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Response of *Pinus sylvestris* roots to sheet-erosion exposure: an anatomical approach

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Abstract. Anatomical changes of exposed tree roots are valuable tools to date erosion events, but the responses of diverse species under different types of erosion need still to be studied in detail. In this paper we analyze the histological changes that occur in roots of Scots pine (*Pinus sylvestris* L.) subjected to continuous denudation. A descriptive and quantitative study was conducted in the Senda Schmidt, a popular trail located on the northern slope of the Sierra de Guadarrama (Central Iberian System, Spain). Measurement of significant parameters allowed the moment of exposure of the roots to be identified. These parameters were: a) width of the growth ring; b) number of cells per ring; c) percentage of latewood and d) diameter of cellular light in earlywood. A one-way analysis ANOVA was also carried out in order to establish statistically significant differences between homogeneous groups of measurements in pre-exposed and exposed roots. Based on these analyses, Scots pine roots show a remarkable anatomical response to sheet-erosion exposure. Increased growth in the ring is accompanied by a slight reduction of the cell lumina of the earlywood tracheids. At the end of the ring, several rows of thick-walled tracheids define latewood tissue and visible annual borders very clearly. Furthermore, resin ducts often appear in tangential rows, increasing resin density in the tissue. All of these indicators made it possible to determine with precision the first year of exposure and to estimate precisely sheet erosion rates.

1 Introduction

Degradation of trekking trails, mainly due to sheet erosion and hiking activities, damages the natural and recreational value of protected natural areas and poses a serious challenge for recreation resource management (Leung and Marion, 2000; Dixon et al., 2004). One example is Senda Schmidt, a trail located in central Spain whose degree of degradation has risen since the 1970s from recreational impact (Bodoque et al., 2002).

To manage trekking trails adequately, managers need to obtain objective and reliable information on track conditions (Cole, 1986). This information permits examination of factors that influence the type, severity, and extent of trail impact. Additionally, such data can be useful to detect changes before impacts become severe or irreversible, to identify trends, and to evaluate the effectiveness of trail management policies (Leung and Marion, 1999).

One of the most important walking track impacts is sheet erosion, which leads to lower environmental value of protected areas as tracks become bare and eroded. There are various methods of studying sheet erosion, ranging from prediction to direct measures (Toy et al., 2002). Different prediction models based on either a conceptual, empirical or a physically based framework can be implemented (Wischmeier and Smith, 1978; Morgan et al., 1998; Parsons et al., 2004). Direct measures are based on the implementation of dynamic and volumetric methods: the first type refers to experimental erosion plots (Stroosnijder, 2005; Desir and Marín, 2007) and the second to erosion pins and microtopographic profiles (Benito et al., 1992; Sirvent et al., 1997).

As direct measures and prediction methods approach the problem from different perspectives, they have separate characteristics and biases. Direct methods are expensive, and the

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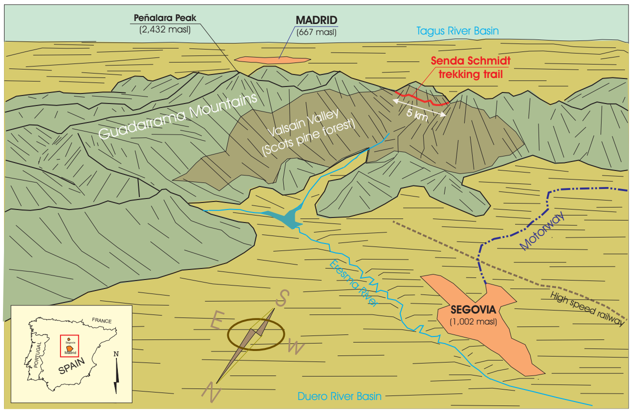

Fig. 1. Location of the sampling site in the Valsaín forest, in the Guadarrama Mountain Range.

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

results are only representative of the sites where they are used. Therefore, spatial and temporal extrapolation of the measures is not always possible. The main shortcoming of indirect methods (based on prediction) is the lack of high precision data or of time series long enough to calibrate and validate the models.

