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Dating and quantification of erosion processes based on exposed roots

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ABSTRACT

Soil erosion is a key driver of land degradation and heavily affects sustainable land management in various environments worldwide. An appropriate quantification of rates of soil erosion and a localization of hotspots are therefore critical, as sediment loss has been demonstrated to have drastic consequences on soil productivity and fertility. A consistent body of evidence also exists for a causal linkage between global changes and the temporal frequency and magnitude of erosion, and thus calls for an improved understanding of dynamics and rates of soil erosion for an appropriate management of landscapes and for the planning of preventive or countermeasures.

Conventional measurement techniques to infer erosion rates are limited in their temporal resolution or extent. Long-term erosion rates in larger basins have been analyzed with cosmogenic nuclides, but with lower spatial and limited temporal resolutions, thus limiting the possibility to infer micro-geomorphic and climatic controls on the timing, amount and localization of erosion. If based on exposed tree roots, rates of erosion can be inferred with up to seasonal resolution, over decades to centuries of the past and for larger surfaces with homogenous hydrological response units. Root-based erosion rates, thus, constitute a valuable alternative to empirical or physically-based approaches, especially in ungauged basins, but will be controlled by individual or a few extreme events, so that average annual rates of erosion might be highly skewed. In this contribution, we review the contribution made by this biomarker to the understanding of erosion processes and related landform evolution. We report on recent progress in root-based erosion research, illustrate possibilities, caveats and limitations of reconstructed rates, and conclude with a call for further research on various aspects of root–erosion research and for work in new geographic regions.

Contents

1. Introduction . . . 19
2. Principles and methods . . . 19
 2.1. Pioneering studies: bibliographic synthesis . . . 19
 2.2. Recent developments: root anatomy and exposure processes . . . 20
 2.3. Reconstructing erosion rates . . . 21
3. Main results of previous studies . . . 22
 3.1. Quantification of continuous denudation rates . . . 22
 3.2. Quantification of channel incision and gullying processes . . . 23
 3.3. Quantification of shore erosion . . . 24
4. Research avenues . . . 25
 4.1. Current limitations — future challenges . . . 26
 4.2. Thematic perspectives . . . 28
 4.3. Target areas for future research . . . 29
5. Conclusions . . . 31
Acknowledgment . . . 31
References . . . 31

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1. Introduction

Soil erosion and mass wasting represent key environmental issues worldwide (e.g., Green, 1982; Larson et al., 1983; Stoffel and Huggel, 2012) and primary drivers of land degradation (Verheijen et al., 2009). The related diminution of fertile lands has been reported to increase with rates comparable to the rapid growth of Earth's population, but is in diametrical opposition to its ever increasing needs for food production (Pimentel et al., 1995). A pressing need, thus, exists to cultivate steadily expanding areas of new land by clearing permanent vegetation cover, particularly in emerging countries. Such surfaces, however, tend to be highly prone to erosion, as they are typically located in environments where climate drives the occurrence of intense exogenous geomorphic processes, surface runoff is powerful and a decrease in resistance to soil erosion can be observed (Knapen et al., 2007; de Aguiar et al., 2010). Erosion is also controlled by a large array of extrinsic controls, such as the nature of cultivation, tillage, land use or the occurrence of fire (Radley and Simms, 1967; Battany and Grismer, 2000; Wu and Tiessen, 2002; Nearing et al., 2005; Shakesby, 2011).

Erosion not only leads to a loss of soil fertility, but also causes off-site effects in the form of downstream sedimentation (de Vente and Poesen, 2005), reduced hydraulic capacity of rivers and drainage ditches, increased flood risks (Sinnakaudan et al., 2003), the blocking of irrigation channels, as well as a reduction of design life of reservoirs (Shen et al., 2009; Romero-Díaz et al., 2012). Soil erosion also leads to the transport of chemicals (such as nitrogen or phosphorous) and thereby contributes to biogeochemical cycling (Quinton et al., 2010), which in turn may cause eutrophication of water bodies (Ghebremichael et al., 2010).

Water is one of the key drivers of soil erosion because it causes the detachment of soil particles by rain splash (Parsons et al., 1994; Sharma et al., 1995; Van Dijk et al., 2003; Nanko et al., 2008) and a downslope transport of soil particles by runoff. Runoff erosion occurs in unconcentrated flows (sheet erosion; Hairsine and Rose, 1992; Le Bissonnais et al., 1998) or concentrated flows (rills or gullies; Poesen et al., 2003; Valentin et al., 2005; Govers et al., 2007), and has been defined as the balance between erosivity (i.e. power of rain splash and runoff to erode soil) and erodibility (i.e. resistance of soils to erosion based on their physical and chemical characteristics such as soil texture, organic matter, or structure).

The presence and state of vegetation and related litter represent a primary soil-extrinsic factor and are, as such, closely and directly related to erosion processes (Thorne et al., 1985). An intact vegetation cover will protect soil against erosion (Francis and Thornes, 1990) by (i) intercepting and reallocating rainfall; (ii) reducing raindrop impact energy and thereby also rain splash effects (e.g., Michaelides et al., 2009; Dunne et al., 2010); (iii) improving aggregated soil stability through the incorporation of organic plant material during edaphogenesis, thereby enhancing soil shear stress and particle cohesion (Degens et al., 1994) as well as favoring soil conditions conducive for the creation of “islands of fertility” (Rango et al., 2006); and by (iv) enhancing soil stability and reducing soil erodibility by rain splash and runoff through the horizontal and vertical reinforcement of soils by roots (Gyssels and Poesen, 2003).

A detailed understanding of erosion processes, erosion rates as well as their drivers is crucial for a proper and appropriate environmental management designed to reduce and ultimately prevent soil loss, particularly with regard to thresholds above which soil loss will require costly and time-consuming remediation. Notwithstanding the huge efforts realized for the characterization of erosion rates in different environments, the capacity of extrapolating results to larger areas remains fragmentary, if nothing else as soil erosion is not only highly variable both in the spatial and temporal dimensions, but also with respect to its geographical position (Bryan and Yair, 1982).

Past monitoring and quantification of erosion rates have often been restricted to small-scale case studies using erosion pins and bars (Godfrey et al., 2008), devices connected to sediment collectors (Mathys et al., 2003), the analysis of drainage patterns and rill morphology (Kasanin-Grubin and Bryan, 2004), comparison of repeat series of digital elevation models (DEM) obtained from aerial photographs (Martínez-Casasnovas et al., 2009), geodetic field (Giménez et al., 2009) or highly-resolved terrestrial laser scanning (TLS) surveys (Lucía et al., 2011) as well as to studies tracing rare earth elements (Zhu et al., 2011). As a result of the great monitoring efforts required, observational time series of long-term erosion rates remain exceptional, and thereby prevent the creation of reliable data on average erosion rates at larger spatial and temporal scales (Cantón et al., 2011). The use of radioisotopes (^{137}Cs, ^{210}Pb and ^{7}Be), for instance, overcomes some of these spatial limitation by yielding erosion rates at the catchment scale and over longer periods (Theocharopoulos et al., 2003; Parsons and Foster, 2011; Fang et al., 2012), but possibly lacks the temporal resolution to identify causes and drivers of erosion needed in soil conservation and land-use management efforts. The replication of measurements and spatial resolution of results are, however, often hampered by the cost of measurements and heavy instrumentation. At the same time, the quality of datings has been reported to be affected by the downward migration of radionuclides by bioturbation or similar processes. For a review and extensive discussion of limitations of radionuclide dating, please refer to e.g., Mabit et al. (2008) and Baskaran (2012).

Other indirect methods might thus be needed to assess longer-term process activity, past erosion rates and the correlation and interdependence of the latter with environmental changes. One such approach is the dendrogeomorphic analysis (Alestalo, 1971; Stoffel and Bollschweiler, 2008; Stoffel et al., 2010) of exposed tree and shrub roots and the interpretation of anomalies registered in their growth rings. The primary application of dendrogeomorphic time series of exposed roots was to estimate sheet erosion rates, but exposure signals in roots have also been used to localize hotspots of bank erosion in torrential catchments (Malik and Matyja, 2008; Stoffel et al., 2012), slope processes on flysch formations (Silhan, 2012) or to infer dynamics of eolian sediment transport in drift-sand areas (den Ouden et al., 2007). Erosion data from roots typically yield medium-term erosion rates as well as high-accuracy estimates of soil lowering or deposition over large areas, provided that homogenous units in terms of erosive process dynamics can be delineated. Dendrogeomorphology also constitutes an alternative to direct estimation methods (e.g., erosion plots), as the latter require quite significant human and economic resources. The main drawback of root-based estimates of erosion lies in its limited temporal representativeness and the reconstruction of mean annual erosion rates, in particular in arid or semi-arid climates where a low number of rainfalls will drive a large proportion of erosion.

In this paper, we review the contribution made by this biomarker to the understanding of erosion processes and related landform evolution. Following a brief appraisal of the initial work on the root-based reconstruction of erosion, we (i) highlight recent advances in dendrogeomorphic research, (ii) summarize key findings obtained through the study of exposed roots, (iii) illustrate possibilities, limitations and caveats of the approach compared to other dating methods and (iv) conclude with a call for further research on various topics and for work in new geographic regions.

2. Principles and methods

2.1. Pioneering studies: bibliographic synthesis

The potential of roots as an indicator of degradation was recognized in the early decades of the twentieth century. In one of the pioneering studies focusing on radial root growth, Glock et al. (1937) concluded that roots would contain virtually no readable ecological information in their radial growth rings. A few years later, however, Schulman (1945) disproved Glock's conclusions and successfully synchronized ring widths from large roots of *Pseudotsuga menziesii* (Mirb.) Franco, thereby obtaining an epoch-making series of soil moisture changes and a fine record of year-to-year fluctuations in runoff for the upper Colorado River.

Using the seminal approaches developed by Schulman (1945), a large body of follow-up studies has focused on root-based soil erosion ever since (e.g., Hueck, 1951; LaMarche, 1961, 1963; Eardley and Viavant, 1967; LaMarche, 1968). Hueck (1951), for instance, employed exposed roots of shrubs to derive rates of eolian denudation in Patagonia. LaMarche (1961, 1963), on the other hand, focused on the asymmetry in transverse sections of millennia-old buttress roots from *Pinus longaeva* D.K. Bailey, to characterize local degradation rates in the White Mountains of California. LaMarche (1963) also realized that the vertical buttress form observed in exposed roots was indeed the result of (i) bark and cambium stripping after abrasion and weathering from the upper root surface and (ii) at the same time reflecting continued secondary growth on the lower root surface. Based on these observations of shape changes and discontinuity of growth rings, he produced the first estimate of root ages at the time of initial cambium reduction and the first quantitative measure (in mm yr^{-1}) of erosion rates over ~3000 yr. Reconstructed rates exhibited a high spatial variability (i.e. from 0.015 mm yr^{-1} on gentle slopes to 0.12 mm yr^{-1} along steep channel banks incised into alluvial fill), but fairly stable, long-term denudation rates at the local scale over much of the period covered by the reconstruction.

