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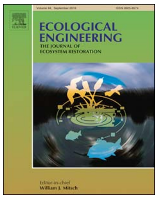

How do root and soil characteristics affect the erosion-reducing potential of plant species?

W. Vannoppen[a,*], S. De Baets[b], J. Keeble[a], Y. Dong[c], J. Poesen[a]

[a] *KU Leuven, Division of Geography and Tourism, Celestijnenlaan 200E, B-3001, Heverlee, Belgium*
[b] *School of Water, Energy and Environment, University of Cranfield, Building B 52a, UK*
[c] *Key Laboratory of Mountain Hazards and Earth Surface Processes, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, 9#, Block 4, Renminnanlu Road, Chengdu, 610041, China*

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ABSTRACT

Plant roots can be very effective in stabilizing the soil against concentrated flow erosion. So far, most research on the erosion-reducing potential of plant roots was conducted on loamy soils. However susceptible to incisive erosion processes, at present, no research exists on the effectiveness of plant roots in reducing concentrated flow erosion rates in sandy soils. Therefore, the prime objective of this study was to assess the erosion-reducing potential of both fibrous and tap roots in sandy soils. Furthermore, we investigated potential effects of root diameter, soil texture and dry soil bulk density on the erosion-reducing potential of plant roots. Therefore, flume experiments conducted on sandy soils (this study) were compared with those on sandy loam and silt loam soils (using the same experimental set up). Results showed that plant roots were very efficient in reducing concentrated flow erosion rates in sandy soils compared to root-free bare soils. Furthermore, our results confirmed that fibrous roots were more effective compared to (thick) tap roots. Dry soil bulk density and soil texture also played a significant role. As they were both related to soil cohesion, the results of this study suggested that the effectiveness of plant roots in controlling concentrated flow erosion rates depended on the apparent soil cohesion. The nature of this soil type effect depended on the root-system type: fine root systems were most effective in non-cohesive soils while tap root systems were most effective in cohesive soils. For soils permeated with a given amount of fibrous roots, an increase of soil bulk density seemed to hamper the effectiveness of roots to further increase soil cohesion and reduce erosion rates. In soils reinforced by tap root systems, the erosion-reducing power of the roots depended on sand content: the higher the percentage of sand, the smaller the erosion-reducing effect for a given amount of roots. This was attributed to more pronounced vortex erosion around the thicker tap roots in non-cohesive soils, increasing soil erosion rates. The results presented in this study could support practitioners to assess the likely erosion-reducing effects of plant root systems based on both root and soil characteristics.

1. Introduction

An important regulating ecosystem function of vegetation is their potential to control soil erosion processes (e.g. De Groot et al., 2002; Wallace, 2007). As such, plant species are frequently used in bio-engineering projects to improve slope stability and control surface erosion processes (Morgan, 2005; Norris et al., 2008; Stokes et al., 2014). Both above-ground and below-ground parts are important to consider depending on the erosion process dealt with (Gyssels et al., 2005; Vannoppen et al., 2015). Plant roots are very effective in controlling concentrated flow erosion and shallow mass movements by modifying both mechanical and hydrological soil properties (e.g. Simon and Collison, 2002; Eviner and Chapin, 2003). Furthermore, Erktan et al. (2016) observed a biological effect of plant roots as soil erodibility decreased with different types of plant communities along a plant successional gradient in a gully bed ecosystem. On the other hand, the effects of vegetation cover is more pronounced for splash detachment and interrill erosion (e.g. Zuazo and Pleguezuelo, 2008; Shinohara et al., 2016). Recently, more attention is paid to root traits and their effects on ecosystem services (e.g. Bardgett et al., 2014). Several studies investigated the relation between specific plant traits and their potential to control soil erosion processes (e.g. Gyssels and Poesen, 2003; Reubens et al., 2007; Stokes et al., 2009; De Baets et al., 2009; Burylo et al., 2014; Ghestem et al., 2014). The recognition of these beneficial

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[*] Corresponding author at: KU Leuven, Division of Geography and Tourism, Celestijnenlaan 200E, B-3001, Heverlee, Belgium.
E-mail address: wouter.vannoppen@kuleuven.be (W. Vannoppen).

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Table 1
Overview of empirical studies reporting an exponential relationship between soil detachment ratio (SDR) and root density (RD) or root length density (RLD), i.e. $SDR = (a)*e^{-b*R(L)D}$ (Eq. (1)) for different soil textures.