Dendrogeomorphology (Alestalo, 1971) has one main advantage over other erosion measurement techniques. The dendrochronological analysis of exposed roots permits erosion rates within the territory and their variations to be estimated, on both the spatial and temporal level (Bodoque et al., 2005). Exposed roots have been used in dendrogeomorphology since the 1960s to determine erosion rates. The method employed is based on the change in the ring-growth pattern (from concentric to eccentric) when the root is exposed. The quotient of the vertical distance between the upper part of the root and the present ground surface divided by the temporal interval of root exposure offers an estimation of the erosion rate in mm/year (LaMarche, 1963, 1968; Eardley and Viavant, 1967; Carrara and Carroll, 1979; McCord, 1987; Danzer, 1996; Bodoque et al., 2005; McAuliffe et al., 2006; Pelfini and Santilli, 2006; Pérez-Rodriguez et al., 2007).

However, change in the ring-growth pattern can not take place simultaneously with root exposure and does not always occur precisely when the root is exposed. This generates uncertainties and errors in the estimation of erosion rates (Bodoque et al., 2005). An alternative and complementary approach is the analysis of the changes in the anatomical structure of the rings due to exposure (Gärtner et al., 2001; Gärtner, 2003, 2007). From a dendrogeomorphological point of view, this modification in the anatomical structure of the root allows the first year of exposure to be determined with precision, and, as a result, estimation of erosion rates is improved (Bodoque et al., 2005; Gärtner, 2007).

These changes are more easily identifiable and best known in softwoods where strong tissue responses appear and where reduction in cell size takes place when a root is exposed (Gärtner et al., 2001; Gärtner, 2007; Hitz et al. 2008). Nevertheless, these studies are not limited only to coniferous trees. Recent studies show that the first year of exposure can be also determined by analyzing anatomical changes in exposed roots of hardwoods (Sahling et al., 2003; Hitz et al., 2008).

The objective of this paper is to describe the anatomical response of exposed roots of *Pinus sylvestris* to a particular continuous denudation event, sheet erosion on hiking trails, in order to estimate the first year of exposure. This methodology has been tested on a popular trail in a Scots pine forest (Senda Schmidt, Spain). The paper aims to provide a methodology and results that are useful to the environmental authorities who manage this trail and its surroundings, as well as to other researchers who use exposed roots to determine erosion rates.

2 Site description

The study was conducted in the Senda Schmidt, in the upper part of the Valsaín forest, which is located on the northern slope of the Sierra de Guadarrama (Central Iberian System, Spain). The Valsaín forest (Latitude N 40°79′, Longitude W 4°05′) is a 10 700 ha mountain woodland that is managed for timber production, wildlife conservation, and recreation, and is administered by the Organismo Autónomo Parques Nacionales. Senda Schmidt (Fig. 1) is on the northern slopes of the Siete Picos Mountains where Scots pine forest is predominant. The upper zone is a shrub-dominated community of broom (*Cytisus oromediterraneus* Rivas-Martínez) and prostrate juniper (*Juniperus communis* subsp. *alpina* (Suter) Celak), with open montane grasslands characterized by *Festuca* gr. *indigesta* Boiss.

Senda Schmidt is one of the most popular mountain trails in the Sierra de Guadarrama, running east to west and connecting Navacerrada and Fuenfría mountain passes. Although used heavily since the 1970s for trekking and mountain biking, the trail has hosted recreational activities since the late nineteenth century. Along this trail a large number of roots have been exposed due to accelerated erosion, a consequence of trampling from hiking (Fig. 2).

This area is 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 track rises from 1780 m to 1870 m above sea level. The hillside mostly faces north and its average slope is 23°. Climate is montane Mediterranean; the average annual temperature is 6°C, and the average rainfall is about 1400 mm/year, concentrated from 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.

3 Materials and methods

Samples of 18 root specimens from different trees were taken along the trail. Sampled trees were distributed uniformly along the trail, spaced on average 150 m from each other. All the roots were oriented in the direction of the maximum slope of the hillside and were sampled at a distance far enough away from the stem to avoid a possible stem-related mechanical effect. The specimens were cut with a hand saw into sections approximately 15 cm long, from which two disk samples of about 2 cm wide were extracted. They were processed following the methods described by Gärtner et al. (2001). One slice was used for dendrogeomorphological studies (see Bodoque et al., 2005) while the other one was prepared for microscopic analysis. The resin content of the xylem in some samples hindered the sectioning procedure, but this was resolved by immersing samples in different mixtures of water and alcohol until the desired quality was achieved.