The techniques developed by LaMarche were revived by Dunne et al. (1978) to estimate erosion rates in the semi-arid rangelands in Kenya. Based on the minimum depth of soil erosion with respect to root exposure, they computed average erosion rates ranging from 8 to 14.7 mm yr^{-1} for the basement rocks and the Kilimanjaro lavas, respectively. The change of growth-ring shape from concentric to eccentric following exposure has been used since in a multitude of studies focusing among others on late Holocene sediment yield and transport in northern Arizona (McCord, 1987) or on slope erosion processes in smaller-scale drainage basins of badlands in the United States and Spain (e.g., Danzer, 1996; Bodoque et al., 2005; McAuliffe et al., 2006; Pérez-Rodríguez et al., 2007; Bodoque et al., 2011).

In an attempt to diversify the indicators of soil erosion in roots, Carrara and Carroll (1979) coupled the occurrence of eccentric ring growth with the initiation of reaction wood. In addition, they declared scars and cambium dieback as further indicators for the definition of initial root exposure in *Pinus edulis* Engelm. and *Juniperus osteosperma* (Torr.) Little. A complete list of root-based erosion studies is given in Table 1.

2.2. Recent developments: root anatomy and exposure processes

After decades of macroscopic analyses focusing on structural changes in roots and variations in ring width, the focus of root-based

Table 1
Overview of work published on dendrogeomorphic reconstructions of erosion (and sedimentation).

Process	Environment	Location	Latitude	Longitude	Rates	Units	References
Bank erosion	Riverbank	Patagonia	40°56' S	71°24′ W	–	–	Stoffel et al. (2012)
Bank erosion	Riverbank	Czech Republic	50°15′ N	15°05′ E	–	–	Malik and Matyja (2008)
Bank erosion	Riverbank (anatomical response)	Switzerland	47°00′ N	8°31′ E	–	–	Hitz et al. (2008a, 2008b)
Bank erosion	Riverbank	Switzerland and Germany	46°17′ N	7°32′ E	–	–	Gärtner et al. (2001)
Caribou trampling	Tundra environment	USA	54°30 N	69°00′ W	–	–	Boudreau et al. (2003)
Caribou trampling	Tundra environment	Canada	58°15′N	65°42′W	–	–	Morneau and Payette (1998)
Gully retreat	Gullies	Czech Republic	49°22′N	18°7′E	150–3000	mm yr^{-1}	Silhan (2012)
Gully retreat	Gullies	Poland	50°21′ N	17°51′ E	0.63	mm yr^{-1}	Malik (2008)
Gully retreat	Gullies	Spain	37°41′ N	1°42′ E	5.6	m^3 yr^{-1}	Vandekerckhove et al. (2001)
Sedimentation	Sedimentation cones	Brazil	–	–	1.4	mm yr^{-1}	Momoli et al. (2012)
Sedimentation	Dunes	Poland	54°41′ N	17°14′ E	2.4–3.5	mm yr^{-1}	Koprowski et al. (2010)
Sedimentation	Cutoff channel infill deposit	France	49°13′ N	5°14′E	6.5–24	mm yr^{-1}	Piégay et al. (2008)
Sedimentation	Drifting sands	Netherlands	51°40′ N	5°05′ E	–	–	den Ouden et al. (2007)
Sedimentation	Drainage basin	USA	33°37′ N	111°50′ W	–	–	McCord (1987)
Sheet erosion	Hillslopes	China	36°69′N	102°71′E	3.3–13.5	mm yr^{-1}	Zhou et al. (2013)
Sheet erosion	Hillslopes	Iran	–	–	0.54	mm yr^{-1}	Bahrami et al. (2011)
Sheet erosion	Badlands	Spain	41°10′ N	3°48′ W	6.2–8.8	mm.yr^{-1}	Bodoque et al. (2011)
Sheet erosion	Gullies	France	44°08′ N	6°20′ E	5.9–6.2	mm yr^{-1}	Corona et al. (2011a)
Sheet erosion	Gullies	France	44°08′ N	6°20′ E	5.9	mm yr^{-1}	Lopez Saez et al. (2011)
Sheet erosion	Hiking trails (anatomical response)	Spain	40°59′ N	4°05′ E	–	–	Rubiales et al. (2008)
Sheet erosion	Forest	Spain	40°12 N	3°34′ W	3.5–8.8	mm yr^{-1}	Pérez-Rodríguez et al. (2007)
Sheet erosion	Hillslopes	USA	36°09′ N	109°33′ W	2.0–3.0	mm yr^{-1}	Wawrzyniec et al. (2007)
Sheet erosion	Hillslopes	USA	36°09′ N	109°33′ W	1.9	mm yr^{-1}	McAuliffe et al. (2006) and Scuderi et al. (2008)
Sheet erosion	Hiking trails	Spain	40°52′ N	4°01 W	2.6–1.6	mm yr^{-1}	Bodoque et al. (2005)
Sheet erosion	Different environments	USA	39°20′ N	106°52′ W	1.18	mm yr^{-1}	Carrara and Carroll (1979)
Sheet erosion	Hillslopes	USA	–	–	0.29	mm yr^{-1}	Eardley and Viavant (1967)
Sheet erosion	Hillslopes	USA	37°37′ N	118°22 W	0.015–0.12	mm yr^{-1}	LaMarche (1961, 1963, 1968)
Shore erosion	Sea	France	42°59′N	6°13′E	22–26	mm yr^{-1}	Rovéra et al. (in press)
Shore erosion	Lakes	Italy	42°36′ N	11°57′ E	28–92	mm yr^{-1}	Fantucci (2007)
Shore erosion	Lakes	USA	32°23′ N	110°42′ W	1	mm yr^{-1}	Danzer (1996)
Shore erosion	Lakes	Canada	46°35′ N	72°01′ W	0.15	m^3 m^{-2} yr^{-1}	Bégin et al. (1991a, 1991b)
Soil erosion	Methodological contribution	N/A	–	–	–	–	Ballesteros-Cánovas et al. (2013)
Soil erosion	Badlands	Italy	43°14′ N	11°33′ E	2.7–37.5	mm yr^{-1}	Bollati et al. (2012)
Soil erosion	Methodological contribution	N/A	–	–	–	–	Osterkamp et al. (2012)
Soil erosion	Badlands	France	44°08′ N	6°20′ E	0.5	mm.yr^{-1}	Corona et al. (2011b)
Soil erosion	Karst area (anatomical response)	China	14°26′ N	105°42′ E	–	–	Luo et al. (2011)
Soil erosion	Rangelands	Patagonia	42°58′ S	64°20′ W	2.4–3.1	mm yr^{-1}	Chartier et al. (2009)
Soil erosion	Methodological contribution	N/A	–	–	–	–	Gärtner (2007)
Soil erosion	Gullies	Poland	50°04′ N	14°24′ E	`	–	Malik (2006)
Soil erosion	Hiking trails	Italy	46°24′ N	10°31′ E	2.7	mm yr^{-1}	Pelfini and Santilli (2006)
Soil erosion	Hillslopes	USA	–	–	1.92–3.16	mm yr^{-1}	Hupp and Carey (1990)
Soil erosion	Roadcut	USA	–	–	10–11	mm yr^{-1}	Megahan et al. (1983)
Soil erosion	Rangelands	Kenya	1°26′ S	36°57′ E	5.5	mm yr^{-1}	Dunne et al. (1978)

reconstructions of erosion recently shifted to the microscopic dating of exposure.

On eroding slopes, roots are likely to be affected by changes and ultimately the loss of edaphic cover which will in turn cause variations in temperature and humidity as well as reduction of soil cover pressure to occur (Corona et al., 2011a,b). Such changes in temperature and moisture may give rise to the formation of ice crystals in sap, air bubbles in xylem conduits and gas-filled conduits, which will ultimately impede water transport (Zimmermann, 1983) and to that effect result in cell embolism and subsequent xylem dysfunction (Tyree and Sperry, 1989; Pitterman and Sperry, 2003; Mayr et al., 2007; Arbellay et al., 2012). To minimize their vulnerability to freezing and embolism, the size of earlywood tracheids in stems has been reported to depend on air temperature and moisture at the start of the growing season (Antonova and Stasova, 1993), with smaller cells being typically formed in periods of unfavorable conditions. Recent research by Corona et al. (2011a,b) has demonstrated that similar reductions in cell lumina (Fig. 1) can be observed in roots as a result of reduced edaphic cover and the related amplification of fluctuations of temperature and humidity.

These anatomical changes are thus not only reflecting the ecophysiological adaptation of roots to new environmental conditions, but can also be consulted to assess the year or season of exposure. Pioneering work on anatomical changes in exposed roots is scarce and mostly limited to the description of “tissue changes” in fine pine roots in a shifting sand dunes in Holland (Seybold, 1930) or to the observations of Patel (1965) that roots produced xylem similar to that of shoots during the season in which exposure occurred. Fayle (1968) observed comparable changes and stated that exposure causes the smaller tracheids, increased radial growth and the possible occurrence of compression wood. At the same time, he reconfirmed the absence of compression wood in buried roots (Onaka, 1935; Hartmann, 1942; Westing, 1965) and associated its presence to light exposure and the related induction of processes typical for stem wood.

The microscopic analysis of tracheids and the description of specific growth features in roots occurring during the first year of exposure have not, in contrast, been investigated until the early twenty-first century. Research on changes in the anatomical structure of roots primarily focused on earlywood tracheids in conifers (e.g., Gärtner et al., 2001; Rubiales et al., 2008) and on vessel size and number in broadleaved species (Hitz et al., 2008a,b). Root samples were typically taken 0.5 to 1 m away from the trunk base so as to prevent noise in reconstructed erosion rates due to the influence of upward pulling of roots by stem movement (Stokes et al., 1998) and/or bending stresses resulting from stem displacement (Watson, 2000).

Based on the analysis of tracheids in conifers, Gärtner et al. (2001) demonstrated that the reduction of cell lumen in latewood tracheids represents a valuable indicator for surface lowering, whereas the peculiar reduction of earlywood tracheid lumen to ~50% would be a clear indicator for the first year of exposure (Fig. 1). In broadleaved trees, Hitz et al. (2008a, b) showed that fibers undergo a distinct decrease in lumen area in the year of exposure, whereas vessel lumina may or may not exhibit a reduction in size.

2.3. Reconstructing erosion rates

The reconstruction of erosion rates from roots consists of several steps as indicated in Fig. 2. Work typically starts with a geomorphic analysis and topographic survey of the site under investigation, followed by collection of root and soil samples. Sampling design will be dictated by the process under investigation (sheet erosion, gully retreat, cliff retreat and related earthfalls). Based on the analysis of rings formed since erosion and the assessment of the thickness of the eroded soil layer, erosion rates are estimated and the results are compared and/or interpreted with hydrological data.

