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Estimation of runoff mitigation by morphologically different cover crop root systems

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SUMMARY

Hydrology is a major driver of biogeochemical processes underlying the distinct productivity of different biomes, including agricultural plantations. Understanding factors governing water fluxes in soil is therefore a key target for hydrological management. Our aim was to investigate changes in soil hydraulic conductivity driven by morphologically different root systems of cover crops and their impact on surface runoff. Root systems of twelve cover crop species were characterized and the corresponding hydraulic conductivity was measured by tension infiltrometry. Relations of root traits to Gardner's hydraulic conductivity function were determined and the impact on surface runoff was estimated using HYDRUS 2D. The species differed in both rooting density and root axes thickness, with legumes distinguished by coarser axes. Soil hydraulic conductivity was changed particularly in the plant row where roots are concentrated. Specific root length and median root radius were the best predictors for hydraulic conductivity changes. For an intensive rainfall simulation scenario up to 17% less rainfall was lost by surface runoff in case of the coarsely rooted legumes *Melilotus officinalis* and *Lathyrus sativus*, and the densely rooted *Linum usitatissimum*. Cover crops with coarse root axes and high rooting density enhance soil hydraulic conductivity and effectively reduce surface runoff. An appropriate functional root description can contribute to targeted cover crop selection for efficient runoff mitigation.

1. Introduction

Hydrology plays a key role for productivity of different biomes, including agriculturally used land. Therefore understanding relevant influences on hydrological processes is fundamental for ecosystem management. Runoff is a key water loss component with strong impact on crop production, vegetation restoration and ecosystem services such as water resource conservation (Gyssels et al., 2005; Valentin et al., 2005). Soil erosion by surface runoff is recognized as the main process causing land degradation and desertification (Karamesouti et al., 2015; Mueller et al., 2014). Worldwide about 90% of agricultural soil is affected by erosion, while in Europe about 30% are under risk of degradation (Pimentel et al., 1995; Van der Knijff et al., 2000). Runoff and erosion are essentially influenced by land use and vegetation type, where agricultural soils are more vulnerable compared to grassland and forest soils (Yang et al., 2003; Souchère et al., 2003; Wang et al., 2012).

Runoff initiation is the result of rainfall intensity exceeding soil infiltrability, thereby leading to temporary saturated conditions at/near the soil surface (Horton, 1945; Cantón et al., 2011). A first scale of analysis therefore regards soil infiltrability (Hillel, 1980). Soil structure in the top soil layers is particularly critical as it dominates water transport in the saturated and near-saturated range (Cresswell et al., 1992) and is strongly management-sensitive (Bronick and Lal, 2005). Plant roots are key drivers of soil structure enhancing aggregate formation and stability (Haynes and Beare, 1997; Kavdır and Smucker, 2005) and improving soil shear strength (Gyssels et al., 2005; De Baets et al., 2008). Root induced macropores are of particular importance for runoff mitigation due to their large diameters and high connectivity, enhancing rapid rainfall infiltration and percolation to deeper soil layers (Cresswell and Kirkegaard, 1995; Ghestem et al., 2011; Horn and Smucker, 2005; Suwardji and Eberbach, 1998).

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Plant effects on soil structure are species dependent. For annual plants root diameter was shown to be an important trait for root induced pore formation, particularly in soil with high mechanical resistance (Bengough, 2012). Bodner et al. (2014) demonstrated that legume species with coarse root axes created substantially more macropores compared to fine rooted species.

At the scale of local to regional hydrological studies, ecohydrology (Rodriguez-Iturbe, 2000) has substantially increased the awareness on how vegetation shapes hydrological processes. Table 1 provides examples of hydrological studies where plant roots were revealed as key drivers for water flow processes and different components of the water balance.

From Table 1 it can be concluded that plant roots influence all main water flow processes that determine the hydrological regime, i.e. runoff, drainage and evapotranspiration. While root distribution and rooting depth are the key parameters for evapotranspiration (that itself influences runoff and drainage), root morphological traits such as density and diameter appear more relevant in their direct effect on runoff, erosion and drainage via changes in soil hydraulic properties.

In spite of the advance in understanding the importance of plant roots in small scale root–soil structure interactions and various hydrological processes, we notice that only few studies combine a quantification of root–soil structure relations with hydrological consequences of relevance for larger scale water cycle considerations. Hydrological studies frequently rely on models where the plant root effect is limited to water uptake without taking into account root induced modifications of soil hydraulic properties. Root–soil structure studies on the contrary increasingly advance toward smaller scales of single root–pore interactions, while ignoring the potential hydrological importance at the ecosystem scale.

