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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.

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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