Erosion rates in roots were initially calculated from the ratio of rings formed since exposure (NR_{ex}) and the thickness of the eroded soil layer (E_r), where E_r was obtained via the height of the exposed part of the root measured with a depth gauge (E_x), and on post-

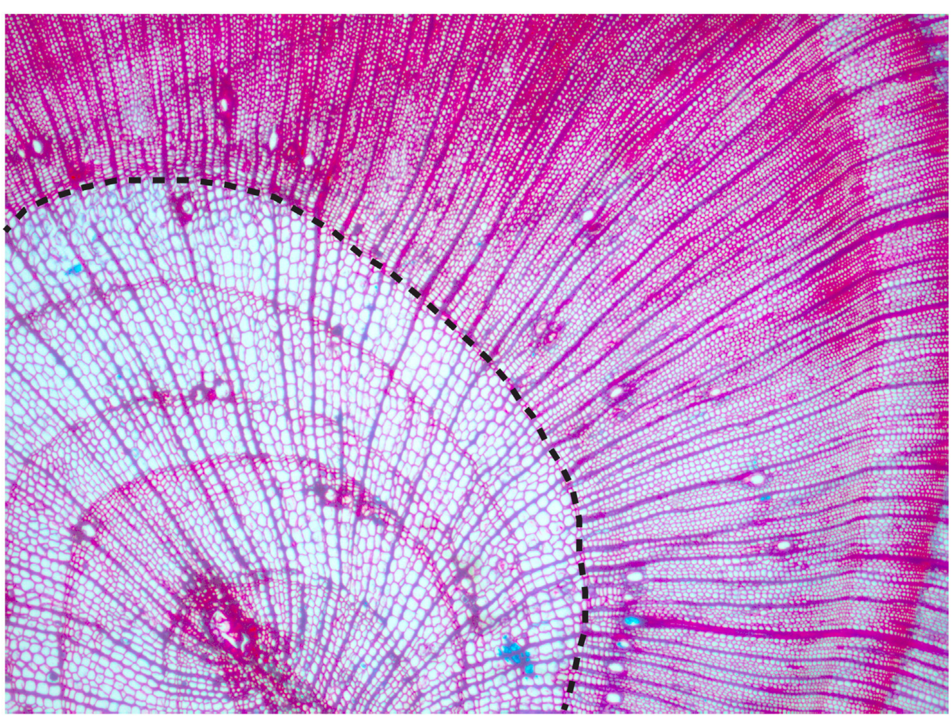

Fig. 1. Anatomical changes in a *Pseudotsuga menziesii* root from the Patagonian Andes (Argentina) following sudden exposure demarcated with the dashed line. Rings formed prior to exposure are much smaller and have larger tracheids with thinner cell walls, whereas the size of tracheids is strongly reduced (but with thicker walls) after the moment of exposure.

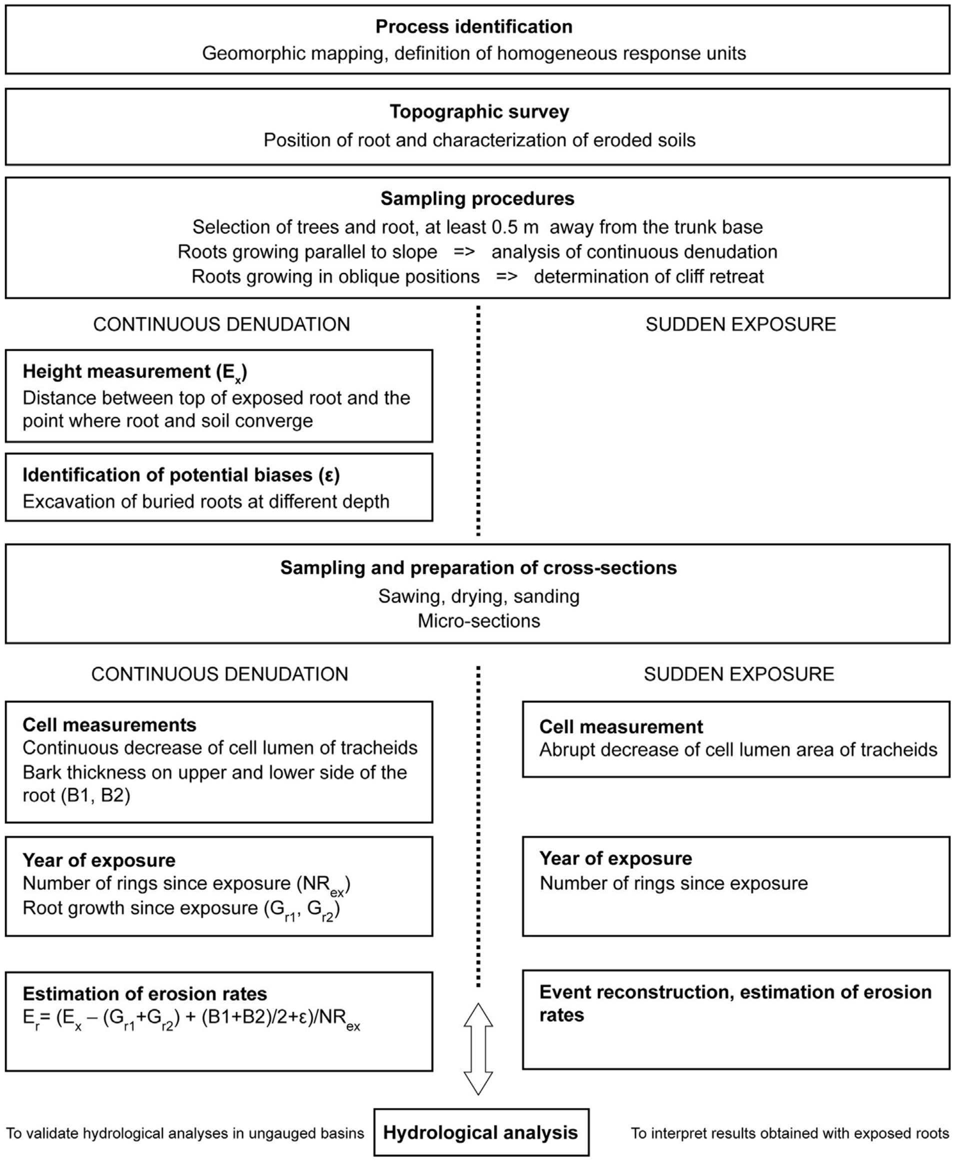

Fig. 2. Working steps and procedures involved in the root-based reconstruction of continuous denudation and sudden erosion processes. For details and explanations on abbreviations see text.

exposure root (G_{r1}, G_{r2}) and bark ($B1$, $B2$) growth on either side of the root axis (Gärtner, 2007). Gärtner et al. (2001) also assumed that anatomical changes start to occur at the moment of (partial) root exposure.

Recent work by Corona et al. (2011a,b), however, demonstrated that changes in root cell anatomy and the associated reduction of tracheid cell lumen area start to emerge as soon as the edaphic cover is reduced to ≤3 cm, resulting in a bias (ε) and inaccuracy of reconstructed sheet erosion. Corona et al. (2011b) realized that reconstructed soil thickness values also depend on the stability of the root axis. If the radial growth pressure exerted by the root is smaller than the mechanical soil impedance, root growth (G_{r1}, G_{r2}) will cause a relative vertical uplift of both root axes after exposure, and E_r must be adjusted to avoid an overestimation of erosion rates (Fig. 3):

$$E_r = E_x – (G_{r1} + G_{r2}) + (B1 + B2)/2 + \varepsilon$$

where $B1$ and $B2$ represent bark thickness on the upper and lower sides of the root. If the root axis remains stable over time, a relative uplift of the root center will occur because root increment in its lower part will be balanced by positive diageotropism (adjustment of root curvature; Coutts, 1989; Polacek et al., 2006). In this case, an overestimation of E_x will result from the subsequent growth of the upper part of the root and E_r has to be calculated as follows (Fig. 3):

$$E_r = E_x – (G_{r1}) + (B1 + B2)/2 + \varepsilon.$$

In both cases, E_r is divided by the number of rings formed since the year of exposure (NR_{ex}) to obtain the mean annual erosion rate Er_a:

$$Er_a = E_r / NR_{ex}$$

3. Main results of previous studies

3.1. Quantification of continuous denudation rates

Much of the initial work on root exposure and the reconstruction of erosion rates focused on continuous denudation processes in areas

