are composed of a very porous and loose detrital layer mainly composed of angular marl fragments contained in a silty matrix and with c- and b-axes of up to 3 cm (Oostwoud Wijdenes and Ergenzinger, 1998).

Table 3

Characteristics of the marking stake network and erosion rates determined from monitoring activities since 2002.

Transect N°	Stake ID	Topographic conditions	Slope (°)	Erosion rate (mm y ⁻¹)
A	1	Interfluve	13	6.1
А	2	Interfluve	15	5.9
А	3	Interfluve	16	6.1
А	4	Gully slope	31	6.0
А	5	Gully slope	41	7.9
А	6	Gully slope	41	4.5
А	7	Gully slope	37	4.2
A	8	Gully slope	28	3.1
В	9	Interfluve	15	5.2
В	10	Gully slope	26	6.4
В	11	Gully slope	33	4.9
В	12	Gully slope	33	4.5
В	13	Gully slope	30	4.7
С	14	Gully slope	21	3.3
С	15	Gully slope	24	4.9
С	16	Gully slope	22	6.4
С	17	Gully slope	27	6.6
С	18	Gully slope	31	10.0
С	19	Interfluve	7	2.1
С	20	Gully slope	26	4.0
D	21	Gully slope	32	3.5
D	22	Gully slope	35	11.5
D	23	Interfluve	15	3.6
D	24	Gully slope	22	9.7
D	25	Gully slope	19	4.6
D	26	Gully slope	18	6.7
D	27	Interfluve	14	4.9
D	28	Gully slope	19	7.8
E	29	Gully slope	22	4.8
E	30	Gully slope	19	3.9
E	31	Gully slope	36	6.0
E	32	Gully slope	23	2.8
E	33	Gully slope	21	5.2
F	34	Gully slope	26	6.3
F	35	Gully slope	33	9.0
F	36	Gully slope	40	8.9
F	37	Gully slope	42	7.9
F	38	Gully slope	43	10.9
F	39	Interfluve	10	2.7
F	40	Gully slope	24	6.5
G	41	Interfluve	16	2.6
G	42	Gully slope	30	6.1
G	43	Gully slope	45	6.3
G	44	Gully slope	43	6.6
G	45	Interfluve	6	1.9
G	46	Interfluve	11	3.5
Average			26	5.7

As a result, roots located in this detrital layer are likely to be exposed to higher temperature variations and moisture oscillations. For example, in the Bouinenc catchment contiguous to the Moulin basin, Rovéra and Robert (2005) measured 23 freeze–thaw cycles at a depth of -10 cm in the fragmented regolith during winter 2000-2001, 61 cycles at -5 cm, and 92 cycles in the loose detrital cover at -1 cm. Similarly, the soil surface was dry during a dry winter period in 2001, but the moisture content remained stable around 6% at -5 cm depth.

Table 4

Mean erosion rates for 10° slope classes according to hypotheses H1 and H2 and data from the marking stake network.

Slope class (°)	Mean erosion rate 1 (E _{ra} 1, mm y ⁻¹)	Mean erosion rate 2 (E _{ra} 2, mm y ⁻¹)	Mean erosion rate 3 (E _{ra} 3, mm y ⁻¹)
0-10	4.1	5	2.2
10-20	3.8	4.5	5.1
21-30	5	6.2	5.4
31-40	6.4	7.3	6.8
>40	8.7	9.8	7.8

These temperature and moisture changes increase the vulnerability of the xylem of woody plants. The formation of ice crystals in sap is known to lead to the creation of air bubbles in xylem conduits. These bubbles nucleate cavitation, leading to gas-filled conduits that impede water transport (Zimmermann, 1983). Similar processes related to water stress in woody tissues growing close to the soil surface can cause tracheid cell embolism following cavitation that induces xylem dysfunction (Tyree and Sperry, 1989). The vulnerability to these freezing and water stress-induced embolisms in woody plants rises with increasing conduit diameter (Pitterman and Sperry, 2003; Mayr et al., 2007). In this respect, Antonova and Stasova (1993) reported that earlywood cell size in stems of *P. sylvestris* growing in central Siberia clearly depends on air temperature and moisture at the start of the growing season. Similarly, the reduction of cell lumen area of earlywood tracheids of roots located in the loose detrital layers close to the soil surface can be interpreted as a response of the vascular system of *P. sylvestris* to thermal and hydric stresses (Antonova and Stasova, 1997), which would increase with thinning soil depth. In contrast to assumptions formulated in previous research, this study ascertains that the reduction of cell lumen area in earlywood tracheids is not related to the moment of actual root exposure and that wood anatomical changes are initiated while the root is still covered by a thin (>30 mm) soil layer.

5.2. Stability of the root axis

The potential influence of root diameter growth following partial denudation and related subsequent uplift of roots on reconstructed mean erosion rates was tested with hypotheses H1 and H2. Interestingly, reconstructed values are very similar between the two approaches and differences in results obtained for H1 and H2 are not statistically significant. Comparison of the dendrogeomorphic erosion rates under H1 and H2 with annual stake measurements does not allow drawing conclusions on the relative uplift of the root axis after exposure either. There is scope and reason to believe that an uplift only occurs if mechanical resistance of the superficial formations to compaction exceeds root growth pressure (e.g., Bengough et al., 1997; Clark et al., 2003). At the Moulin basin, weathering of black marls with clayed shale facies leads to several superposed layers with density and compactness increasing from 0 to 5 MPa in the loose detrital cover to >35 MPa in the resistant marl bedrock (Maguaire et al., 2002), but thickness and compactness of superficial formations exhibit strong spatial heterogeneity as they depend on local structural and topographic conditions. In comparison, the maximum radial pressure exerted by tree roots is comparably small with ca. 0.8 MPa (MacLeod and Cram, 1996).

