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Effects of three morphometric features of roots on soil water flow behavior in three sites in China

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ABSTRACT

Soil physical properties, infiltrability, and water flow behavior are closely associated with root morphology. In this study, dye tracer experiments were conducted in the field to assess the effects of roots with various morphometric features on soil water flow behavior and soil infiltrability. Preferential flow is the dominant type of water flow in the three study sites (Minqin, Dongtai, and Mengla). The presence of roots caused noncapillary porosity and saturated hydraulic conductivity to increase by 26% and 252% in the Minqin, 92% and 93% in the Dongtai, and 234% and 96% in the Mengla, respectively, relative to that in in soils without roots. The various morphometric features of roots affect water flow behavior in soil. The fibrous roots of maize induced water to flow and distribute evenly throughout the plough layer of the study site in Minqin. Furrows and ridges in this site exhibited different soil physical and hydrological properties. Furrows could store higher amounts of water than ridges, thereby increasing the likelihood of water absorption by plants. In Dongtai, ponding and surface runoff occurred when water infiltration was inhibited by the mud layer, which exhibited a high soil bulk density value of 1.43 g cm^{-3} and a low saturated hydraulic conductivity value of 1.67×10^{-5} cm s^{-1}. These phenomena were not observed in plots the smooth roots of *Spartina alterniflora* penetrated the mud layer. In this site, preferential flow and lateral flow, which is triggered by the sandy loam layer, are important for water discharge from the beach to the ocean. In Mengla, water flowed evenly on hard soil, which exhibited a high bulk density value of 1.43 g cm^{-3}. The fine roots of rubber could guide water infiltration into deep soil layers (73.54 cm), thereby redistributing water to the root zones of rubber trees. Therefore, our findings indicated that water infiltration behavior, which is crucial for water distribution, is affected by the various morphometric features of roots.

1. Introduction

Water infiltration through soil is associated with surface runoff, soil erosion, plant water storage, and groundwater recharge (Lipiec et al., 2006). In addition to water infiltration amount, water flow behavior is increasingly recognized as a major factor of water distribution in soils (Jiang et al., 2017c).

Types of water infiltration through soil generally include matrix and preferential flows. Matrix flow is defined as the slow movement of water and solutes through bulk soil (Allaire et al., 2009). Preferential flow is defined as the physical movement of water and solutes along certain pathways while bypassing a fraction of the pore matrix (Hendrickx and Flury, 2001). In this case, water and solutes move to far greater depths than the depths predicted through Richards' equation, which is based on area-averaged moisture contents and pressure heads (Beven and Germann, 1982). Preferential flow occurs in most soils and is often attributed to macropore flow through cracks, fissures, or voids and between peds or through biopores, such as earthworm burrows, roots channels, and crab burrows (Flury and Flühler, 1995; Xin et al., 2016). Preferential flow in soils does not only result from macropore flow but also from on-homogeneous infiltration, lateral flow, and wetting front instabilities (Allaire et al., 2009; Bundt et al., 2001). Lateral flow refers to the infiltration of laterally moving water (Oostindie et al., 2013; Ritsema and Dekker, 1995; Wine et al., 2012). Dye tracers may be used to visualize preferential flow paths in soils (Flury and Flühler, 1994; Ghodrati and Jury, 1990). Dye patterns could

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be classified by processing the original dye-stained soil profiles through image analysis programs. Thus, different types of water flow behavior (e.g., preferential flow and lateral flow) and their quantitative information (e.g., dye-stained width, depth, and area) can be directly interpreted from the classified dye patterns (Cey and Rudolph, 2009; Ghodrati and Jury, 1990).

Water infiltration in soil is affected by several external factors, such as tillage and management practice (Jiang et al., 2017a; McGarry et al., 2000); vegetation cover and soil texture (Castellano and Valone, 2007); and compaction through trampling by livestock, traffic, and machines (Fleischner, 1994; Wang et al., 2015). Moreover, internal factors, such as soil structure, water repellency, soil bulk density, thermal conductivity, evapotranspiration rates, and soil microorganisms could affect soil water infiltration (Bond, 1964; Bond and Harris, 1964; Czarnes et al., 2000; DeBano et al., 1977). Other factors that affect soil water infiltration include the formation of ash particles resulted from vegetation fires (Mallik et al., 1984); incorporation of objects (e.g., residual plastic film, straw, and stones) into soil (Jiang et al., 2017b; Kodešová et al., 2012; Laine-Kaulio et al., 2015); features of roots (Gibbs and Reid, 1988); channels of roots (Beven and Germann, 1982; Flury and Flühler, 1995); and soil fauna (Tebrügge and Düring, 1999).

The influenced of roots and their morphometric features on preferential flow should be considered. Old roots channels that have openings at the soil surface (Wang and Strong, 1996) and decaying roots that appear at deep penetration depths in the vertical direction (Mitchell, 1995) are considered as soil macropores. Roots channels are a type of macropore with specific properties, organization, kinetics, and control factors. Root architecture and traits, such as diameter, length, orientation, topology, sinuosity, and decay rate, influence the creation of roots channels and thus affect preferential flow. In particular, root diameter can be smaller than rhizopore diameter, thus presenting a cylindrical space for potential water flow (Ghestem et al., 2011). In addition, fibrous or smooth roots could induce different kinds of water infiltration behavior. However, the effects of roots with different morphometric features on water infiltration characteristics through soil have never been reported in the literature. Thus, the effects of roots on water infiltration behavior should be monitored and quantified. In this study, we selected three kinds of roots with various morphometric features from three sites. In addition to acquiring soil physical property (e.g., bulk density and porosity) measurements, we conducted dye tracer experiments to simultaneously measure water infiltrability and trace water movement in soil. Moreover, we aimed to reveal the ecological significance of water infiltration behavior in the three study sites.