Soil texture	Root type	BD (g cm^{-3})	b	R^2	n	RD range (kg m^{-3})	RLD range (km m^{-3})	Plant species	Source
Sand	Mixture[a]	NA	0.24	0.51	31	0.33 – 13.72	NA	*T. vulgaris; G. scorpius*	(Bochet et al., 2012)
Sandy loam	Rhizoid	1.56	1.98	0.73	10	0.20 – 4.25	NA	*B. orientale, C., parasiticus, D., pedata, N. auriculata, P. vitata*	(Chau and Chu, 2017)
Sandy loam	Fibrous	0.82–1.43	0.80	0.74	20	0.31–7.14	NA	*A. aciculate, E. cynosuroides, P. maxima, S. munja.*	Shit and Maiti (2012)
Sandy/silt loam	Mixture	0.90–1.44	1.75	0.51	83	0.00–4.00	NA	*P. paucifolia, S. bungeana, Z. mays, R. pseudoacacia*	(Geng et al., 2015)
Silt loam	Fibrous	1.25–1.30	5.97	0.89	7	0.43–2.25	NA	*L. perenne, A. sativa, S. cereale*	(De Baets et al., 2011)
Silt loam	Fibrous	1.25–1.30	0.26	0.89	7	NA	9.86–28.29	*L. perenne, A. sativa, S. cereale*	(De Baets et al., 2011)
Silt loam	Tap	1.25–1.30	1.32	0.20	22	0.02–1.73	NA	*S. alba, P. tanacetifolia, R. sativus*	(De Baets et al., 2011)
Silt loam	Tap	1.25–1.30	0.18	0.21	22	NA	0.79–44.98	*S. alba, P. tanacetifolia, R. sativus*	(De Baets et al., 2011)
Silt loam	Mixture	1.25–1.30	1.93	0.10	29	0.02–2.25	NA	*L. perenne, A. sativa, S. cereale, S. alba, P. tanacetifolia, R. sativus*	(De Baets et al., 2011)
Silt loam	Mixture	1.25–1.30	0.19	0.20	29	NA	0.79–44.98	*L. perenne, A. sativa, S. cereale, S. alba, P. tanacetifolia, R. sativus*	(De Baets et al., 2011)
Silt loam	Mixture	1.30	2.25	0.59	58	0.01–1.83	NA	*H. vulgare, G. max*	Gyssels et al. (2006)
Silt loam	Fibrous	1.21–1.28	6.85	0.76	26	0.04–0.62	NA	*S. bungeana, B. ischaemum*	Li and Li (2011)
Silt loam	Mixture	0.91–1.22	0.29	0.87	5	1.76–14.29	NA	*C. korshinskii* Kom. mixtured with grasses	(Li et al., 2014)
Silt loam	Mixture	1.2–1.5	4.63	0.43	125	0.15–7.41	NA	Grassland, orchard, wasteland, shrub land, woodland	(Li et al., 2015)
Silt loam	Fibrous	1.3	0.03	0.93	15	NA	21.20–119.50	*H. vulgare*	(Liu et al., 2005)
Silt loam	Tap	1.3	0.02	0.46	13	NA	4.30–88.50	*G. max*	(Liu et al., 2005)
Silt loam	Mixture	1.3	0.07	0.60	30	NA	0.50–44.37	*H. vulgare, G. max*	(Liu et al., 2005)
Silt loam	Mixture	1.12	0.03	0.84	30	NA	0.15–24.21	*M. sativa, L. perenne*	Mamo and Bubenzer (2001a)
Silt loam	Tap	NA	0.23	0.54	15	NA	2.97–6.89	*G. max*	Mamo and Bubenzer (2001b)
Silt loam	Mixture	1.19–1.27	6.79	0.92	36	0.31–7.86	NA	*G. max, A. capillaries, A. sacrorum, S. bungeana*	(Wang et al., 2013)
Silt loam	Mixture	1.19–1.28	0.12	0.23	30	5.10–22.46	NA	*G. max, S. bungeana, A. sacrorum, C. lanceolata, A. giraldii*	(Wang et al., 2014)
Silt loam	Fibrous	1.13	1.70	0.72	7	0.01–1.04	NA	*Z. mays*	(Yu et al., 2014)
Silt loam	Fibrous	1.13	16.15	0.89	7	0.01–0.14	NA	*P. miliaceum*	(Yu et al., 2014)
Silt loam	Tap	1.09	6.20	0.50	7	0.02–0.21	NA	*G. max*	(Yu et al., 2014)
Silt loam	Tap	1.09	4.01	0.26	7	0.00–0.15	NA	*S. tuberosum*	(Yu et al., 2014)
Loam	Mixture	1.31–1.39	0.84	0.73	27	0.76–4.60	NA	*C. dactylon, V. negundo*	(Liu et al., 2016)
Loam	Mixture	1.31–1.39	0.56	0.72	26	NA	0.40 – 5.84	*C. dactylon, V. negundo*	(Liu et al., 2016)
Loam	Fibrous	1.21	0.41	0.36	409	0.30–17.98	NA	*P. virgatum*	(Zhang et al., 2013)

