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A review of the mechanical effects of plant roots on concentrated flow erosion rates

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ABSTRACT

Living plant roots modify both mechanical and hydrological characteristics of the soil matrix (e.g. soil aggregate stability by root exudates, soil cohesion, infiltration rate, soil moisture content, soil organic matter) and negatively influence the soil erodibility. During the last two decades several studies reported on the effects of plant roots in controlling concentrated flow erosion rates. However a global analysis of the now available data on root effects is still lacking. Yet, a meta-data analysis will contribute to a better understanding of the soil-root interactions as our capability to assess the effectiveness of roots in reducing soil erosion rates due to concentrated flow in different environments remains difficult. The objectives of this study are therefore: i) to provide a state of the art on studies quantifying the effectiveness of roots in reducing soil erosion rates due to concentrated flow; and ii) to explore the overall trends in erosion reduction as a function of the root (length) density, root architecture and soil texture, based on an integrated analysis of published data. We therefore compiled a dataset of measured soil detachment ratios (SDR) for the root density (*RD*; 822 observations) as well as for the root length density (*RLD*; 274 observations). A Hill curve model best describes the decrease in SDR as a function of R(L)D. An important finding of our meta-analysis is that *RLD* is a much more suitable variable to estimate SDR compared to *RD* as it is linked to root architecture. However, a large proportion of the variability in SDR could not be attributed to *RD* or *RLD*, resulting in a low predictive accuracy of these Hill curve models with a model efficiency of 0.11 and 0.17 for *RD* and *RLD* respectively. Considering root architecture and soil texture did yield a better predictive model for *RLD* with a model efficiency of 0.37 for fibrous roots in non-sandy soils while no improvement was found for *RD*. The unexplained variance is attributed to differences in experimental set-ups and measuring errors which could not be explicitly accounted for due to a lack of additional data. Based on those results, it remains difficult to predict the effects of roots on soil erosion rates. However, by using a Monte Carlo simulation approach, we were able to establish relationships that allow assessing the likely erosion-reducing effects of plant roots, while taking these uncertainties into account. Overall, this study demonstrates that plant roots can be very effective in reducing soil erosion rates due to concentrated flow.

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1. Introduction

Vegetation is frequently used in ecological restoration programs to reduce the severe impact of soil erosion processes on e.g. agricultural fields, steep slopes, side walls along roads and levees (e.g. Gray and Leiser, 1982; Thornes, 1990; Morgan and Rickson, 1995; Morgan, 2005; Stokes et al., 2007; Blanco and Lal, 2008; Norris et al., 2008; Maetens et al., 2012; Stokes et al., 2014). Vegetation cover can prevent soil erosion in several ways: 1) it provides protection of the soil surface against raindrop impact and against erosion by surface runoff, 2) it reduces runoff volume and velocity by increasing infiltration rate and surface roughness and 3) it reduces sediment transport by trapping sediments (e.g. Rey, 2003; Rey et al., 2004; Morgan, 2005; Blanco and Lal, 2008; Zuazo and Pleguezuelo, 2008; Gumiere et al., 2011).

Most studies on the effectiveness of vegetation in reducing soil erosion mainly focused on the effects of above-ground vegetation as the effects of plant roots in controlling soil erosion rates are much more difficult to study and often referred to as 'the hidden half' (Eshel and Beeckman, 2013). As a consequence, the role of below-ground vegetation in controlling erosion processes have been less studied (Poesen et al., 2003; Gyssels et al., 2005; Reubens et al., 2007; Stokes et al., 2014).

Nevertheless, studies from the last two decades indicate that plant roots play a dominant role in reducing soil detachment rates due to concentrated flows and can therefore be very effective in controlling rill and gully erosion (e.g. Gyssels et al., 2005; De Baets and Poesen, 2010). This is highly relevant because rill, gully and bank erosion often contribute significantly to catchment sediment yield and to offsite impacts such as flooding and reservoir sedimentation (e.g. Poesen et al., 2003; de Vente and Poesen, 2005; Vanmaercke et al., 2011, 2012). Also in the light of the predicted climate changes and sea level rises (IPCC, 2013), root systems can play a crucial role in protecting levees against the erosive effects of wave-overtopping (e.g. Hoffmans et al., 2008; Quang and Oumeraci, 2012).