Cross sections along the radial direction, aprox. 1 cm wide and 20 micra thick, were obtained using a sliding microtome. Slices were stained with safranin as described by Schweingrüber (1990) and dehydrated with alcohol (40 and 96 per cent) and a citrus oil clearing agent (Histoclear). After the staining procedure, sections were mounted on coated slides, coverslipped with a hardening epoxy (Eukit) and dried at ambient temperature. Samples were observed and photographed with a digital imaging system under optical microscopy. Measurements were made with the image analyzer on the digital photographs of the following parameters: a) width of the growth ring; b) number of cells per ring; c) percentage of latewood; and d) diameter of cellular light in earlywood. The occurrence of resin ducts was also assessed. The measurements taken were carried out perpendicular to the growth ring. The cell size measurements on tracheids were determined by measuring randomly the length of 12 cells per growth ring. A one-way analysis ANOVA with Multiple Range Tests (Method: 95 percent LSD) was performed

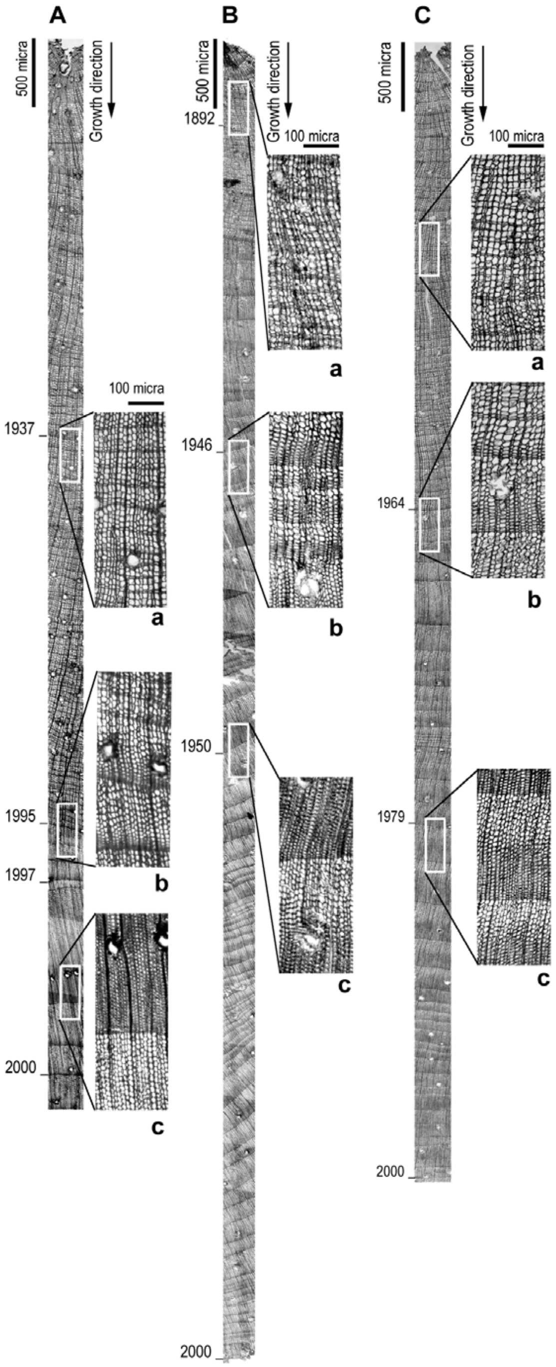

Fig. 3. Cross sections of three representative sampled specimens of exposed *Pinus sylvestris* exposed tree roots. In each micrograph, the three zones are recognized. **(a)** narrow growth rings, absence of latewood and ring boundaries hardly perceptible. **(b)** Appearance of latewood, defining a true ring boundary. Decrease of lumen on the earlywood tracheids. **(c)** Wide rings with latewood tissue with thick-walled cells defining clear ring boundaries. Micrographs A, B and C correspond to samples VAL10, VAL04 and VAL07 respectively.