In addition, uplift of the root axis will also depend on the ability of a root to keep contact with the soil surface after exposure. The roots sampled for analysis were mostly lateral surface roots from the upper part of the taproot and were growing parallel to the ground surface. They are the first to explore the upper, nutrient-rich layers of the soil, and because of their rapid rate of secondary thickening, they become major structural members of the root system for support and anchorage (Coutts and Nicoll, 1991). Such lateral roots are very rigid and often present cross-sectional shapes in the form of T-beams after exposure — well designed to compensate for soil lowering (Nicoll and Ray, 1996).

5.3. Reliability of erosion rates derived from dendrogeomorphological measurements

Average erosion rates derived from both hypotheses are, respectively, 5.9 mm y⁻¹ for H1 and 6.9 mm y⁻¹ for H2. The comparison of dendrogeomorphic results with denudation rate data obtained from a series of systematic iron stake measurements confirms the reliability and accuracy of our reconstructed results. At the plot scale, bias-adjusted (ε),



Fig. 7. Comparison of linear regression models resulting from anatomical changes in roots (ErS1, ErS2) and marking stakes (ErS3). ErS1 is derived from hypothesis H1 and assumes that the radial growth pressure exerted by the root is lower than the mechanical impedance of the soil. ErS2 is derived from hypothesis H2 and assumes the stability of the root axis through time. Both models are significant at the 0.05 level.

average erosion rates derived from both hypotheses match with data obtained from denudation measurements performed across a network of 46 marking stakes. On the contrary, without bias-adjustment, the erosion rates are underestimated on both interfluves and slopes.

Our results also agree with data from several other studies using denudation measurement devices in similar locations of the Southern French Alps over variable periods of monitoring: Descroix (1994) and Descroix and Olivry (2002) obtained erosion rates of 4-17 mm y⁻¹ at six study sites monitored over 6 years; Rovéra et al. (1999) measured erosion rates of 3-10 mm y⁻¹ in the Saignon catchment between 1997 and 1998; and Bufalo (1989) measured soil losses on bare marls of 11.5 mm y⁻¹ in small catchments and based on data obtained over a 3year measurement campaign. When analyzed in greater detail, we realize that erosion measurements and linear regression models ErS1 and ErS2 (taking account of slope and erosion rate) exhibit a strong variability, especially for the high slope classes. As the measurements of soil erosion were realized on bare marls, we may argue that this standard deviation mainly stems from the dip and structural configuration of the outcrop (Rovéra et al., 1999; Descroix and Mathys, 2003; Boix-Fayos et al., 2007). Indeed, the angle formed by slope and dip has been demonstrated to represent an important discriminating factor for erosion rates. Surfaces parallel to the dip, are usually more resistant to weathering, while cross-cut outcrop is more subject to both freezing and wetting front penetration (Descroix, 1994).

At the catchment scale, erosion values obtained with dendrogeomorphic techniques are slightly lower than the average sedimentation rate measured in the retention dam at the outlet of the Moulin basin since 1988 (i.e., 4.1 mm y⁻¹ when only the bare marl surfaces are considered; Mathys, 2006). This discrepancy should be due to temporary sediment storage within the catchments, thus resulting in an underestimation of erosion rates at the outlet of the Moulin basin (Oostwoud Wijdenes and Ergenzinger, 1998). Our results show much better fits when compared with the rates measured in dams by Cemagref (Mathys, 2006) at the outlets of the nearby Roubine $(0.13 \text{ ha}, 6.3 \text{ mm y}^{-1})$ and Laval basins $(86 \text{ ha}, 6.4 \text{ mm y}^{-1})$. Interestingly, they also coincide with Combes (1981) estimates (6.8 mm y⁻¹) for the erosion of bare marls in the Saignon catchment (Sasse Valley, Alpes de Haute-Provence). His estimates were derived from the entire volume of sediment (180,000 m³) deposited in the Saignon dam, located at the outlet of a 3.6-km² basin, between its construction in 1962 and complete filling in 1979.

6. Conclusion

The analysis of anatomical changes in exposed tree roots for the quantification of erosion rates is recent. In the past, the approach was mainly used for the reconstruction of abrupt and severe erosion pulses resulting from gullying or torrential activity, but less frequently for a quantitative analysis of continuous and areal erosion processes. In this study, we demonstrate that decennial erosion rates from exposed roots of *Pinus sylvestris* can be determined with high accuracy and precision in marly badlands and that results do not differ significantly from erosion time series obtained with more sophisticated and continuous measurements obtained from iron stakes on slopes or sediment yield measurements at the outlet of basins.

The study was also successful in demonstrating that, in the case of continuous denudation, the decrease of mean lumen area of earlywood tracheids - traditionally used as the main indicator for the determination of the year of exposure (Gärtner, 2007) - starts to occur in roots that are still <30 mm below the soil surface. Future studies will need to take this bias into account and determine the depth under the current soil surface at which roots start to develop stem-like structures so as to avoid spurious errors in erosion rate reconstructions and related underestimation of ground lowering. While we also realize that the behaviour of the root axis after denudation remains highly variable depending on root pressure and mechanical impedance of the soil, results clearly show that this uncertainty does not have a significant influence on reconstructed values of erosion rates. The regression model presented uses the slope as an independent variable and properly predicted erosion rates. A general consensus exists about erosion rates on black marls, in the French Alps subject to Mediterranean climatic influences. Our model could therefore be used in future research to determine and to map soil erosion in this part of the Alps without the need for expensive instrumentation. We therefore believe that the present study also confirms the usefulness and importance of dendrogeomorphic approaches for the quantification of erosion in marly environments, particularly for catchments where instrumental data are scarce or completely missing.

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