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Research papers

Hydraulic redistribution and its contribution to water retention during short-term drought in the summer rainy season in a humid area

Long Sun[a], Lei Yang[a,*], Liding Chen[a,b], Fangkai Zhao[a,b], Shoujuan Li[a,b]

[a] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

Hydraulic redistribution (HR) in sites with shallow soils and its response to random droughts during the summer rainy season in humid areas remains poorly understood. We investigated the soil moisture dynamics, HR and water buffer of shallow soils by monitoring the soil moisture content at multiple depths during a random drought event in the summer rainy season, in typical forestland and orchard in a subtropical area. Soil moisture sensors were installed at depths of 5, 10, 15, 20 and 30 cm at three sites (forest, peach1, and peach2). The total and net daily water use and water buffer capacity of the root zone were defined and calculated. During the short-term drought, the HR of soil moisture occurred at all sites, suggesting that it could be an important process in both forest and orchard land in response to short-term drought. HR occurred at both daily and multiple-day timescales in the shallow soils. The net daily water use had less difference between the sites than the total daily water use. Principal component analysis of the total and net daily water use showed only evident clustering characteristics for the total daily water use, indicating an important plant-soil interaction effect. The depth-averaged magnitude of daily HR varied from 0.385 mm (0.0077 $m^3 m^{-3}$) at the forest site to 0.725 mm (0.0145 $m^3 m^{-3}$) at the peach1 site. The redistributed water replenished over 75% of the water depleted from the shallow soil. In particular, soil moisture was better retained in 15–20 cm root zone than in other soil layers. Furthermore, the water buffer capacity of the forest site was not higher than those of the two peach sites (where land use converted from forest), indicating that land use conversion does not necessarily weaken soil water retention. The study results highlighted that HR has a significant influence on water recharge and water retention in humid area, thus benefiting plant drought tolerance and total water utilization. This study provides more insights to evaluate HR's effect on water retention and enhance our understanding of HR in shallow soils during random droughts in the summer rainy season in humid areas.

1. Introduction

Soil moisture is a key factor controlling plant growth and ecological and hydrological processes across multiple spatial scales in terrestrial ecosystems (Brooks et al., 2002; Dawson, 1993; Tang et al., 2015; Vereecken et al., 2014; Zehe et al., 2010; Zhao et al., 2016a). Soil moisture dynamics are closely related to plant activities and many other hydrological processes, such as transpiration, water retention/storage, overland flow initiation and even floods (de Boer-Euser et al., 2016; Domec et al., 2010; Luo et al., 2016; Oswald et al., 2011; Shaw et al., 2013; Spence et al., 2010; Sun et al., 2016b; Yang et al., 2014; Yang et al., 2012; Zehe et al., 2010). Many areas of earth are covered with shallow soils underlain by bedrock (Gaines et al., 2016; Hasenmueller et al., 2017; Schwinning, 2010), where stored soil water is limited and prone to loss. However, this limited water resource is important for plant water use (Dawson, 1993; Gaines et al., 2016). The limited water storage of shallow soil usually results in temporary water shortages, even in humid climates (Clermont-Dauphin et al., 2013; Fu et al., 2007; Miyamoto et al., 2004; Sun et al., 2006). Therefore, clear characterization of soil moisture variations and water retention in shallow soils is important, even in humid areas (Gaines et al., 2016; Isarangkool Na Ayutthaya et al., 2011).

Besides land use and vegetation, soil moisture variation is closely related to soil properties, such as texture, bulk density, and porosity (Lee et al., 2007; Meißner et al., 2014; Zhao et al., 2016a). In particular, soil porosity commonly determines the potential soil water storage (de Boer-Euser et al., 2016; Zhao et al., 2016a). Soil porosity and bulk density are usually related to water infiltration and retention (Zehe

* Corresponding author.
E-mail address: leiyang@rcees.ac.cn (L. Yang).

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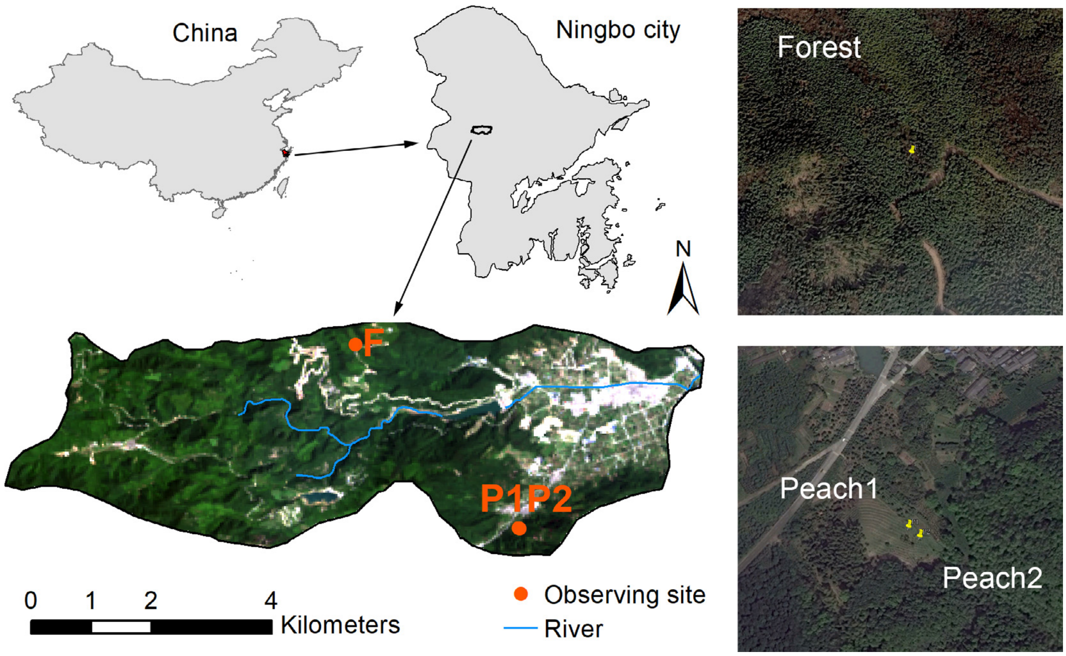