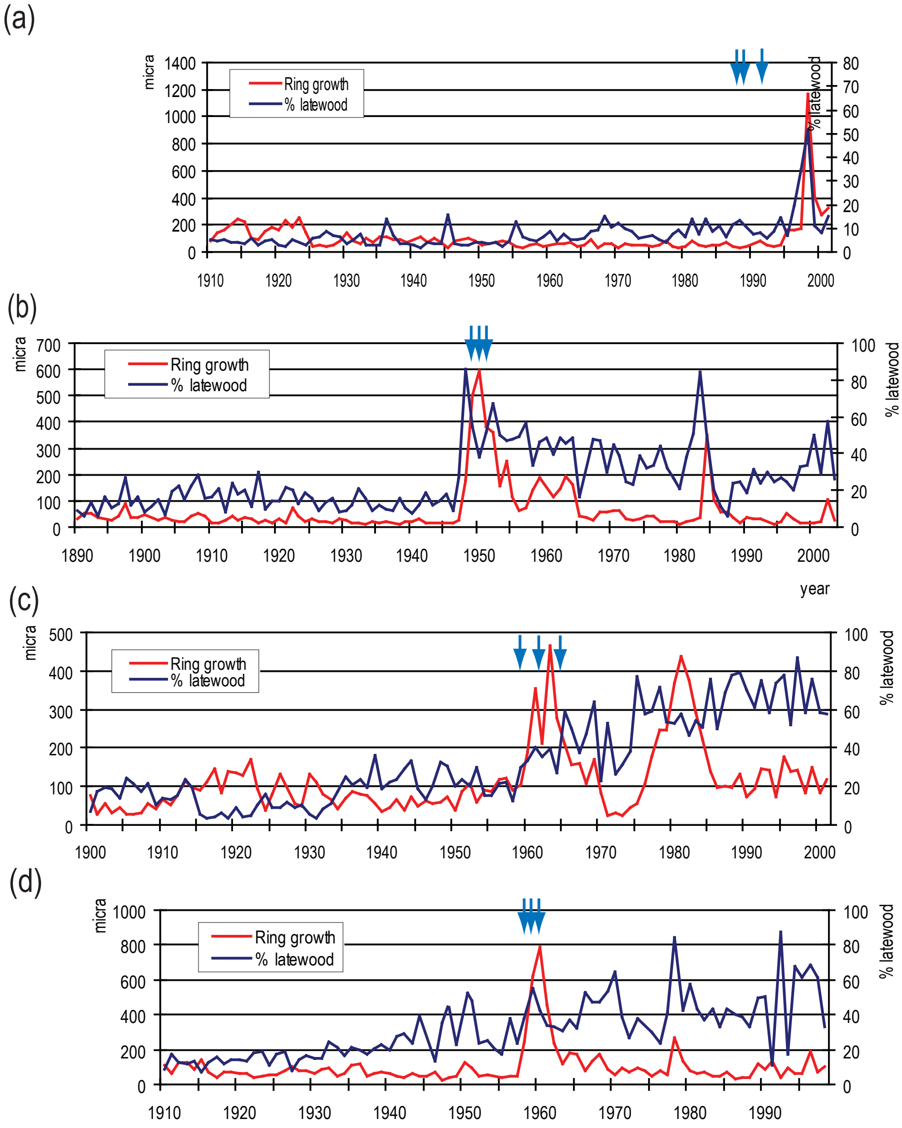

Fig. 4. Growth pattern over time of four selected samples. Sample **(a)** VAL10 shows a non-exposed pattern of growth during most of its life, changing at the end of the sequence. Samples **(b)** VAL09 **(c)** VAL06 and **(d)** VAL02 show different growth patterns, but always with an abrupt change in the first year of exposure. In (b) ring growth and latewood change at the same time. Arrows are located in the ring presenting a higher proportion of resin ducts.

for the variables considered in the anatomical analysis in order to verify the existence of a statistically significant difference between the two groups of measurements (in pre-exposed and exposed rings).

Rings forming the annual growth series were synchronized simply by counting. The dating of the ring series by visual examination alone can introduce a degree of uncertainty into the datings, as false or missing rings are not fully controled. Age can thus only be considered to be approximate.