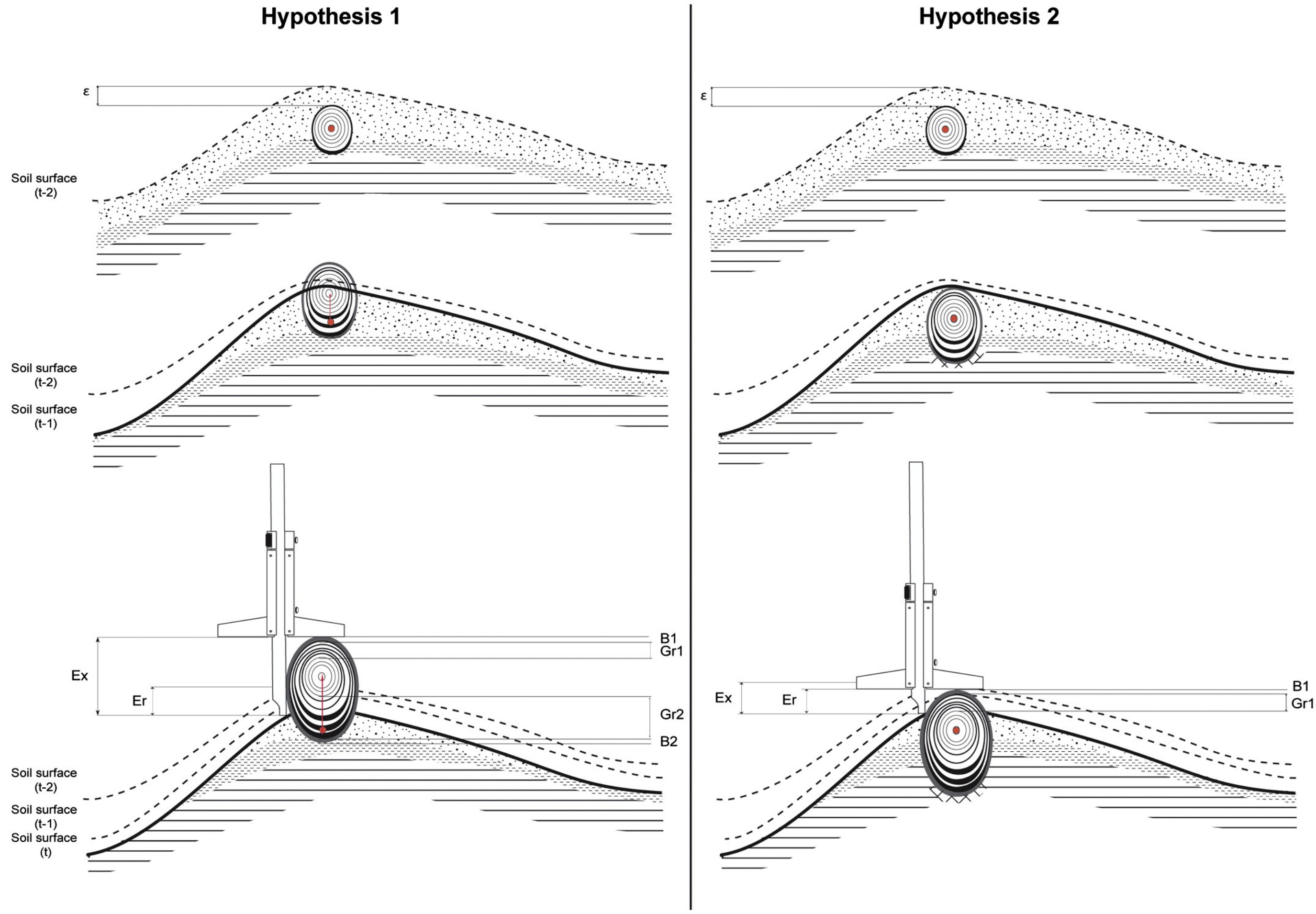

Fig. 3. Cross section of root exposure illustrating the parameters used for the calculation of erosion rates with hypotheses H1 (relative uplift of the root axis relative to the subsequent growth after exposure) and H2 (stability of the root axis). E_r = thickness of the eroded soil layer; E_x = height of the exposed part of the root as measured in the field; G_{r1}/G_{r2} = subsequent growth of the upper/lower side of the root after exposure; *B1*/*B2* = thickness of bark at the upper/lower side of the root; ε = bias.
Adapted from Corona et al. (2011b).

dominated by rather fragile, poorly consolidated lithologies (e.g., marls or sandstones) which are particularly susceptible to erosion (Hueck, 1951; LaMarche, 1961, 1963; Eardley and Viavant, 1967; LaMarche, 1968). The main findings of these pioneering studies were summarized in the previous sections. Over the past decade, the focus of denudation research has somewhat shifted from slopes without anthropogenic influence to hiking trails, where increased pressure from tourism has considerably enhanced erosion processes and the localized destructurization of soils. Bodoque et al. (2005), for instance, analyzed root exposure and mean erosion rates in *Pinus sylvestris* along a path in the Sierra de Guadarrama (Spanish Central System). Interestingly, significant differences in average erosion rates existed between the initial portion of the path (2.6 mm yr^{-1}) and more remote sectors of the trail (1.7 mm yr^{-1}). Trampling scars (i.e. debarking lesions produced by hooves) on superficial roots were also used to access information on caribou (*Rangifer tarandus*) activity in boreal forests of Canada (Morneau and Payette, 1998) and allowed evaluation of demographic trends of the caribou population over the past 100 yr.

Corona et al. (2011b) used exposed roots from *P. sylvestris* to quantify sheet erosion processes on interfluve (0–15°) and gully slopes (15–45°) in marly badlands of the Southern French Alps and obtained bias-corrected (ε) erosion rates of 5.9 ± 2.6 mm yr^{-1}. Comparison of reconstructed erosion rates with a series of systematic measurements performed across a network of 46 marking stakes not only shows almost identical rates (5.7 ± 2.3 mm yr^{-1}), but also points to the fact that values would have been underestimated on the interfluves and gully slopes without the bias-adjustment. Dendrogeomorphic records of erosion rates have also been coupled with stake data and LiDAR-generated slope maps so as to develop a linear regression model and to generate highly-resolved soil erosion maps (Fig. 4; Lopez Saez et al., 2011). The regression model was statistically significant and the average erosion rates obtained from areal erosion maps of three micro-catchments proved to be well in concert with average annual erosion rates measured in traps at the outlet of the same catchments since 1985 (Mathys et al., 2003).

Recent work on poorly consolidated sands of the Spanish Central System (Bodoque et al., 2011) has demonstrated that vegetation patches are closely linked with erosive landforms (Fig. 5). Results from the root-ring records (6.6–8.8 mm yr^{-1}, Bodoque et al., 2011) differed by ~36% from those obtained through direct observation (60 erosion pins and 12 pedestals; 11.9 mm yr^{-1} for a period of observation of three hydrological years, Lucía et al., 2011), thereby pointing to the strong influence of a high-intensity rainfall event on monitoring data and the smoothening of extremes in medium-term rates of erosion obtained with dendrogeomorphology.

3.2. Quantification of channel incision and gullying processes

The quantification and understanding of channel incision processes are important issues for channel control strategies and problems of land degradation (e.g., Gyssels et al., 2005; Corenblit et al., 2007).

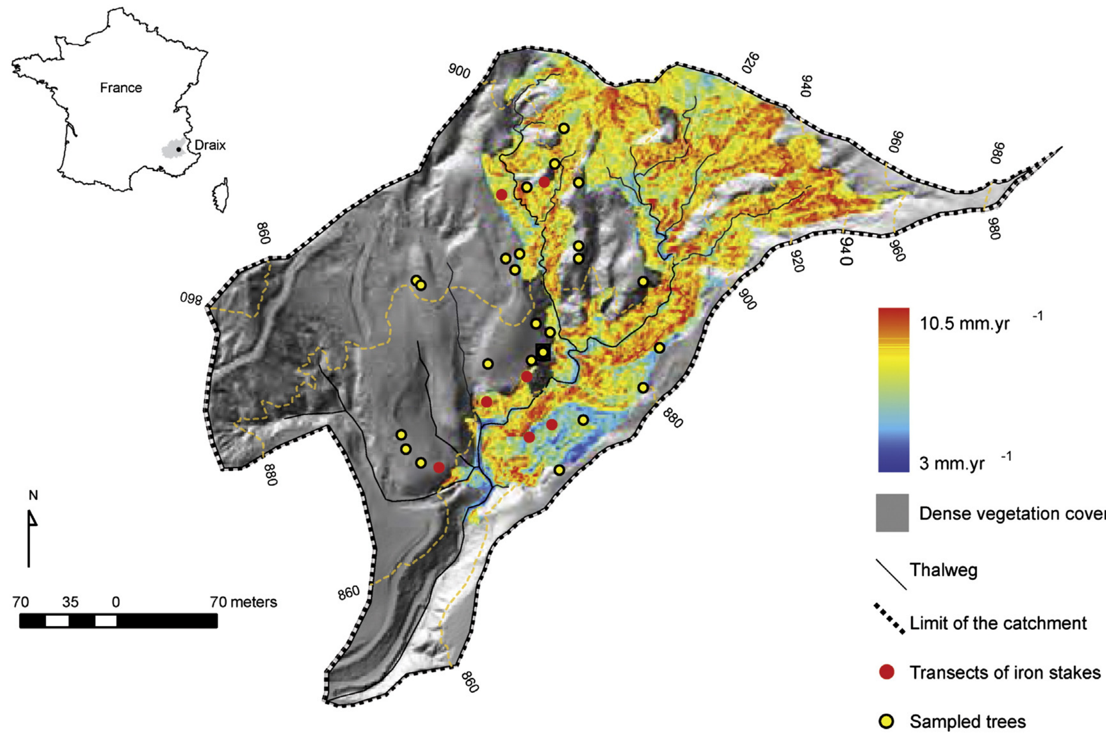

Fig. 4. High-resolution erosion maps for the Laval catchment, Draix experimental basin, southern French Alps. Predicted erosion maps are obtained through a coupling of (i) the linear regression model obtained from dendrogeomorphic erosion rates from *Pinus sylvestris* roots (yellow dots) with (ii) high-resolution slope maps of the Laval catchment derived from a LiDAR-generated DEM.
Adapted from Lopez Saez et al. (2011).

Incision has been described to start locally and as a result of intense run-off causing material scour and a subsequent unbalance in the hydraulic gradient, thereby forcing the channel to new erosive processes up-stream (Lane, 1955). Channel incision represents a non-continuous process and is sometimes caused by an upstream migration of knickpoints, which in turn are controlled by obstacles in the channel such as rocks or transverse roots (Lucía et al., 2011; Fig. 6).

The evolution of gully retreat has repeatedly been addressed through short-term field monitoring of headcuts or the interpretation of diachronic aerial photographs (Martinez-Casasnovas, 2003; Marzolff and Poesen, 2009; Marzolff et al., 2011), but has only rarely been studied with dendrogeomorphology in the gully itself. Vandekerckhove et al. (2001) were the first to use "datable objects" in gullies in southeast Spain to come up with an estimate of gully-head retreat rates (medium-term erosion rate: 6 $m^3\ yr^{-1}$) and gully sidewall processes (erosion rate per unit sidewall length: 0.1 $m^3\ yr^{-1}$). Comparison of their findings with erosion rates obtained from short-term headcut retreat monitoring suggests a high reliability of values. Floating *Pinus pinaster* Ait. roots spanning incised gullies have also been observed in the sandy badlands of the Spanish Central System (Fig. 6), where averaged retreat rates of merely 0.53 $m\ yr^{-1}$ have been observed (Lucía et al., 2011). An in-depth assessment of headcut retreat and sidewall processes yet needs to be done at this site, but the abundance of roots and their position within the gullies suggest that analysis of channel processes will be possible in four dimensions and for a period spanning several decades.

Exposed roots are also common in torrential systems where hydrogeomorphic activity represents the main driver of erosion and sedimentation processes (Osterkamp et al., 2012; Stoffel and Wilford, 2012). Here, root exposure will be sudden and typically related to the occurrence of storm-induced floods and flows. In this case, the resulting signals in roots will include abrupt changes in cell lumina and the formation of abrasion scars. Roots from torrential and river environments were for instance used in Poland, Czech Republic and Switzerland to date the occurrence of bank erosion processes (e.g., Malik, 2006; Hitz et al., 2008a,b; Malik and Matyja, 2008). Based on the evidence conserved in the root-ring record of *Picea abies* (L.) Karst., *Fagus sylvatica* L., or *Fraxinus excelsior* L., the authors were also successful in linking the information contained in the roots with the occurrence of extraordinary floods in the wider study region. Based on a comparable approach but a much denser network of century-old samples of *Austrocedrus chilensis* (D.Don) Pic-Serm. & Bizzari, *Nothofagus dombeyi* (Mirb.) Blume and *P. menziesii* roots, Stoffel et al. (2012) modeled the spatial distribution of hotspots of erosion and demonstrated that the recurrence of erosion episodes was closely related to the presence of steps and pools (Fig. 7) in a flash flood channel in the Patagonian Andes (Argentina).

