

Insights into the processes and effects of root-induced changes to soil hydraulic properties

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Abstract

Root-induced changes to soil hydraulic properties (SHP) are a vital component of the soil-vegetation hydrological feedback, and the change in water balance that occurs following a change in land use such as revegetation of mine earth covers. In this paper we review our recent work that attempts to quantify the processes by which soils modify SHP and the consequences of this for the water balance. We illustrate the dominant mechanism by which roots modify SHP is the modification of pore geometry. We developed models to predict the effect of roots on SHP, based upon the assumption that the geometry of roots within pore space can be represented by concentric cylinders. Model predictions agreed with observations: the greatest effect of roots on SHP is in near- to saturated hydraulic conductivity; however, the size of the effect depends upon soil texture, root decay, and the connectivity of root modified pores. Simulation modelling showed that the root modification of SHP caused the greatest change to the water balance in fine-textured soils, mainly because of an increase in infiltration rate and subsequent decrease in runoff. We identify a number of areas that require further investigation to improve our understanding of how roots modify SHP.

Key Words

Roots, soil, water, model, hydraulic conductivity, ecohydrology

Introduction

Root-induced changes to soil hydraulic properties (SHP) can have a significant effect on the hydrology of an ecosystem. In arid environments, these changes are an important component of the soil-vegetation hydrological feedback, where they contribute to increased water availability to plants by increasing the rate and /or depth of rainfall infiltration where vegetation is present. This feedback can lead to the development of spatial vegetation patterns that form an optimal run on – run off system. Also, when a land use change occurs such as from annual crops to forestry, or the revegetation of mine-site covers.

Until recently, the most common approach to modelling root-induced changes to SHP employed an empirical relationship between vegetation density and infiltration rate (HilleRisLambers *et al.*, 2001). This model has been used to investigate the effect of environment factors on the spatial organisation of vegetation in arid areas (e.g. Ursino, 2007). However, this relationship is not universally applicable to all ecosystems and it assumes an instantaneous increase in infiltration rate, whereas in reality there is a time lag between plant establishment and an increase in infiltration rate that is dependent upon the lifespan and rate of decay of the root system. The development of a model that was process based and applicable to a range of soils and plant types was a major motivation of the work we report here.

In this paper we review our recent work that attempts to bridge the gap between studies on root physiology and root-induced changes to SHP. First, we discuss the processes associated with root growth that lead to changes in SHP. We then present a modelling framework for quantifying the impact of roots on soil hydraulic conductivity and water retention, which has the advantage of being compatible with physically-based water flow models and we illustrate the impacts of root-induced changes on the water balance by combining the two. Finally, we discuss the research questions that our work has raised which need to be addressed to improve our capacity to predict the impact of root-induced changes on SHP at an ecosystem level.

Processes by which roots modify soil hydraulic properties

The evidence available suggests that changing pore space geometry is the dominant mechanism by which roots modify SHP (Scanlan, 2009). First, changes to pore geometry are more permanent, lasting for time periods of months to years (e.g. Petersson *et al.*, 1987), while changes to fluid properties and aggregation persist over much shorter time scales (e.g. Norton *et al.*, 1990). Second, the changes to pore geometry lead to changes in SHP of a greater magnitude. For example, changes in saturated hydraulic conductivity of -90%

(Barley, 1953) to 650% (Li and Ghodrati, 1994) have been attributed to roots blocking pore space, and creating macro-pores when they decay respectively. In contrast, changes to fluid properties only changed water content by 7% where the whole soil solution was treated, whereas in reality only the solution in the vicinity of the root is affected. Based upon this, we developed a modeling framework that considered root-induced changes to pore geometry only.

Modeling Framework

The central assumption to our modelling framework is that the geometry of roots with pores can be simplified to concentric cylinders (Scanlan, 2009) (see Figure 1). To calculate capillary rise within concentric cylinders h_c we derived an expression based upon the same assumptions used to calculate capillary rise within a single cylinder h_s . Specifically, these assumptions are that capillary rise is due to a balance of upward and downward forces acting on the liquid, where the upward forces are a product of cylinder radius, surface tension and wetting angle, and the downward forces are a product of cylinder radius, liquid density and gravitational acceleration. Expressions for flux between concentric cylinders had been derived previously (Cutlip and Shacham, 1999; Wantanabe and Flury, 2008).

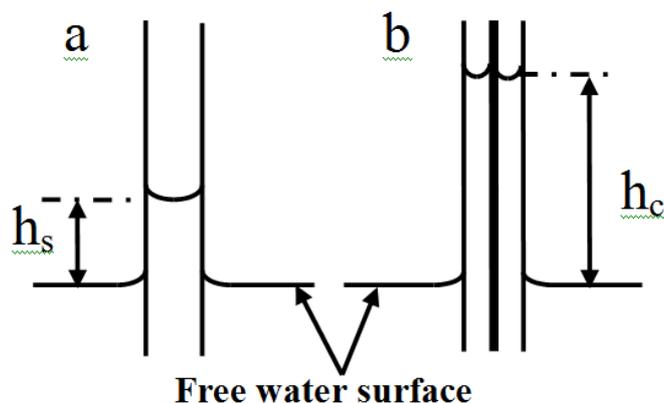


Figure 1. Cross-sectional illustration of capillary rise within a single cylinder (a) and within concentric cylinders (b). Note – drawing not to scale.

To quantify how capillary rise, flux and volume within a single cylinder will change when an inner cylinder is introduced we derived dimensionless expressions that are a function of the ratio of root radius to pore radius β only (Scanlan 2009). These ratios are presented graphically in Figure 2. We followed this approach because it allowed us to examine the effect of varying root radii on soil hydraulic properties.