4 Results

Most of the samples analyzed suffered severe cambial damage in the upper (first exposed) side of the root. This often involved the death of the cambium on the upper side, resulting in severe changes in the growth pattern, which shifted from concentric to eccentric growth. Figure 3 shows the annual growth rings of three representative roots of *Pinus sylvestris* growing very close to the trail path. The roots show increased growth and different anatomic features since the exposure year. Taking this into account, three zones can be identified.

Table 1. Matrix of comparisons of groups N (non-exposed ring) and E (exposed ring) for each sample of wood analyzed. The homogeneous groups are made under Fisher's least significant difference (LSD) procedure. Values in italic type indicate that this pair does not show a statistically significant difference at the 95.0% confidence level.

	No. Samples	Zone	Yearly growth (mm)		Growth ring width (number of cells)		Latewood rate (%)	
			Mean	Homogenous groups	Mean	Homogenous groups	Mean	Homogenous groups
VAL01	107	N	0.45	a	5.50	a	25.59	a
	10	E	1.88	b	30.90	b	49.32	b
VAL02	47	N	0.68	a	4.87	a	22.00	a
	12	E	2.74	b	26.92	b	45.92	b
VAL03	25	N	0.59	a	5.52	a	16.84	a
	12	E	3.40	b	53.00	b	36.50	b
VAL04	19	N	0.48	a	4.79	a	19.25	a
	30	E	1.15	b	15.00	b	45.15	b
VAL05	20	N	0.17	a	3.20	a	18.36	a
	9	E	0.68	b	28.33	b	37.70	b
VAL06	19	N	0.48	a	4.79	a	19.25	a
	14	E	1.16	b	15.00	b	45.16	b
VAL07	32	N	0.29	a	4.12	a	25.20	a
	20	E	1.14	b	17.20	b	43.73	b
VAL08	15	N	1.94	a	14.90	a	25.49	a
	6	E	2.90	b	25.00	b	55.61	b
VAL09	58	N	0.29	a	3.59	a	29.00	a
	18	E	2.11	b	30.56	b	48.56	b
VAL10	88	N	0.85	a	5.78	a	*18.90*	*a*
	4	E	5.43	b	49.25	b	*21.55*	*a*
VAL11	43	N	0.184	a	5.85	a	2.28	a
	17	E	1.288	b	33.76	b	45.06	b
VAL12	40	N	0.314	a	5.57	a	8.17	a
	26	E	0.878	b	27.23	b	58.24	b
VAL13	73	N	0.181	a	4.33	a	4.28	a
	27	E	0.986	b	21.33	b	44.11	b
VAL14	42	N	0.344	a	8.57	a	*29.45*	*a*
	26	E	1.283	b	33.50	b	*30.92*	*a*
VAL15	33	N	0.555	a	12.24	a	*39.88*	*a*
	20	E	1.471	b	32.3	b	*44.97*	*a*
VAL16	46	N	0.215	a	5.08	a	5.11	a
	41	E	0.612	b	13.19	b	31.63	b
VAL17	26	N	0.794	a	7.61	a	*23.60*	*a*
	21	E	1.992	b	21.05	b	*30.06*	*a*

Zone 1 presents the usual tissue of buried *Pinus sylvestris* roots. Growth rings are quite narrow, there are a low number of tracheids per ring and latewood cells are usually limited to one or two discontinuous rows of thin-walled cells, occupying a very small proportion of the whole ring. Resin canals appear along the rings but are never arranged in tangential bands. As latewood cells are few and thin-walled, growth ring boundaries are frequently hardly distinguishable.

Zone 2 shows remarkably increased growth that is particularly noticeable in one, two or three successive rings. Resin ducts often appear in tangential rows in earlywood, increasing in density in the tissue. At the end of the ring, several rows of thick-walled tracheids define latewood tissue and visible annual borders very clearly, and some false rings (rows of small, thick-walled cells, typical from latewood, growing into earlywood) are detected. The increase of cells in the ring and the thickening of the tracheids walls are accompanied by a reduction of the cell lumina.

In zone 3, which occurs after the strong and obvious change in the overall anatomical structure, the growth pattern is not constant. Latewood tissue and numerous thick-walled cells are however always identified in the exposed tissue. In some specimens (Figs. 3, 4), high growth-ring rates, resin duct occurrence and the other features characteristic of exposure are maintained over time. In others, narrow and wide growth rings alternate, and the ratio earlywood/latewood and cell size is variable. The origin of the different types of growth anomalies following exposition can not be determined precisely although trampling, rather than geomorphic processes, seems to be the cause of the damage.