3.3. Quantification of shore erosion

Interestingly and despite the demonstration of the obvious potential of the approach by Bégin et al. (1991a,b), very limited attention has been paid to the dendrogeomorphic reconstruction of shore erosion processes in the past. In their pioneering work, Bégin et al. (1991a,b) used roots of North American broadleaves (*Acer saccharinum* L., *Fraxinus pennsylvanica* Marshall., *Populus balsamifera* L., *Populus deltoides* W. Bartram ex Marshall., *Tilia americana* L., *Ulmus americana* L.) to reconstruct isopach maps of sediment removal from the base of trees along the St. Lawrence stream, Canada. The authors demonstrated that the degradation of shoreline forests, landward displacement of shorelines (up to 3–4 m) and related sediment removal (mean: 0.15 $m^3\ m^{-2}\ yr^{-1}$) were related to extreme flood levels in the estuary which occurred primarily during the 1970s.

Using a similar approach, Fantucci (2007) established a map of coastline erosion for the Bolsena Caldera Lake in central Italy based on roots of *Alnus glutinosa* (L.) Gaertn., *Populus nigra* L., *Robinia*

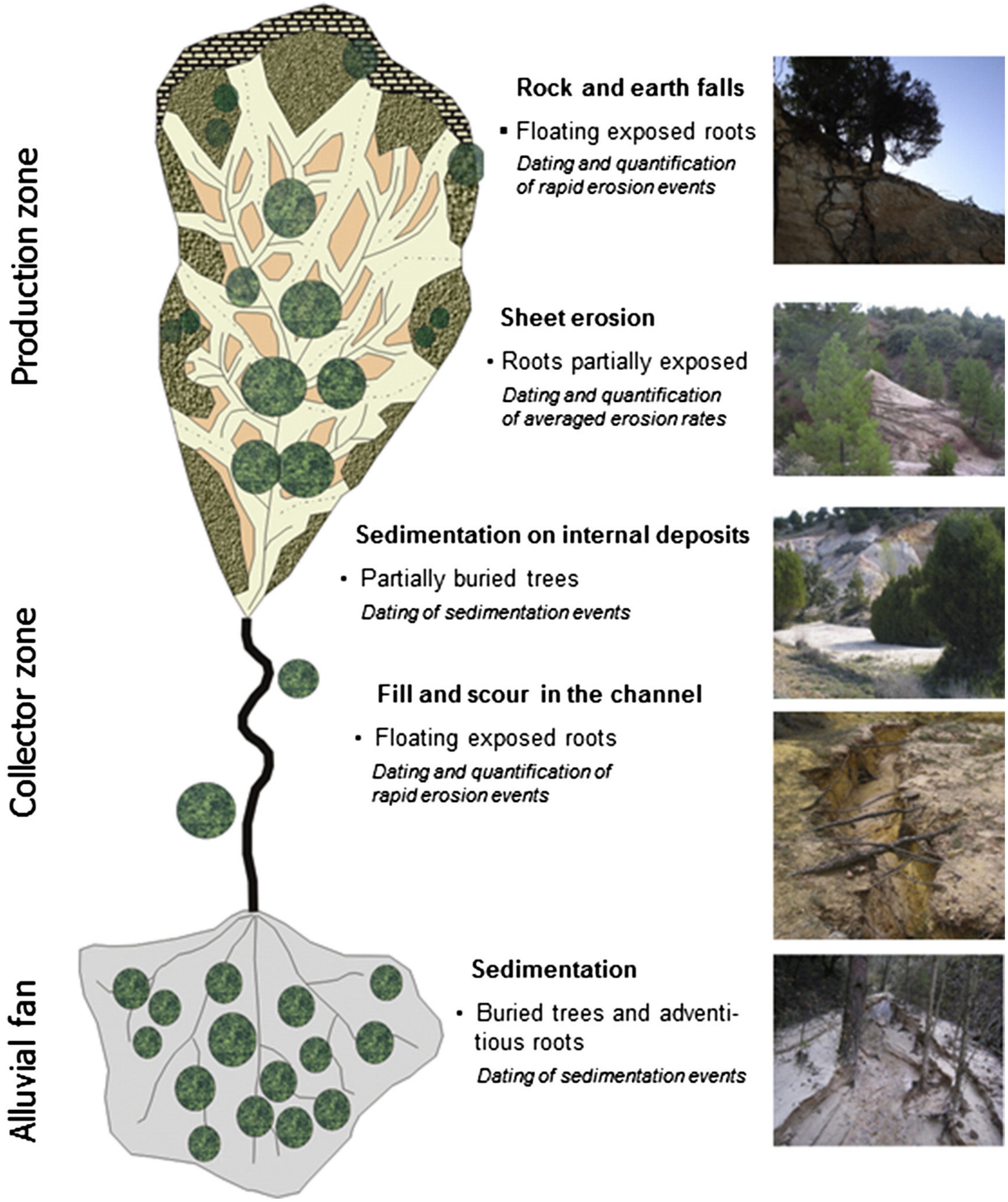

Fig. 5. Schematic view of a badland environment with zones of production, transport and deposition of sediment and characteristic phenomena of erosion and deposition which in turn depend on the hydrological response units (HRU) in which they are located. Variability of reconstructed erosion rates can be minimized if determined separately for the different HRU (adapted from Bodoque et al., 2011).

pseudoacacia L., and *Salix alba* L. In her case, erosion rates were obviously related to the intensity and frequency of wind which was most often affecting the southern and northern shores of the lake.

In an attempt to quantify shore erosion in the Mediterranean Sea, Rovéra et al. (in press) analyzed anatomical evidence of exposure in *Pinus halepensis* Mill., roots hanging from decametric, detritic cliffs of Porquerolles Island (Var, France). Reconstructed rates of erosion range from 13 to 34.5 mm yr^{-1} in the present case, and are thus comparable with results from Lake Ontario where Stephenson and Finlayson (2009) analyzed cliff retreat in detritic coastal formations using a micro-meter. At the same time, Rovéra et al. (in press) demonstrate that reconstructed rates in detritic cliffs are significantly lower than those obtained for pocket sand beaches (200 mm yr^{-1}) for which analysis was based on diachronic aerial photographs. The main contribution of the paper by Rovéra et al. (in press), however, lies in the design of the study and the selection of oblique roots (Fig. 8), thus allowing a coupled reconstruction of cliff erosion rates and temporal changes in cliff profiles, not at least in relation with recent (and possible future) sea level changes and/or changes in storminess.

4. Research avenues

The examples presented in the previous paragraphs merely represent snapshots of recent developments in root-based reconstructions of various types of erosion processes in different geographic settings

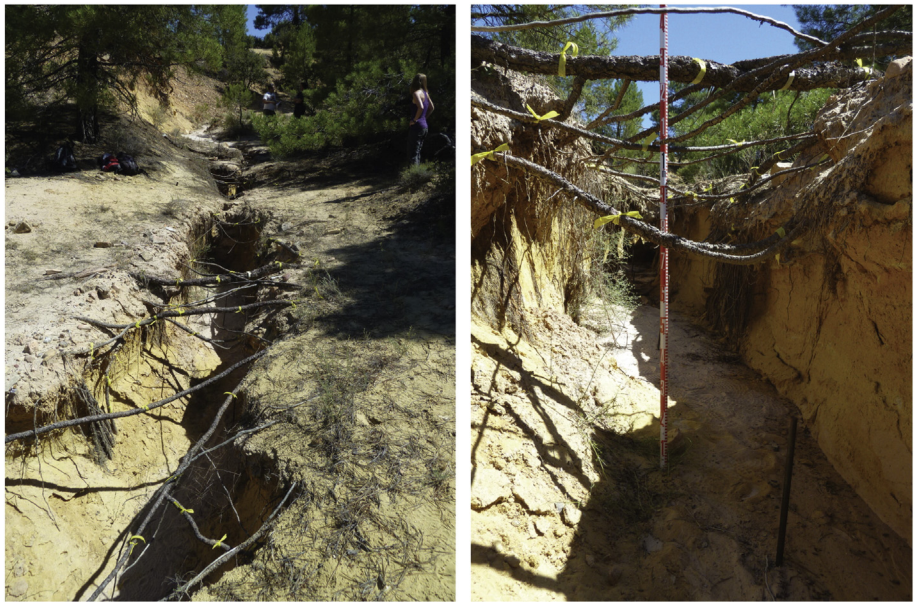

Fig. 6. Floating *Pinus pinaster* roots spanning an incised gully in a sandy badland of the Spanish Central System. The abundance and distribution of horizontal, lateral and oblique roots located at varying depths within the gully are expected to allow an in-depth assessment of headcut retreat, channel incision and widening processes (i.e. sidewall erosion) spanning several decades.

around the globe. The examples and illustrations given are also deemed reflective of the discipline's journey since the seminal work of Schulman (1945) and LaMarche (1961) and of recent achievements in the field (see Table 1). The various contributions also demonstrate the critical role of dendrogeomorphology in erosion research (Fig. 9), as rates can typically be reconstructed with (sub-) annual precision over decadal timescales and with reasonable spatial resolution.

The approach may thus have clear advantages over the shorter time series obtained with repeat monitoring (e.g., TLS, sensors, erosion pins, sediment traps) or over longer, but more coarsely resolved records obtained from aerial photographs or radio-nuclides (e.g., cosmogenic beryllium and chlorine), as shown in Table 2. The resolution of dendrogeomorphic data and the time windows typically covered (Fig. 9) by roots also facilitate the comparison of averaged erosion rates with meteorological records, and the analyses also exhibit a much better cost–benefit ratio than most other techniques used to infer erosion. At the same time, some of the approaches of root-based reconstruction of erosion rates remain somewhat hampered by natural and methodological limitations, and will be addressed in the following.

4.1. Current limitations — future challenges

The key limitation of root-based analysis of erosion is related to the presence of trees and shrubs in the study area and to the age of roots available for analysis, which does not normally exceed more

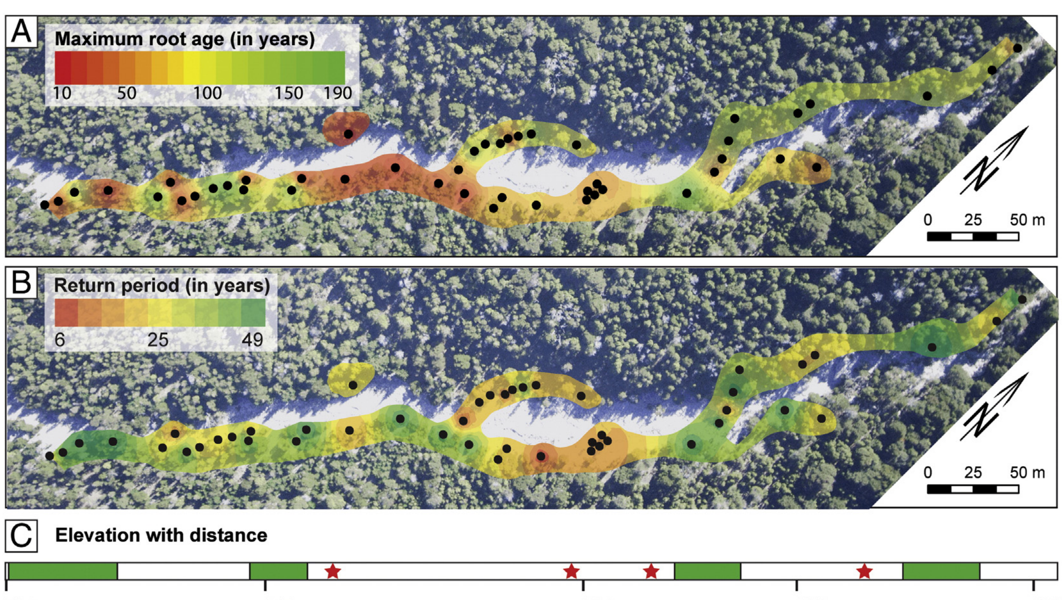

Fig. 7. Spatial interpolation of (A) maximum root age and (B) return periods of channel wall erosion events at Los Cipreses (San Carlos de Bariloche; Patagonian Andes, Argentina) derived from erosion signals in *Austrocedrus chilensis*, *Nothofagus dombeyi* and *Pseudotsuga menziesii* roots. (C) Representation of step-and-pool zones and flatter channel segments. Major areas of sediment entrainment are more common in wider channel segments downstream of steps (red stars) than in flatter, less turbulent, segments of study stretch (green surfaces; adapted from Stoffel et al., 2012).

