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Soil water and root distribution of apple tree (*Malus pumila Mill*) stands in relation to stand age and rainwater collection and infiltration system (RWCI) in a hilly region of the Loess Plateau, China

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ABSTRACT

Soil water status and fine root distribution is the basis of implementing water management in semiarid rain-fed orchards. Exploitation of rainwater is an effective avenue for alleviating water scarcity in semiarid regions since ground water is generally unavailable there. Through the method of space-for-time substitution, we investigated the soil moisture and root distribution along a range of stand ages (6, 9, 12, 18 and 21 years) in rain-fed apple (*Malus pumila Mill*) orchards and the effects of rainwater collection and infiltration systems (RWCI) on root-zone soil water and fine root distributions in matures apple orchards (21 years) in the semiarid Loess Plateau of China. The results showed that the mean soil moisture content (SMC) in the shallow layer (< 2 m) decreased with apple tree age (6 to 18 years); the deep SMC (> 2 m) was higher than shallow soil layers (< 2 m) in most cases and the SMC increased with depth in stands of all ages. Fine roots (< 2 mm diameter) showed an obvious trend of extending deeper with apple tree age - nearly 8 m in a 12-yr-old apple plantation and > 8 m in plantations > 12 years old. Dry root weight density (RWD) decreased sharply with depth, but densities at each depth were greater in older stands. The RWCI system significantly increased SMCs from the surface down to the maximum rainfall infiltration depth (MRID) (2 m depth) ($P < 0.05$), especially in the 0.2–1 m soil layer. Further, we found that apple tree water requirements could be sustainably met when RWCI system and a low-volume of irrigation water was applied. The distribution of root system was greatly affected by the RWCI system, which led to higher root densities close to the wetted area in the shallow soil layers (2 m soil depth) under RWCI system, down to a depth of 3 m in the soil. Overall, the application of RWCI system could be an effective water management strategy for providing sustainable water resources for semiarid orchards.

1. Introduction

Adequate infiltration of precipitation is critical to the persistence and productivity of rain-fed orchards in water-limited areas (Cao et al., 2009; Talon and Si, 2004). The semiarid region of the Loess Plateau of China has the largest aggregated planting area of apple trees in the world thanks to the deep and loose soils, abundant sunshine and large day-night temperature difference (Huang and Gallichand, 2006). Due to the complex topography and deep ground water (30-100 m) (Mu et al., 2003; Yang et al., 2012), the cost of irrigation is expensive in this region and thus the majority of apple orchards here are rain-fed. Rain-fed apple (*Malus pumila Mill*) production requires adequate and accessible soil water storage for a high, stable yield and best fruit quality (Ruiz-Sanchez et al., 2005). Thus, soil water (usually at > 2 m from soil surface) becomes especially during prolonged droughts. Understanding the role of this deeper soil water storage in meeting the water requirements of apple orchards is fundamental to developing soil water management practices to enhance tree growth and yield.

The root distribution defines the soil volume that trees can potentially explore to extract water and nutrients (Schulze et al., 1996).

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However, information remains inadequate on how tree roots are distributed in the Loess soil of northern China, and to what extent, soil water is accessible and utilized by the roots in the various depth increments of the soil profile. Soil textural changes have been shown to influence the root distribution patterns and soil water storage over a 21-m soil profile in seasonally dry environments (Oliveira et al., 2005; Wang et al., 2013). Nevertheless, soil water and tree root distribution over deeper soil profile depths has been much less studied compared to shallow profile depths. Most studies are based on sampling depths < 5 m instead of the maximum tree rooting depth because of the difficulty of collecting soil samples at deep depth increments (Schenk and Jackson, 2002; Schume et al., 2004; Huang et al., 2005; Li et al., 2008; Yao et al., 2012). For example, Song et al. (2016) showed fine roots of mature apple trees were concentrated with 3 m of the surface, with most in the 0–1 m depth. It is necessary to investigate and fully understand the relationships between root and soil water distribution over the entire rooting depth (Ma et al., 2013).