2. Materials and methods

2.1. Morphometric features of roots

The features of roots in three sites (Minqin, Dongtai, and Mengla) are shown in Fig. 1. The majority of the biomass of the fibrous roots of maize (*Zea mays* L.) was confined to the upper 20 cm soil layer. The smooth roots of *Spartina alterniflora* easily penetrated soil (Fig. 1 middle). The fine roots of rubber tree (*Hevea brasiliensis*) were primarily distributed in the upper 30 cm soil layer (Fig. 1 right). The root biomass per plot at each site is presented in Fig. 2.

2.2. Experimental site and design

To reveal the ecological significance of water infiltration behavior in various soils, different sites with special roots features were selected, namely Minqin having the fibrous roots of maize, Dongtai having the smooth roots of *Spartina alterniflora*, and Mengla having the fine roots of rubber tree (Fig. 3). The geographic locations and soil particle size distributions of the sites are provided in Table 1.

The Minqin Oasis is located in the northwest Gansu Province of China. The site has an arid continental climate with an average annual temperature of 7.8 °C. The mean precipitation and the average evaporation in the area is 110.5 mm year^{-1} and 2646.4 mm year^{-1}, respectively. Soils at the site developed from alluvial sediments with > 100 cm in depth. Its soil is classified as Anthropic Camborthids (IUSS Working Group WRB, 2014) (Fig. 3. I). The study site is under ridge-furrow cropping and is fully mulched with plastic film. It is cultivated with various crops, such as maize and sunflower. A detailed description of the experimental site is given in Jiang et al. (2017b). Loose top soil layers of 2 cm and 12 cm were carefully removed from the furrows and ridges, respectively, to prepare quadrants with horizontal surfaces. Center quadrants in the furrows matched sites of roots growth. Center quadrants in the wide ridge matched axle wires. Three quadrants with roots in the furrows were randomly selected as the roots plot, whereas three other quadrants without roots in the ridges were randomly selected as the no roots plot (Fig. 4. B). All quadrants were prepared from May 5 to 15 (2014), which corresponded to the jointing stage of spring maize (the roots was not large enough to stretch in ridges).

Dongtai is located in the central Jiangsu Province of China. The site has a monsoon climate ranging from warm-temperate to northern subtropical. The mean annual precipitation and temperature of the site is 1022.9 mm and 14.36 °C, respectively. The muddy flats in the site are even, with widths of 2–6 km. The widest width is 13 km. The width of the upper mudflat, which is suitable for *S. alterniflora* growth, is between 1 and 4 km. The soil under study is classified as Saline-alkaline (IUSS Working Group WRB, 2014) with alternating sandy loam and mud layers (Fig. 3. II). *S. alterniflora* seeds are carried by tidal waves to the higher flats of northwestern Tiaozini, where they germinate. Field observations showed that the *S. alterniflora* clump area was 5–30 m^2 with a mean density of 50–70 culms m^{-2}. Mean culm height was 1.0 m (maximum 2.0 m), and mean culm diameter was 0.45 cm. Single or several seedlings and small clumps sparsely grow around the external margins of the clump area, and three quadrants were randomly selected as the roots plot. Meanwhile, the other three quadrants (100 m to the sea), which were distance from the clump area, were randomly selected as the no roots plot (Fig. 5. B). All quadrants were prepared from April 10 to 20, 2015.

Mengla County is located in the southern Yunnan Province of China. The local climate is dominated by tropical southern monsoons from the Indian Ocean between May and October and subtropical jet streams between November and April. This area experiences three seasons: rainy, foggy cool, and hot dry. Climate records over the past 40 years showed that the area has a mean annual air temperature of 21.7 °C and mean annual rainfall of 1487 mm. Most of the precipitation (87%) occurs between May and October. The soil depth under vegetation is approximately 2 m. The soil in the study area is well drained and has a clay loam texture. The soil is classified as Ferralic Cambisol (IUSS Working Group WRB, 2014) that developed from alluvial deposits derived from sandstones. It exhibits an ochric A horizon and a cambic B horizon with ferralic properties (Vogel et al., 1995) (Fig. 3. III). A typical field with a land area of 60 m × 18 m and planted with 50-year-old rubber trees (clone PB86) was selected for this study. Owing to long-term cultivation and management measures, the field has a terrain slope of nearly 0°. Rubber trees were arranged 2 m apart in double rows, which were 3 m apart, and each set of double rows was separated by a gap 18 m in width. Roots and biomass changed along with the distance from the axle wire between two rows to rubber planted rows. Almost no roots were observed in the axle wire between two rows (18 m wide gap); thus, three quadrants within the axle wire (9 m to rubber tree) were randomly selected as the no roots plot. Meanwhile, the other three quadrants, which were 4 m to the nearest rubber tree, were selected as the roots plot (Fig. 6. B). All quadrants were prepared from October 1 to 10, 2016.