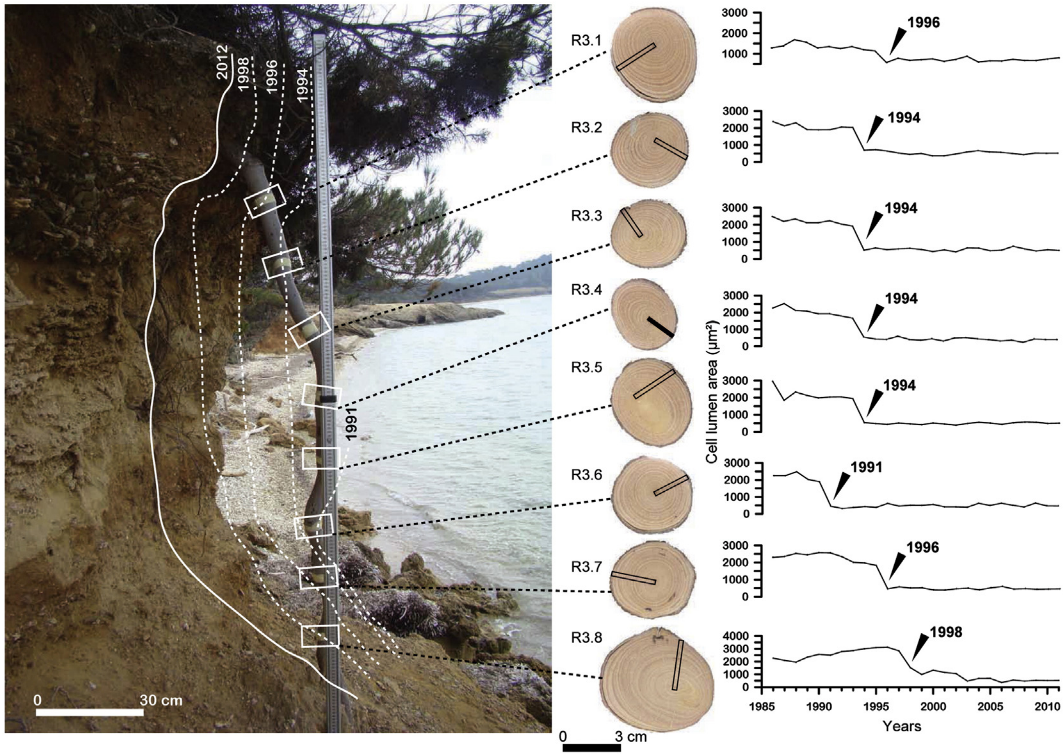

Fig. 8. Reconstructed rates of cliff erosion derived from exposed *Pinus halepensis* roots hanging from decametric, detritic cliffs of Porquerolles Island (Var, France). The analysis of oblique roots also allows analysis of temporal changes in cliff profiles, and thus could become a valuable tool for the assessment of the temporal frequency or changes in storminess.

than some decades. The long erosion series presented by LaMarche (1961, 1963, 1968), Carrara and Carroll (1979) or more recently by McAuliffe et al. (2006) are clearly exceptional and limited to the unique environment and particular distribution of tree species in the Western United States.

Dendrogeomorphic reconstructions of erosion rates are also limited to partly exposed, alive roots with growing tips still in the ground. The cross-dating of roots has proven impossible so far, even between roots of the same tree (Krause and Eckstein, 1993; Krause and Morin, 1999), and dead material cannot therefore be used for analysis. The restriction of analysis to living trees condition is, in fact, a key limiting factor for the determination of erosion in regions with massive sheet erosion or incision processes, and again limits the length of the reconstruction.

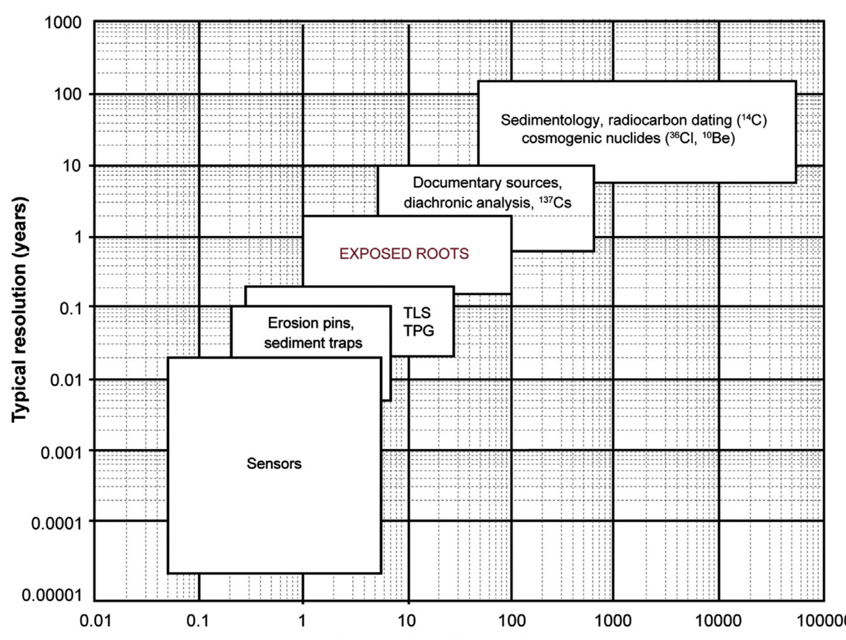

Fig. 9. The illustration of approaches used to infer rates of erosion demonstrates the critical role that vegetation-based assessments of erosion may play, because rates can typically be reconstructed with (sub-) annual precision over decadal timescales and with reasonable spatial resolution.

Table 2
Advantages, limitations and future challenges of root-based reconstructions of erosion rates.

Advantages of root-based erosion studies	Limitations of the approach	Future challenges
Quantification of erosion rates in undocumented areas Analysis possible with conifer and broadleaved trees	Presence/absence of trees, problem of non-homogeneous spatial distribution of sampling points	Reconstruction with perennial herbs, shrubs and tropical species; include more evergreen broadleaves from Mediterranean and tropical environments; dating criteria for these species
Multi-decadal, continuous reconstruction with sometimes sub-seasonal resolution	Data on averaged rates of denudation	Compute annually resolved erosion rates
Cover a large range of processes	Not available for intense processes	Determination of the connectivity between processes
Easy realization (excellent cost-benefit ratio)	Destructive sampling (cross-sections), limited to living roots	Cross-dating of living with dead roots as well as root with stem series
Method calibrated and validated on accurately monitored sites with continuous denudation processes	Approach is difficult to be calibrated in the case of discrete events	Calibration and validation on documented sites (historical archives, aerial photographs), integration of results from exposed roots in hydrological modeling to reduce methodological uncertainties
Intermediate time window (years, decades, centuries; Fig. 9)	Increased uncertainty with increasing timescale	Precise identification of the temporal scales in which the method is reliable
Quantification at the plot scale	Biases related to root size, root position, sheltering effects, relative uplift of roots after (partial) denudation	Determination of the impact of possible biases on the reconstruction, experimental exposure and burial of roots; use of roots perpendicular to the flow direction.

In the case of sheet erosion, the reliability of root-based reconstructions of medium or long-term erosion rates is likely to suffer from limitations similar to those reported for documentary sources or radioisotopes (Poesen et al., 2003). In many instances, soil erosion will reflect a non-linear response of a slope to a small number of extreme rainfalls (Favis-Mortlock and Boardman, 1995). The concept of "average erosion rates" may not therefore be appropriate in this context because it reduces the impact of the magnitude of rare extreme rainfalls in the process, and because it might render averaged rates highly skewed (Boardman and Favis-Mortlock, 1999).

In addition, as erosion processes are controlled by topographic, geomorphic and soil properties, changes in land use and climatic condition (Poesen, 1986; Janeau et al., 2003; Valentin et al., 2005; Castaldi and Chiocchini, 2012), one should also consider the high spatial variability of erosion rates (Regüés et al., 2000), thus hampering a generalized upscaling of point information to regional scales. To reduce uncertainty in estimates of erosion over larger surfaces and to approximate uniformity in runoff and transport, comparative root-based erosion studies should be limited to homogenous units in terms of erosive process dynamics – called erosion response units (ERU) – so as to compare rates for areas with similar physiographic properties and comparable management of their natural and human environment (Sidorchuk et al., 2003). Through the use of ERU, probability distributions of erosion rates can be derived, even if the analysis is restricted to a limited number of samples (Bodoque et al., 2011; Lopez Saez et al., 2011).

The relative uplift of roots following erosion is another possible caveat which needs to be taken into account in the field and during analysis (Corona et al., 2011a,b), as is, in fact, the sheltering effect of roots (Fig. 10a). Indeed, erosion rates obtained with dendrogeomorphic techniques have been hampered repeatedly in the past from improper characterization of the height of the exposed part of the root measured in the field (E_x). This height has often been defined as the distance between the top part of the exposed root and the point where root and soil converge. Such an approach will, however, likely be fraught by different sources of uncertainty, which are due to (i) ERU roughness as a direct consequence of the sheet erosion processes and to (ii) the effect of enhanced erosion (or *overdeepening*) downslope of roots growing perpendicular to the slope. Such influences may have quite drastic consequences on reconstructed absolute and mean erosion rates, as visualized in the DEM obtained from TLS in Fig. 11.

The spatial analysis of the DEM nicely illustrates how transversal soil profiles measured on both sides of an exposed root may develop a concave micro-topography. This effect will only disappear at some distance from the root at which the profile will again reflect topographic variability driven by soil roughness. Based on these findings, measuring E_x at the point where the root converges with the soil seems to be misleading, because the value obtained would not be representative of the magnitude of erosion.