Fig. 1. Locations of three observation sites: a forest site (F) and two peach sites (P1 and P2).

et al., 2010). Soil properties significantly influence soil moisture movement and storage; however, soil moisture is more prone to being affected by land use, which mainly concerns plants (Good et al., 2015; Lu et al., 2013; Schlesinger and Jasechko, 2014; Zhao et al., 2016a). Plants play an important role in hydrological processes in ecosystems as well as soil moisture dynamics (Isarangkool Na Ayutthaya et al., 2011; Lu et al., 2013; Tan et al., 2011). For instance, transpiration water loss can exceed water uptake by plant roots during growing seasons when water is in low supply (Dawson, 1993; Luo et al., 2016). In such cases, plants respond to drought by reducing their transpiration by stomatal closure, to prevent excessive water deficits (Domec et al., 2010; Isarangkool Na Ayutthaya et al., 2011). Importantly, plant roots, as an integral component of the root zone, can release water stored in deep soil layers to the upper layers via hydraulic redistribution (HR) during drought periods (Brooks et al., 2002; Dawson, 1993; Gaines et al., 2016; Guswa, 2008; Priyadarshini et al., 2016; Quijano and Kumar, 2015).

The occurrence of chronic or random droughts during growing seasons could lead to trees capable of HR, i.e., the movement of water from moist to dry soil through their roots (Brooks et al., 2002; Cavender-Bares and Bazzaz, 2000; Dawson, 1993; Gaines et al., 2016; Neumann and Cardon, 2012; Schwinning, 2010). HR is movement from moist soil to drier soil, in the upward (hydraulic lift), downward, and lateral directions (Brooks et al., 2002; Yu and D'Odorico, 2014). HR increases the water potential in drier soil layers during the night (Dawson, 1993) and other periods when transpiration is reduced (Brooks et al., 2002; Luo et al., 2016; Nadezhdina et al., 2010). HR is usually reflected by diel fluctuations/oscillations in soil moisture content (Brooks et al., 2002; Dawson, 1993; Neumann and Cardon, 2012). For example, Dawson (1993) reported HR-induced diel fluctuations in soil moisture content at 20 and 35 cm soil depths and at 0.5, 1.0 and 1.5 m from the base of mature sugar maple trees. Redistributed water is available for reabsorption by the same plant or neighboring plants (Brooks et al., 2002; Dawson, 1993; Ishikawa and Bledsoe, 2000; Richards and Caldwell, 1987). HR has been recognized worldwide within a range of ecosystems and plant species; however, most studies have been conducted in temperate and (semi-) arid environments (Jordi and Josep, 2014; Nadezhdina et al., 2010; Neumann and Cardon, 2012; Priyadarshini et al., 2016; Yu and D'Odorico, 2014; Yu et al., 2013), or ecosystems with long summer droughts or even those receiving high precipitation (Brooks et al., 2006).

HR in sites with shallow soils and its response to random droughts during the summer rainy season in humid areas remains poorly investigated. HR may be an important determinant of soil moisture dynamics and associated water retention/storage (Bishop et al., 2011; de Boer-Euser et al., 2016; Isarangkool Na Ayutthaya et al., 2011; Oswald et al., 2011; Spence, 2007). Given the HR effect on soil moisture and soil-plant interactions, soil moisture variations in the shallow root zone are expected to be more complex in humid areas than previously understood (Isarangkool Na Ayutthaya et al., 2011; Luo et al., 2016; Neumann and Cardon, 2012; Prieto et al., 2012; Priyadarshini et al., 2016). HR has been measured for decades, and recent studies have primarily focused on its effects on nutrient cycling, plant interactions, drought tolerance, and climate change, while less characterization of its effect on water retention/storage has been completed (Armas et al., 2012; Brooks et al., 2002; Dawson, 1993; Domec et al., 2010; Neumann and Cardon, 2012; Priyadarshini et al., 2016; Richards and Caldwell, 1987; Tang et al., 2015; Yu and D'Odorico, 2014).

In this study, we investigated soil moisture dynamics in shallow soil layers in response to a typical random drought during the rainy season. Our hypothesis is that soil moisture would exhibit a non-monotonically declining trend and different water retention at different depths in the root zone. A related question regards whether and when HR occurred during the random drought in this period. The primary objectives of this study were (1) to characterize soil moisture variations at multiple depths, (2) to determine whether and when HR was triggered, and (3) to characterize the capacity of the water buffer at multiple depths during the random drought under different vegetation covers.

2. Materials and methods

2.1. Study area and experimental sites

The study area is situated in a humid area of eastern China (29°48′N, 121°19′E) (Fig. 1). The soil types in this area are mainly red, yellow and paddy soil. The soil layer in the watershed is shallow (ca. 30 cm on average) and is dominated by a silt loam in the 0–20 cm soil profile and sandy loam in the 20–30 cm soil profile. Beneath the shallow soil (> 30 cm) is generally weathered, fractured rock. The region has a moderate subtropical monsoon climate with warm and humid weather from April to September. The region has an annual