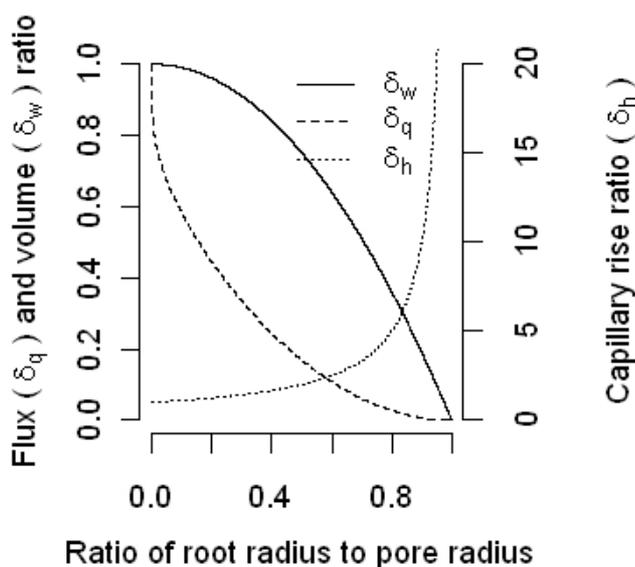


Figure 2. The effect of the ratio of root radius to pore radius on the change in flux, volume and capillary rise in pores with roots present (Scanlan, 2009).

Figure 2 illustrates the effect that the ratio of the radius of the inner cylinder to the radius of the outer cylinder has on flux, capillary rise and volume. The steepest increase in capillary rise occurs when β is greater than 0.8. The steepest decrease in flux occurs at values of β near to 0, which occurs because the inner cylinder is placed where velocity is highest in a single cylinder.

We modified existing models that predict the hydraulic conductivity and water retention functions of soil to include our scaling functions for flux, capillary rise and volume for root-occupied pores (Scanlan 2009). We modified the capillary bundle model by conceptualising the pore volume as bundles of pores with and without roots present. We assumed that roots modified the radius of pores that they occupy according to their root radius frequency distribution. We then modified the van Genuchten-Mualem model (van Genuchten 1980) using the multi-domain approach (e.g. Ross and Smetteml 1993), conceptualising the soil as two domains: pore space with and without roots. While both of these models predict the same output, they are fundamentally different. The capillary bundle model is based upon physical principles with only one empirical parameter that describes the connectivity of the flow path, whereas the (van Genuchten 1980) effective saturation function requires empirical parameters that describe the shape of the hydraulic conductivity and water retention functions. The differing basis of these models provided a complementary approach in our attempt to quantify the most important factors leading to root-induced changes to SHP.

Comparison of predicted changes in SHP with observations

Overall, the changes in hydraulic conductivity and water retention predicted by our models are in agreement with observations. The greatest effects predicted and observed due to root-induced changes were in the near-to saturated range of hydraulic conductivity (K_s). Our models also predicted either an increase or a decrease in K_s depending upon β , soil texture and the connectivity of root-occupied pores. This is in agreement with observations, where a decrease in K_s due to roots typically occurs when the plant is young and the roots are fully intact (e.g. Barley, 1954), then an increase in K_s occurs when the roots decay and create macro-pores (e.g. Li and Ghodrati, 1994): analogous to high and low values of β respectively.

Simulation modelling showed that root profile and soil texture determined the amount of change to the water balance. We implemented the modified van Genuchten (1980) model in a one dimensional soil-water flow model and simulated infiltration under ponded conditions for a loam soil one metre deep with free drainage at the bottom of the profile (Scanlan, 2009). When comparing infiltration rate in the loam before and after root modification we found that it was only greater, by approximately 700%, when the connectivity of root-modified pores was high and where roots were evenly distributed throughout the profile. This is slightly greater than the range of 200% (Meek *et al.*, 1989) to 600% (Rachman *et al.*, 2004) increases in ponded infiltration rate in field conditions that have been attributed to root-modification of SHP. However, there are two important differences between the simulated and real conditions: the vertical distribution of roots in real soils is typically exponential (e.g. Jackson *et al.*, 1996), and under real ponded infiltration lateral divergence of water flow occurs. Comparison of the simulated and observed changes in ponded infiltration rate suggests that the increase in infiltration rate that has been observed is due to a small number of relatively straight root-induced macro-pores.

Year-long simulations using high resolution rainfall data showed that root-induced changes had a significant effect on the water balance on fine-textured soils. We compared runoff, storage, and uptake for perennial plants growing on a sand, loam and clay with and without root-induced changes to SHP. Storage and uptake were significantly greater on the root-modified clay compared to the clay in its original state, which was due to an increase in hydraulic conductivity near the soil surface and as a result, a greater amount of rainfall infiltrating into the soil. This work provided a valuable first step in assessing how root induced changes will affect the water balance, however, further work is required as the impact of these changes on the water balance is likely to be sensitive to the combination of soil texture, plant type and rainfall distribution (Fernandes-Illescas *et al.*, 2001).

Outlook

Our research has highlighted a number of areas of research that require further work to improve our capacity to predict how root-induced changes to SHP affect the water balance. Field and laboratory measurement of SHP before and after root modification is required to test the validity of our assumptions: the connectivity of root-modified pores in particular. Also, in our work the parameterisation of the domain with roots was based

upon 'fine' roots only, which were usually excised from larger roots. The multi-domain structure of our modified van Genuchten model is ideally suited to incorporating large roots and warrants further work. We anticipate that moving from one- to two-dimensional analysis will also help to improve our understanding of how root-induced changes affect the water balance.

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