In addition, recent advances in vegetation-based reconstructions of erosion indicate that large exposed roots may bias "real" erosion rates (Haubrock et al., 2009; Bodoque et al., 2011) in the sense that the level of a bare soil would be lower than what is measured at the contact between soil and root in the immediate vicinity of the latter. In this sense, we present new evidence (Fig. 12) suggesting that erosion rates derived from large roots would underestimate real values, and that an obvious negative trend would exist between reconstructed erosion rates and root thickness. This troubling result clearly calls for a critical analysis and possible calibration of this apparent bias in old(er) roots.

Many of the ecosystems in regions with distinct seasons and the presence of trees are clearly dominated by broadleaved species (*angiosperms*). Despite their abundance, not least in areas affected by erosion, they have only rarely been used so far to reconstruct erosion processes, presumably as a result of their more complex wood anatomy and the existence of frequent growth anomalies (Cherubini et al., 2003). Some of the limitations of reconstructions with Mediterranean broadleaves have been illustrated by Bodoque et al. (2005). Roots of broadleaved trees growing in the more temperate climatic zones of Europe appear to be less affected by cambium stress and the formation of false or double rings and therefore have been used occasionally to infer erosion processes in the past (Malik, 2006; den Ouden et al., 2007; Hitz et al., 2008a,b).

Shrubs and perennial herbs have been demonstrated to (i) form annual rings, (ii) cross-date within species, to (iii) register climatic signals in their series, and to (iv) cover periods of up to a few decades (e.g., Bär et al., 2008; Elmendorf et al., 2012). Erosion studies based on shrubs and herbs are completely missing so far, despite the fact that they would enlarge the geographic areas for reconstructions in terms of latitude, longitude and altitude.

4.2. Thematic perspectives

Based on the above limitations and in an attempt to increase accuracy of reconstructions (while reducing the effect of biases), further calibration and validation of dendrogeomorphic results are needed on sites where erosion rates are monitored continuously and with high accuracy (Fig. 10b, c). Such monitoring initiatives are characteristic for sites affected by sheet erosion (denudation processes) and often conceptualized at the plot scale. Here, vegetation-based reconstructions of erosion rates could be compared with data from manual resurvey techniques such as total station data, GPS, leveling or erosion pin resurveys (Hooke, 1979; Lawler, 1993).

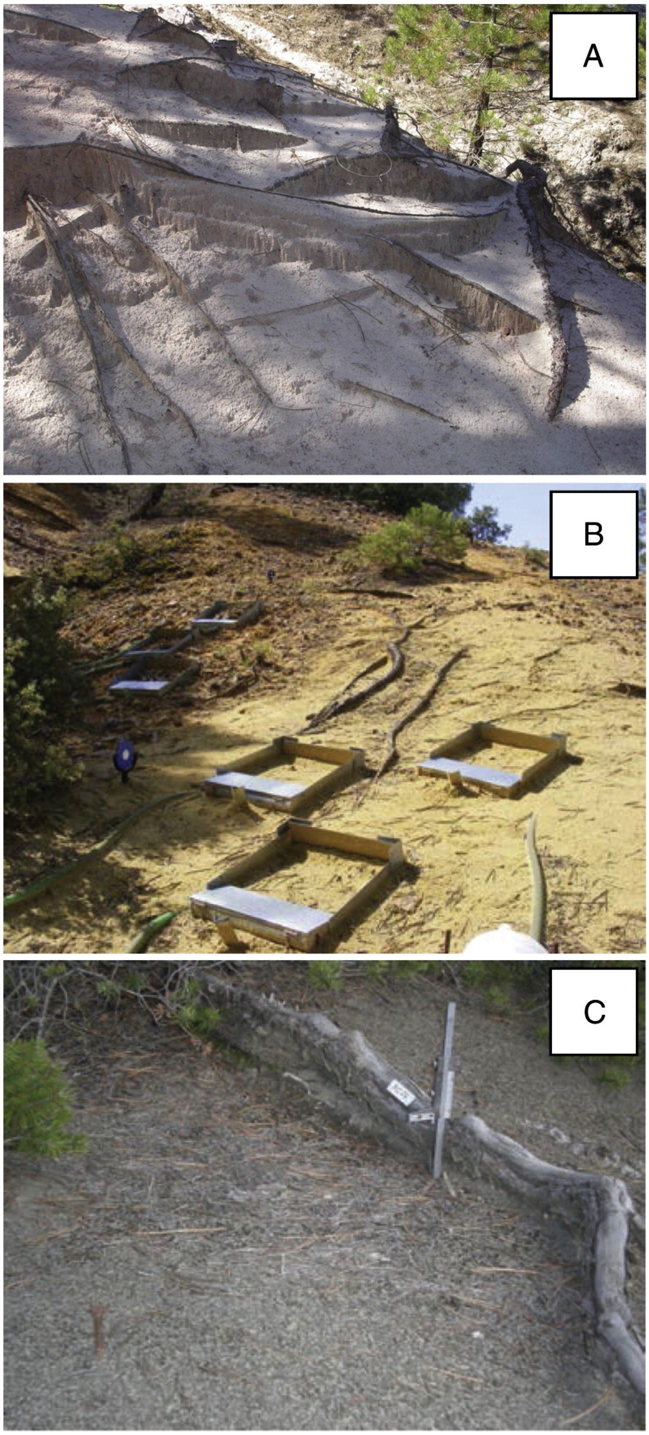

Fig. 10. (A) The sheltering and barrier effects of roots growing perpendicular to the slope or in oblique positions may hamper appropriate measurement of erosion in the field. Therefore, only roots growing parallel to the slope should be sampled in vegetation-based erosion studies. In addition, data from dendrogeomorphic erosion analyses should be more frequently and systematically compared, calibrated and validated with data gathered with some of the more conventional monitoring devices such as (B) Gerlach troughs or (C) erosion stakes.

The use of TLS has proven useful not only for the detailed monitoring of erosion processes on larger surfaces (Lucía et al., 2008), but also for the identification of possible sources of biases in erosion rates occurring next to or underneath roots. Based on the preliminary results presented in Fig. 11, we call for more research focusing on the validation of root-based erosion rates and the analysis of differences in height between the root–soil contact and the neighboring soil surface. In any case, the use of high-precision DEMs will greatly enhance accuracy and reduce uncertainty of depth determination of eroded soils at various cross-sections within a root segment and in the longitudinal direction with respect to the main axis of erosion.

In areas with rapid erosion, such as detritic coastal cliffs, lake shores or along banks (sidewalls) of fluvial systems, comparative studies should be realized that aim at the calibration of vegetation-based erosion rates against data from repeat photography (Harvey, 1977), terrestrial photogrammetry (Lawler, 1989, 1993; Lane et al., 1993, 1998) or remotely sensed data (Micheli and Kirchner, 2002). Dendrogeomorphic records should also be used more often to obtain (interpolated) maps of erosion (Lopez Saez et al., 2011; Stoffel et al., 2012) rather than averaged erosion rates, and results of such maps should be validated more systematically with diachronic data from aerial or terrestrial photographs. On a temporal scale, data on the occurrence of erosive events and the interval at which photographs are taken would presumably facilitate the determination of event-based rather than averaged erosion rates.

More attention should also be paid to the actual selection of the most promising and representative roots to reconstruct continuous denudation (sheet erosion) and sudden erosion events. In the case of epidermic denudation, we advocate the systematic sampling of roots growing parallel to the slope, whereas roots growing perpendicular to the slope or in oblique positions should be clearly avoided, as they tend to form barriers and will thus affect erosion rates.

Although the concept of dendrogeomorphic root sampling goes back to the 1960s (LaMarche, 1961, 1968), systematic approaches quantifying the effect of root orientation or changing slope angles on reconstructed erosion rates have not been realized so far. In the case of sudden erosion processes (e.g., floods, storms), Rovéra et al. (in press) have recently demonstrated that pre-event profiles can be reconstructed for micro-cliffs provided that exposed roots grow an oblique positions with respect to the cliff. This finding not only opens new doors to the analysis of cliff retreat but also calls for more research on the reconstruction of (sub-) vertical profiles in other environments, such as retreating gully sidewalls, headwalls, or river banks. The sudden opening of fissures in landslide bodies is yet another field where roots could be used to assess crack widening rates. In addition to the dating of sliding phases (which can be done through the analysis of trees on the landslide body), roots would probably yield more accurate information on the initiation of instability and on landslide precursor signals.

With regard to a better understanding of anatomical reactions of roots, we suggest the realization of experimental work focusing on the artificial exposure and burial of roots. While there is common agreement that the loss of edaphic cover will result in the formation of stem-like cells in roots, their reaction to sedimentation after initial exposure still is unknown. We also call for a comparison of rates obtained with different botanical benchmarks. Erosion rates obtained from roots could, for instance, be compared with data reconstructed from stock unearthing in vines (Brenot et al., 2008; Casalí et al., 2009) or mounds forming around trees in olive orchards (Vanwalleghem et al., 2010). Comparative studies could also be performed between cosmogenic caesium (^{137}Cs) and dendrogeomorphic techniques.

4.3. Target areas for future research

The assessment of erosion rates based on root exposure has been applied successfully in the past and in a large variety of ecosystems where trees and shrubs form annual growth rings. Fig. 13 and Table 1 provide an overview on where work has been performed in the past. At the global scale, this restriction of seasonality excludes desert regions where vegetation is largely missing as well as the tropics where trees form growth zones but no tree rings (Stoffel and Bollschweiler, 2008). In regions with suitable climatic conditions,