[a] Mixture refers to a mixture of fibrous and tap roots. BD is topsoil bulk density, b is parameter value of Eq. (1), n is number of observations, NA is not available.

traits can be used to select species to control soil erosion processes (De Baets et al., 2009; Burylo et al., 2014; Bochet and García-Fayos, 2015). Considering concentrated flow erosion, root density (RD), whether or not in combination with root diameter (D), and root length density (RLD) are the most frequently used root traits to estimate the erosion-reducing potential of plant species and to select the most suitable plant species for controlling soil erosion processes (e.g. De Baets et al., 2009; Pohl et al., 2009; Burylo et al., 2012; Vannoppen et al., 2016). The relationship between the erosion-reducing potential and root density or root length density is most often described by a negatively exponential relationship (Eq. (1); Table 1):

$$SDR = e^{-b*R(L)D} \tag{1}$$

with SDR the soil detachment ratio expressed as the ratio of the absolute soil detachment rate of a root-permeated soil and a root-free bare soil, R(L)D respectively the root density (RD, kg m^{-3}) and the root length density (RLD, km m^{-3}) and b a regression parameter. The higher the value of b, the more expressed is the erosion-reducing effect of plant roots.

A large number of studies quantified the erosion-reducing effects of plant roots (Vannoppen et al., 2015; Table 1). This erosion-reducing effect depends on root system type (e.g. De Baets et al., 2007; Reubens et al., 2007; Stokes et al., 2009). Given a certain root density, a root system consisting of fibrous roots is hypothesized to have a larger erosion-reducing potential compared to a tap root system due to the larger root-soil contact (Dissmeyer and Foster, 1985). As such root diameter is important to consider as well when using RD as independent variable to predict the erosion-reducing potential of plant roots (e.g. De Baets and Poesen, 2010; Burylo et al., 2012). While most of the reported studies are focused on silt loam soils, sand or sandy loam soils are barely studied. However, coarse-textured soils can be very prone to incisive soil erosion processes. Infiltration rates in coarse-grained soils are, in general, higher compared to fine-grained soils (e.g. Moldenhauer and Long, 1964). However, once those soils are saturated or a less permeable surface layer is formed due to sealing and crusting (Poesen, 1986; Valentin, 1991), overland flow will occur, leading to incisive erosion processes on sloping land due to the low soil strength at saturation of coarse-grained soils (Poesen, 1992). This may then lead to intense soil erosion and/or infrastructural damage such as: 1) the formation of large gully systems (e.g. Poesen et al., 2003; Imwangana et al., 2015; Vanmaercke et al., 2016), 2) the destruction of sandy levees causing flood risk (e.g. Vannoppen et al., 2016) and 3) the destruction of earth-banks along roads or at construction sites (e.g. Jägerbrand and Alatalo, 2014).

Soil characteristics are also important to consider when studying concentrated flow erosion rates as they influence the soil erodibility (Knapen et al., 2007). A commonly used variable in the assessment of soil erodibility is soil texture as an increase in sand content generally increases the soil's erodibility (e.g. Elliot et al., 1989; Sheridan et al., 2000a, 2000b). On the other hand, an increased clay fraction decreases the soil's erodibility due to their bonding forces (Smerdon and Beasley, 1959). Poesen (1992) also observed an increasing apparent cohesion with decreasing particle size in saturated soils; i.e. from 1–2 kPa for sandy soils to 4–6 kPa for silt loam soils. In addition dry soil bulk