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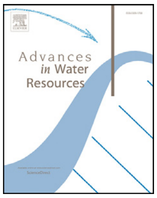

Water percolation through the root-soil interface

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ABSTRACT

Plant roots exude a significant fraction of the carbon assimilated via photosynthesis into the soil. The mucilaginous fraction of root exudates affects the hydraulic properties of the soil near the roots, the so called rhizosphere, in a remarkable and dynamic way. After drying, mucilage becomes hydrophobic and limits the rewetting of the rhizosphere. Here, we aim to find a quantitative relation between rhizosphere rewetting, particle size, soil matric potential and mucilage concentration. We used a pore-network model in which mucilage was randomly distributed in a cubic lattice. The general idea was that the mucilage concentration per solid soil surface increases the contact angle between the liquid and solid phases consequently limiting the rewetting of pores covered with dry mucilage. We used the Young–Laplace equation to calculate the mucilage concentration at which pores are not wettable for varying particle sizes and matric potentials. Then, we simulated the percolation of water across a cubic lattice. Our simulations predicted that above a critical mucilage concentration water could not flow through the porous medium. The critical mucilage concentration decreased with increasing particle size and decreasing matric potential. The model was compared with experiments of capillary rise in soils of different particle size and mucilage concentration. The experiments confirmed the percolation behaviour of the rhizosphere rewetting. Mucilage turned hydrophobic at concentrations above 0.1 mg/cm^2. The critical mucilage concentration at matric potential of -2.5 hPa was ca. 1% [g/g] for fine sand and 0.1 % [g/g] for coarse sand. Our conceptual model is a first step towards a better understanding of the water dynamics in the rhizosphere during rewetting and it can be used to predict in what soil textures rhizosphere water repellency becomes a critical issue for root water uptake.

1. Introduction

The rhizosphere is the layer of soil next to plant roots that is actively modified by root growth and exudation [17,21]. This layer of soil has an extent of millimetres up to a maximum of a few centimetres and it has a profound impact on soil hydrology. In fact, all the water that flows through the soil-plant-atmosphere continuum, which corresponds to 40% of the terrestrial precipitation [5], flows across the rhizosphere. Sposito [36] defined the flow of water through the rhizosphere as *productive green water* and suggested that rhizosphere processes are an essential element for sustainable and efficient use of soil-water resources.

The rhizosphere is where plants and soil meet and interact, and its physical, chemical and biological properties differ from those of the adjacent bulk soil [21]. In this study we focus on the physical properties of the rhizosphere and how they affect the water flow through the root-soil interface. Our starting-point are recent observations of water repellency in the rhizosphere [13,29]. Carminati et al. [13] found that the rewetting rate of the rhizosphere after a drying/wetting cycle was markedly slower than that of the bulk soil. They found that the rhizosphere of lupines subject to a drying cycle and then irrigated by capillary rise remained drier than the bulk soil for 1–2 days. Moradi et al. [29] showed that the slow rewetting of the rhizosphere was caused by the high contact angle of dry rhizosphere. Carminati [10] observed that rhizosphere hydrophobicity was more marked when the soil was let dry until the plants started to show wilting symptoms, which happened at volumetric water contents below 0.05. However, water repellency in the rhizosphere was also visible when the samples were kept relatively wet (at volumetric water contents above 0.10–0.15). These observations suggest that rhizosphere water repellency is more evident in dry soils, but it also occurs in a broader range of water contents.

Carminati [11] proposed that the water repellency of the rhizosphere resulted from mucilage exuded by roots. Mucilage is primarily exuded at the root tips and consists mainly of polysaccharides and a few percentages of phospholipids [18,28,30]. Guinel and McCully [18] reported that mucilage of maize (*Zea mays*) had a remarkable ability to swell and adsorb water and found that at saturation the

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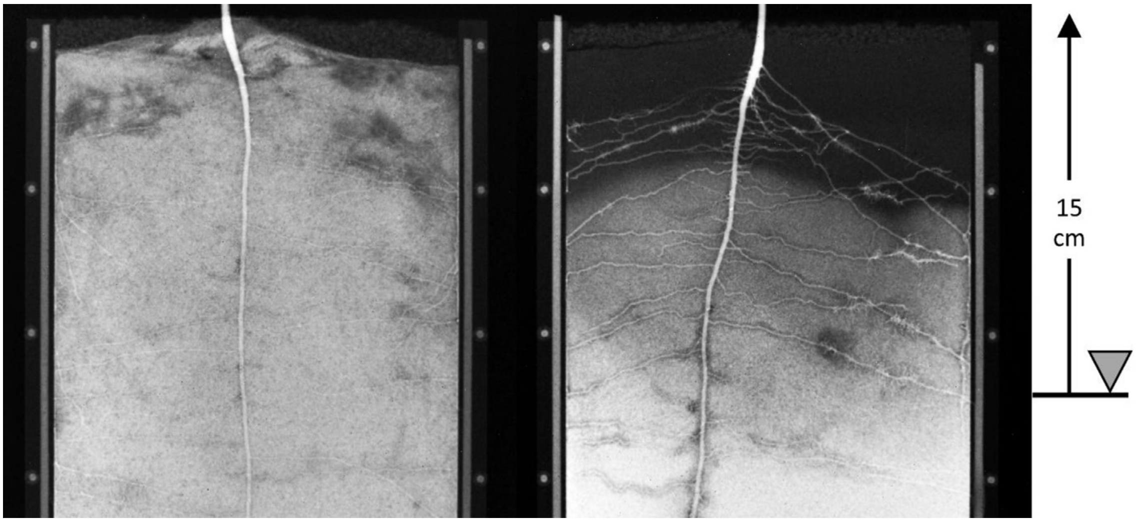