The erosion-reducing potential of plant roots are the result of complex interactions within the root-soil matrix changing the mechanical and hydrological properties of the soil (e.g. Eviner and Chapin, 2003; Gregory, 2006). As a result, the effectiveness of plant roots in reducing concentrated flow erosion rates is influenced by several root and soil characteristics: e.g. root (length) density, root architecture, soil texture, soil moisture and dry soil bulk density (e.g. De Baets et al., 2007a; Burylo et al., 2012). Differences in the erosion-reducing potential of different plant root systems call for a selection of the most appropriate plant species in programs of erosion control or hillslope stabilization (e.g. De Baets et al., 2007b; DeBaets et al., 2009; Stokes et al., 2009; Reubens et al., 2011; Burylo et al., 2014; Mwango et al., 2014). However, the extrapolation of the relationships between root properties and erosion rates, observed in individual case studies, to other sites, with differences in climate, root and soil characteristics, remains difficult (Stokes et al., 2014).

What is currently lacking is a meta-analysis of studies quantifying the erosion-reducing potential of root systems during concentrated flow. Such meta-analysis is a first step in the development of a general model that allows estimating the erosion-reducing potential of roots, based on factors that are known to be relevant. The main objectives of this research are therefore: i) to provide a state of the art on studies quantifying the effectiveness of roots in reducing soil erosion due to concentrated flow; and ii) to explore the overall trends in erosion reduction as a function of the root (length) density, root architecture and soil texture, based on an integrated analysis of published data. First an overview is given of studies reporting on the effects of plant roots in reducing rates of erosion processes by water together with factors that control this erosion-reducing potential. Next, a quantitative analysis of all experimental data is made in order to explore the overall trend in root effects on concentrated flow erosion rates. As such, this study represents a progress toward a better understanding of the mechanical effects of plant root characteristics on concentrated flow erosion rates in a range of environments.

2. Erosion-reducing potential of roots: mechanisms and controlling factors

To provide an overview of root effects on erosion processes by water, i.e. splash detachment, interrill erosion, rill and gully erosion and river bank erosion, an extensive literature review was made resulting in 36 empirical studies. Table 1 gives an overview of these studies describing the erosion processes considered, the investigated root characteristics, the overall root effects on soil erosion rates and the methods used. Several methods have been used, either in the field or in the laboratory, to measure the erosion-reducing effects of plant roots. Laboratory experiments include rainfall simulations (e.g. Ghidey and Alberts, 1997; Katuwal et al., 2013) and hydraulic flume tests (e.g. Mamo and Bubenzer, 2001a; De Baets et al., 2006). Field measurements and experiments include the use of rainfall simulations (e.g. Li et al., 1991; Cogo and Streck, 2003), micro erosion plots (e.g. Pierret et al., 2007b), concentrated flow simulations (e.g. Mamo and Bubenzer, 2001b; Li and Li, 2011), measurements of rill and gully densities (Li et al., 2015) and rill and (ephemeral) gully cross sections (e.g. Gyssels et al., 2002). A large variability in measured root morphological traits and erosion variables is observed. Root density (*RD*, kg m^{-3}) and root length density (*RLD*, km m^{-3}) are the most commonly used root characteristics, representing respectively the dry mass and the total length of the living plant roots in a certain volume of soil. Also a large variability exists in the reported erosion variables which can be divided into: 1) variables related to soil detachment rates (D_r, kg m^{-2} s^{-1}) and 2) variables related to soil erodibility (K).

Only two studies investigated the effect of plant roots on splash detachment. While Ghidey and Alberts (1997) reported no root effect on splash erosion the study of Katuwal et al. (2013) showed a significant negative effect of below-ground biomass on splash erosion rate. The effects of plant roots on interrill erosion are also not univocal. Bui and Box (1993) and Pierret et al. (2007b) found no significant root effects. Those findings contrast with studies reporting significant effects of plant roots on 1) interrill detachment rates (Zhou and Shangguan (2007, 2008); Katuwal et al., 2013) and 2) interrill erodibility (K_i) (Ghidey and Alberts (1997); Katuwal et al., 2013). The interrill erodibility (K_i) can be estimated based on the relationship between soil detachment, slope and the rainfall intensity or runoff discharge (e.g. Meyer and Harmon, 1984; Kinell, 1993; Ghidey and Alberts, 1997). For rill and gully erosion (i.e. concentrated flow erosion) all case studies reported a significant erosion-reducing effect on soil detachment rates (D_r) as well as on soil erodibility (K_r; Eq. (1)) (Table 1).

Experiments with both above- and below-ground biomass indicated that vegetation cover was more effective in reducing splash detachment (Katuwal et al., 2013) while plant roots were more efficient in reducing (inter-)rill erosion (Zhou and Shangguan, 2008; Zhang et al., 2012). Sigunga et al. (2015) showed that roots of *Eucalyptus citriodora* trees fused, forming a dense network of closely woven mass of roots holding large amounts of soil and thereby controlling erosion by water and