5 Discussion

Pinus sylvestris roots exposed because of sheet erosion appear to follow a similar pattern to that recorded in research on other softwood species (see Fayle, 1968; Gärtner, 2001; Gärtner et al., 2003; Hitz et al., 2008). Furthermore, in this case, the change in the anatomical structure is correlated with the overall growth shape structure (shift from concentric to eccentric) and thus helps to validate the analytic models to assess local erosion rates based on macroscopic analysis (Bodoque et al., 2005) .

In this case study, we considered sheet erosion to be the main origin of disturbance leading to important anatomical changes in our roots. The increase in width of the growth ring (in absolute terms and in number of cells per ring) and the percentage of latewood are significant parameters indicating the first year of exposure (Table 1). Moreover, when exposure is about to occur following a continual lowering of the soil surfaces, a common root structure (sensu Gärtner, 2003) is discernible along the record. Shape and thickness of the latewood tracheids and its cellular lumina markedly change when continuous denudation affects buried roots. Latewood tracheids become thick-walled, several rows of which constitute a true tissue in which ring boundaries are easily distinguishable. The lumen of the earlywood cells always decreases, although we have detected cases in which it just barely occurs (Fig. 5).

The physiological interpretation of these anatomical changes could be related with the response of the coniferous vascular system to the stress that arises when environmental conditions change. The thinning of the soil depth around and in contact with the root will immediately provoke higher temperature and moisture oscillations that probably affect the processes of cytogenesis, as occurs in stems (see, e.g., Antonova and Stasova, 1993, 1997). For example, changes on earlywood and latewood tracheid sizes and wall thickness allow wood to be more resistant to xylem cavitation and mechanical damage. Under a synergic humidity and temperature stress from drought and freezing, xylem cavitation would make trees highly vulnerable. A narrowing of tracheid sizes protects against embolism and can be seen as an advantageous adaptation (Pitterman and Sperry, 2003; Willson and Jackson, 2006).

The *Pinus sylvestris* root (like all softwoods with the exception of *Taxus*) has a well developed resin canal system in both the bark and xylem tissues. The resin is comprised of terpenoid and phenolic compounds as well as fatty acids and esters. Flowing over the resin duct system to places of damage, the volatile terpenes can evaporate to leave a plug that hardens and constitutes a barrier to water and pathogens such as bacteria and fungi (Hillis, 1987; Pearce, 1996). Therefore, resin ducts located around the whole root circumference form barrier zones in the secondary xylem. Resin duct occurrence in *Pinus sylvestris* has been reported to be a valuable dendroecological variable (Rigling et al., 2003) but at the same time, some authors do not consider it as suitable for the dating of geomorphic processes (see Stoffel, 2008). In our case study, although resin duct production seems to be positively linked to radial growth, it does not always occur at the same time of exposure (see Fig. 4c and d) and alone, it does not seem to be a relevant feature for characterizing this erosive event. Resin ducts after exposure are not always tangentially arranged, and distinction between traumatic and spontaneous canals becomes also problematic. If the root does become exposed, tissues damaged by trampling can respond to wounding rather than to geomorphic events.

Exposed roots allow a reliable reconstruction of the relative position of the soil surface over time. However, some aspects are still unknown, and they must be correctly understood in order to assess precise erosion rates. The dating of the geomorphic processes is surely the crucial point in this process. False, double and wedge rings are sometimes detected and crossdating is not always possible, as the erosive processes that affect each tree do not have to occur simultaneously (see Bodoque et al., 2005). Hence, the study of the whole root sections, accompanied by anatomical analysis when possible, is strongly recommended. Recently, Gärtner (2007) presented a detailed overview of tree root applicability to model erosional processes, proposing new equations that improve on those LaMarche (1968) offered in the late 1960's. Using these methods, the resulting error is minimized, but some inaccuracies may still exist. Research areas that are still unexplored include soil strength (compressibility) and its role into the mechanical response facing secondary growth in roots, and how the organic matter balance influences soil development upwards. Further research on wood anatomical features related to the position of the roots in the soil and the overall study of the connected environmental factors can help to validate and develop the existing models, by providing a more detailed reconstruction of erosional processes and assessing erosion rates.