Particularly for agriculture however such a link is of key importance: soil erosion from agricultural catchments is a key environmental concern, while management measures strongly impact on soil structure. Cover cropping has become such a common agricultural tool to improve soil quality and to reduce runoff and soil erosion (Dabney, 1998; Dabney et al., 2001; Hartwig and Ammon, 2002). Most studies interested in runoff and erosion focus on the role of surface coverage by canopy/mulch (e.g. González et al., 2004). Still the cover crop root system is known to essentially influence structure related soil properties (Kabir and Koide, 2002; Liu et al., 2005; Joyce et al., 2002; Carof et al., 2007; Bodner et al., 2008) and therefore can play a key role in reducing water losses by surface runoff.

Our study therefore aims to link the ability of cover crop root systems to modify soil hydraulic conductivity with the hydrological implication of these changes for runoff mitigation from agricultural soils. For this purpose we combined empirical root and soil structure research through hydrological modeling. Our objectives were to (i) quantify the extent of root induced changes in soil hydraulic conductivity by different cover crop species; (ii) analyze which root system traits most strongly condition soil hydraulic conductivity; and (iii) estimate the resulting impact on surface runoff under different rainfall scenarios. The results should demonstrate the root system contribution to runoff and erosion mitigation in crop rotations including cover crops for soil protection.

2. Materials and methods

2.1. Study site and experimental design

The study was carried out in a field experiment at the Experimental Station Groβ Enzersdorf of the University of Natural Resources and Life Sciences, situated in Lower Austria (48°14′N,

Table 1
The role of plant roots in hydrological studies at different scales. Studies are ordered by year of publication and by author name within the same year.

Author/Study type	Process/scale	Root parameter	Key result
Feddes et al. (2001)/Review	Water uptake/local to regional	Root distribution, rooting depth	Root parameterization and model type are essential for accurate modeling of hydrological cycles; development of improved models requires better databases for parameterization
Gyssels et al. (2005)/Review	Soil erosion/local	Root mass, root density	For rill and gully erosion prevention, roots are equally important than canopy cover
Zhou and Shangguan (2005)/Experimental	Soil erosion	Root surface area density	Root surface area density in top-soil exponentially increased erosion stability in a loess soil
Hayashi et al. (2006)/Experimental	Pore size distribution/local	Presence of roots (*qualitative assessment*)	Intense rooting of forest soils enhances structural macroporosity
Laio et al. (2006)/Modeling	Water uptake/local	Root distribution	Root distribution and water uptake profiles of vegetation in water limited ecosystems are controlled by mean rainfall infiltration depth
Pannell and Ewing (2006)/Review	Water table depth/regional	Rooting depth	Land use change from deep rooted perennials to shallow rooted annual crops increases the risk of rising saline water tables
Seyfried and Wilcox (2006)/Experimental	Groundwater recharge/regional	Rooting depth	Reduced rooting depth of post fire rangeland vegetation results in increased groundwater recharge rates
De Baets et al. (2007a)/Experimental	Soil erosion/local	Root density, root diameter	Dense top soil root systems of native grasses have highest potential to reduce erosion in Mediterranean erosion prone sites
Shen and Phanikumar (2010)/Modeling	Catchment flow/regional	Rooting depth/root efficiency	Rooting depth together with a root efficiency factor is required to assess the role of different plant types in a new hydrological model
Donohue et al. (2012)/Modeling	Catchment flow/regional	Rooting depth	Long term catchment water flow is highly sensitive to effective rooting depth
Jost et al. (2012)/Experimental	Runoff/local	Rooting depth	Tree species that differ in rooting system lead to different runoff responses in the same soil type
Schwärzel et al. (2012)/Experimental	Preferential flow/local	Root architecture	Tree roots funnel water from stem-flow and constitute a preferential path for subsurface water flow
Wang et al. (2012)/Experimental	Runoff/catchment	Root water uptake	Land use types with low root water increase runoff at catchment scale
Yu et al. (2012)/Experimental	Colloid transport/local	Root density	Dense root systems contribute to reduced colloidal contaminants in surface runoff
Öztürk et al. (2013)/Modeling	Catchment flow/regional	Rooting depth	Root depth is a key parameter for coupling land use model and hydrodynamic models