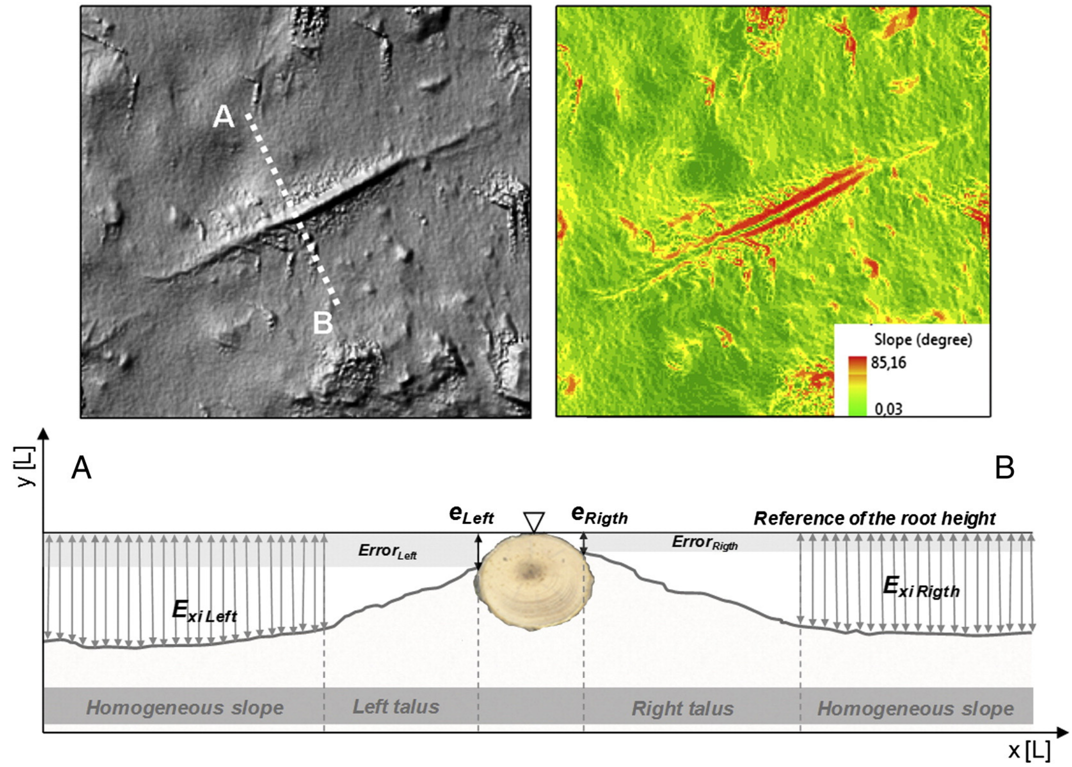

Fig. 11. High-resolution TLS-derived DEM of a sandy badland environment with an exposed root and illustration of the impact of the root on micro-topography and transversal soil profiles on both sides of the root. This effect only disappears at some distance from the root, the height of the exposed part of the root (E_x) should not be measured at the point where the root converges with the soil.

erosion has to be sufficient to expose roots while allowing them to keep their tips in the ground. Such conditions are typically met in regions with continuous denudation of soils and rocks – such as sandstones, marls, gypsum, schists, or peat – or to environments with extreme climatic conditions and the occurrence of repeated freeze–thaw cycles or intense precipitation. In this respect, three scales become relevant for the determination of future target areas of root-based erosion research. At the local scale, future research should

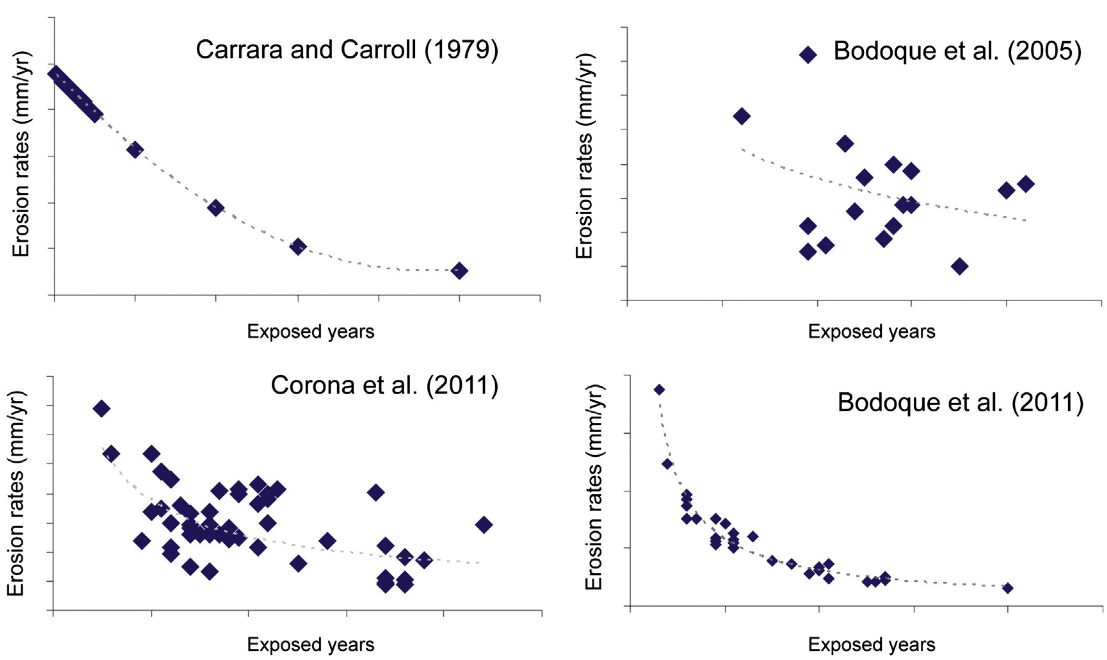

Fig. 12. Recent advances in vegetation-based reconstructions of erosion indicate that large exposed roots cannot necessarily be used immediately for the reconstruction of erosion rates as the level of bare soils would be lower under natural conditions than what is measured at the contact between the soil and root in the immediate vicinity of the latter. A negative trend obviously exists between reconstructed erosion rates and root thickness, and clearly calls for a critical analysis and possible calibration of this apparent bias in old(er) roots.

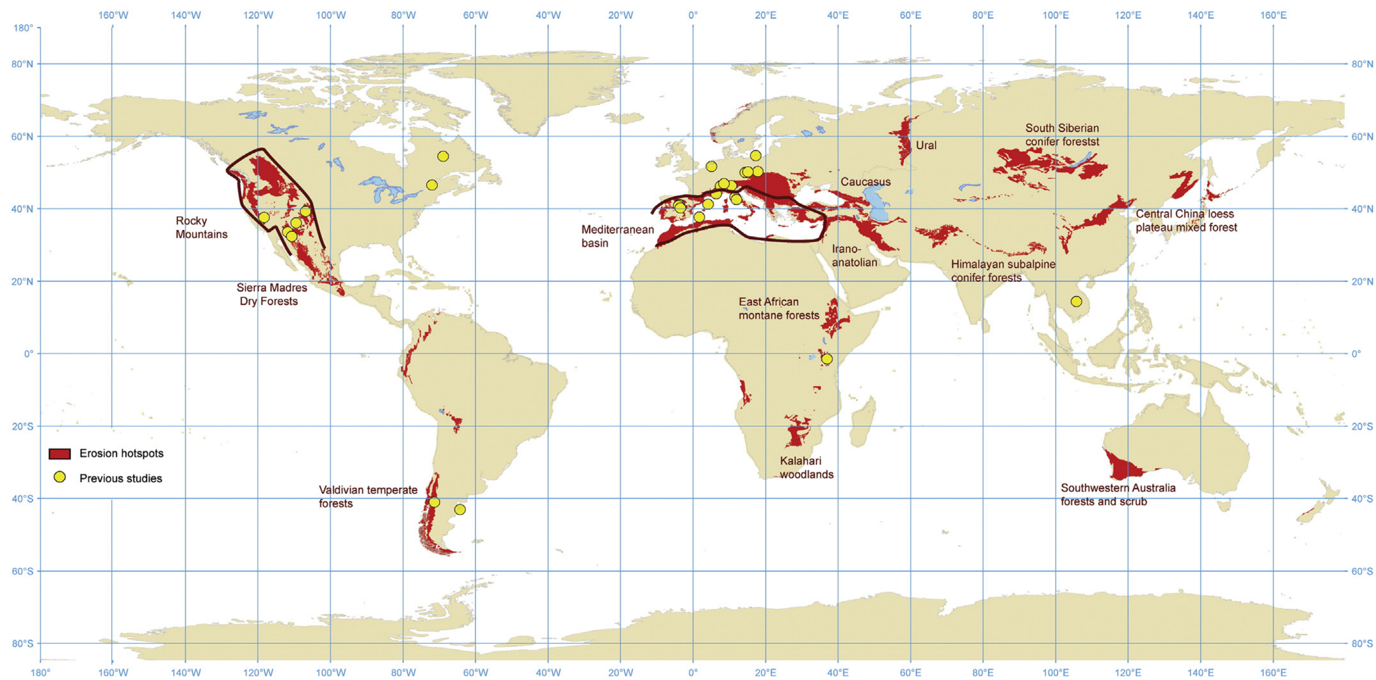

Fig. 13. Illustrations of possible target areas of future vegetation-based erosion research. The map was obtained through a blending of climate, ecosystems, and erosion data, namely (i) a map of Köppen–Geiger climate classification, (ii) a map of terrestrial ecoregions, and (iii) a map of areas sensitive to erosion. Several of the target areas identified have been the subject of past research (yellow dots), whereas most of the target areas in Central and South America, East and South Africa, most of areas east of the Mediterranean and Australia have only received very limited or no attention in the past.

focus on vulnerable hillslopes, roadsides, lakes and hydrogeomorphic systems (e.g., torrential channel, river bank). At the global scale, littorals affected by shore erosion should become a focus of future research, since they have been largely neglected by vegetation-based erosion assessments in the past. At the level of bioclimatic zones and major ecoregions, target areas of future dendrogeomorphic research have been defined through a blending of climate, ecosystems, and erosion data. In detail, we used (i) the world map of Köppen–Geiger climate classification (Rubel and Kottek, 2010), where environments with equatorial, tropical and polar climates were excluded (because trees will fail to form annual increment rings in these regions); (ii) the map of terrestrial ecoregions (WWF, 2012), where biogeographic regions with conifer, broadleaved, dry forests, and the transition of forests to savannah environments were selected; and (iii) the map of areas sensitive to erosion (Oldeman et al., 1990) because it allows delineation of regions subjected to strong hydric or eolian erosion processes. Several of the target areas identified in Fig. 13 have been the subject of past research (e.g., Rocky Mountains, Alps, Mediterranean basin), whereas the Sierra Madre dry forests of Central America, the Valdivian temperate forests (covering much of the Patagonian Andes), the East African montane forests and Kalahari woodlands, most of the northern hemispheric target areas east of the Mediterranean (e.g., Caucasus, Ural, or Himalayan subalpine conifer forest) and the Southwestern Australia woodlands have only received very limited or no attention in the past, despite the fact that several of these regions are among the most heavily affected by erosion.

5. Conclusions

The reconstruction and quantification of erosion processes using exposed tree roots have expanded significantly over the past decade, and substantial progress has been achieved in the field of dendrogeomorphic erosion analysis. Through the systematic comparison of exposure signals in roots and mean erosion rates with data obtained from monitoring devices (e.g., pins, stakes, sediment traps, TLS), the precision of dendrogeomorphic approaches has been improved substantially. Despite the possible limitations illustrated in the previous sections, we believe that growth series from exposed roots clearly have the potential to yield acceptable estimates of soil erosion over comparably large areas and at reasonably low cost. Root-based erosion assessments therefore constitute a valuable alternative to empirical models, especially in regions where data for calibration and validation are completely missing. At the same time, however, the value of root-based erosion data remains somewhat limited in semi-arid and arid environments, where erosion will be driven by rare extreme events and where the definition of mean erosion rates may thus be misleading. Further work is needed here, but also with respect to the quantification of erosion rates over longer (centennial) time scales, the reconstruction of annual rather than averaged rates of denudation or the expansion of studies to geographic regions which have not been in the focus of root-based assessments of erosion so far.

Acknowledgment

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