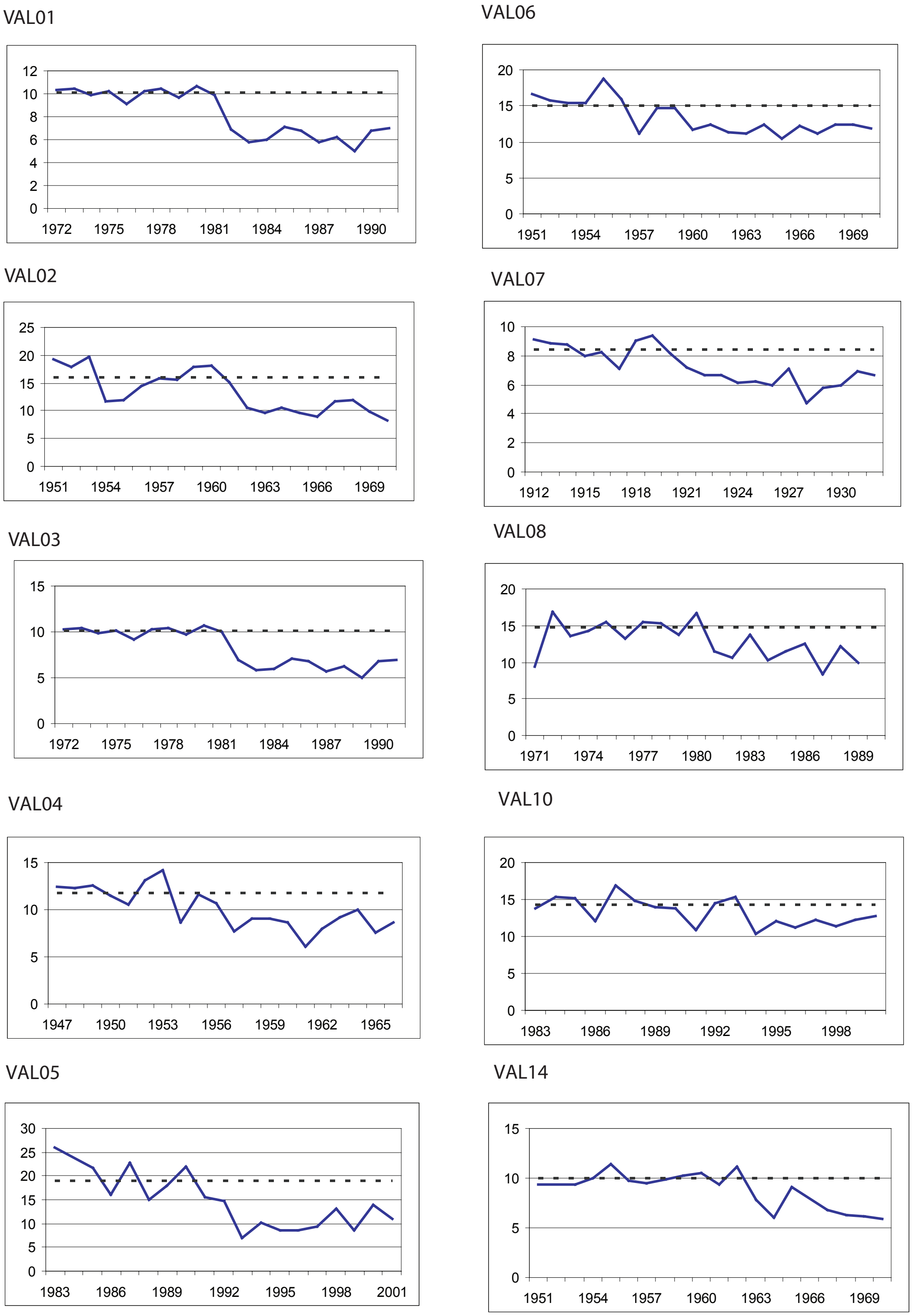

Fig. 5. Cell size variations of earlywood tracheids in *Pinus sylvestris* roots at the moment of exposure. The dotted lines correspond to the mean cell size before exposure. Ordinates are in micra.

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