Fig. 1. Neutron radiographs of water distribution around the roots of lupines after irrigation. Left: lupine in a sandy soil; right: lupine in a coarse quartz sand. The samples were rewetted by capillary rise, with the water table at a depth of 15 cm from the soil surface. The grey values are proportional to the water content (dark=dry, bright=wet). Dry zones are visible around the roots, in particular in the coarse quartz sand (right).

weight of wet mucilage is 1000 times higher than its dry weight. Read et al. [31] measured similar mucilage water contents for fully hydrated maize mucilage. Impressed by the ability of mucilage to absorb water, McCully and Boyer [28] tested whether mucilage can hold large volumes of water also when the water potential decreases. They found that most of the water stored in fully hydrated mucilage was actually lost at water potentials less negative than −10 kPa. Nevertheless, Carminati [11] argued that the remaining mucilage water content is sufficient to increase the soil moisture of a few percentages. Young [38] came to a similar conclusion after measuring a higher water content in the rhizosphere of wheat compared to the adjacent bulk soil. Recently, Ahmed et al. [1] and Kroener et al. [26] showed that mucilage exuded by chia seeds increases the water content of a sandy soil at any water potential if the system is in hydraulic equilibrium. Similar observations were made by Deng et al. [16], who investigated the effect of mucilage exuded from the seed coating of *Capsella bursa-pastoris* L. Medik. on the water retention curve of a sandy clay loam. They found an increase in the saturated water retention due to the presence of seeds and/or mucilage. The increase in water content was visible for water potentials less negative than −10 kPa.

Although these studies suggest a positive effect of mucilage on increasing the water content in the rhizosphere, other studies showed an apparently opposite behaviour. Read and Gregory [32] observed that mucilage surface tension was smaller than the one of water. Read et al. [30] explained this reduction in surface tension as the effect of phospholipids. The reduction of surface tension is likely to decrease the capillary forces and to reduce the soil water content at negative water potential, as shown for an analogue of mucilage phospholipids (lecithin) mixed with a sandy loam [30]. The importance of the surface tension of mucilage is currently poorly understood, but it is likely to play an important role on rhizosphere hydrology, in particular in shaping the initial penetration of mucilage through the soil pores.

Upon drying, the phospholipids present in mucilage are expected to induce some degree of water repellency. In fact, Czarnes et al. [14] observed that soils mixed with polygalacturonic acid (one of the main components of mucilage) became water repellent. Hallett et al. [19] investigated the impact of four plant species on the hydraulic properties of rhizosphere soil and observed different magnitudes of water repellency among the samples. Furthermore, they suggested the idea that the rewetting rate of mucilage was reduced by mucilage swelling and consequent pore clogging. Moradi et al. [29] measured contact angles higher than 90° in the rhizosphere of lupine roots. Carminati et al. [13] used neutron radiography, to image the water content distribution around the roots of lupines in a sandy soil. They found that during drying the rhizosphere was wetter than the bulk soil. On the contrary, after irrigation the rhizosphere remained dry and it rewetted in a few days. Carminati [11] suggested that these two apparently contrasting behaviours are not in contradiction, but they are rather the result of the dynamic and time-dependent effect of mucilage on the hydraulic properties of porous media. At equilibrium conditions mucilage is capable of holding large volumes of water and it increases the soil water content at any water potentials [26]. After drying mucilage turns hydrophobic and delays the rhizosphere rewetting for a period of hours up to a few days [11], resulting in time-dependent and hysteretic hydraulic properties of the rhizosphere [26].

In the present study we investigate the water dynamics in the rhizosphere during the initial stage of the rewetting phase after the soil was let dry. Our objective was to quantitatively relate the rewetting kinetics of the rhizosphere to mucilage concentration, soil particle size and soil water potential.

To better motivate our study we refer to Fig. 1, which shows the water content distribution around the roots of lupines a few minutes after rewetting subsequent to a severe drying. The grey values are proportional to the water content (dark=dry, bright=wet). The images were obtained using neutron radiography. The details of the experiments are described in Carminati [10]. The samples were 30 cm high and were irrigated by capillary rise, with the water table being placed at 15 cm below the soil surface. The lupine plant on the left side was grown in a sandy soil composed of coarse sand (6.59%), medium sand (49.9%), fine sand (31.5%), coarse silt (3.35%), medium silt (1.8%), fine silt (1.81%) and clay (5.05%). The lupine on the right side was grown in quartz sand with a particle diameter of 0.2 to 0.63 mm. The radiographs show that in both samples the water content in the direct vicinity of roots was reduced, but the reduction was much more marked and evident in the coarser quartz sand (sample on the right side). Note that the reduction in water content near the roots was caused by the altered contact angle of the rhizosphere and could not be trivially explained as the effect of water depletion due to root uptake. Indeed, the soil water content in the two samples was high enough to allow a fast redistribution of water in the soil. The water that roots took up from the rhizosphere was very quickly replaced by water flowing from the bulk soil adjacent to the rhizosphere.