Water availability is the primary factor limiting growth for many species such as apple tree in loess hilly region (Zhang et al., 2011). In most cases, continuous drought during critical stages of plant growth with only short, intense rainfall events together with low nutrient input tend to decrease plant output (Barron and Okwach, 2005; Fox et al., 2005;Gao et al., 2018). This unmatched supply-demand relationship is exacerbated by surface runoff losses. Developing water saving irrigation has been identified as a very effective intervention to continue the sustained development of agriculture. However, water-saving techniques such as sprinkler systems, drip irrigation and micro-irrigation are not feasible for the hilly region of the Loess Plateau because the orchard land of each peasant household is small (usually < 1 ha), discontinuous, and the high expense associated with irrigation equipment for small-holding farmers and difficulties associated with pumping water from gully bottoms to reservoirs on the top of hill-slops (at least 30 m change in elevation) (Song et al., 2016, 2017). In this area, rainwater is the most valuable water resource, and water erosion is still very severe in the hilly rain-fed orchards. Rainfall runoff regulation is an important way to solve the problem of drought and soil erosion. And the exploitation and utilization of rainwater as resources is an effective measure for alleviating water scarcity (Zhao et al., 2005).

In recent years, in-situ rainwater collection and infiltration (RWCI) systems for individual trees has been developed and used by some small-holding farmers in the hilly orchards near Yanan City, Shaanxi Province to harvest rainwater in order to provide a sustained supply of water and nutrients for apple tree growth (Song et al., 2016, 2017). In these systems, rainwater and runoff is diverted in order to infiltrate deeper into the rhizosphere of the individual trees. These systems are designed to increase soil water storage and availability during the dry periods by reducing runoff and soil evaporation and improving rain use efficiency. However, few studies have investigated soil water and root distribution of apple trees at a range of stand ages in these systems on in the Loess Plateau.

The primary objective of the present study was (1) to investigate the distribution of soil moisture and fine roots over a depth of 8 m in apple orchards under a range of stand ages on the semiarid region of the Loess Plateau, and (2) to probe the effects of the RWCI system on soil moisture and root distribution of apple trees.

2. Materials and methods

2.1. Study location

The field study was conducted in rain-fed apple orchards of Tianhe watershed near the city of Yanan (109°21′–109°25′E, 36°37′–36°40.5′N), which is in the middle of the Loess Plateau in northern Shaanxi Province (Fig. 1) and is typical of the Loess Plateau of hilly-gully region. The main landform types are ridge, hills and gully. The main soil types in this study area are Inceptisols developed from loess parent material with low fertility and high vulnerability to soil erosion (Song et al., 2016). Intense rainfall events during the rainy season can result in run-off and soil erosion. The maximum rainfall infiltration depth (MRID) for this area is 2 m (Chen et al., 2005; Zhao et al., 2009; Chen et al., 2011; Yang et al., 2012; Ma et al., 2013). The area has an arid to semiarid climate, with an average, annual rainfall of 400–600 mm and a mean annual air temperature of approximately 7–11 °C (Bao et al., 2012). The daily highest and lowest temperature and daily precipitation in 2015 are shown in Fig. 2. The annual frost-free growing season lasts 170–186 days. The physical characteristics of undisturbed samples of this Loess over the depths of 0–200 cm are in Table 1. The annual water consumption (2003–2009) of apple trees on the rain-fed apple orchards in Yanan is presented in Table 2 (Meng, 2011) (Fig. 3).

2.2. Experimental units

The study area consisted of sloping (15% slope) and flat land with stands between 6 and 21 years old (established in 2009, 2006, 2003, 1997 and 1994, respectively). There were six apple orchards selected (space-for-time substitutions), which were A1 = 6 years, A2 = 9 years, A3 = 12 years, A4 = 18 years, A5 and A6 = 21 years at the sampling time in 2015. The experimental units were 9 randomly-selected trees in each of the 6 stands of rain-fed ‘Fushi’ apple (*Malus pumila Mill*) trees in a contiguous area of the Loess Plateau shown in Fig. 1. The 9 trees in each stand were chosen based on uniformity in canopy, height, and diameter as shown in Table 3. There was a trend of increasing trunk diameter with the increase of apple tree age (from A1 to A5). However, the value of trunk diameter in A5 (with in-situ RWCI system) was greater than that in A6 (without in-situ RWCI system). Tree height and crown diameter did not show the same changing rule as trunk diameter due to pruning and training fruit tree. Four stands were on flat land with trees aged 6, 9, 12, and 18 years spaced 4 m within rows and 5 m between rows. These were designated as A1 through A4 in order of increasing age. Two stands with 21-year old trees designated as A5 and A6 were on the hill-slope spaced 4 m along the west-facing slope and 5 m down-slope. The in-situ RWCI system was implemented for trees in stand A5 in 2013, in A1 to A4 in 2015, but not in A6. These two stands were included to determine whether there were any marked effects with and without the RWCI system on the hill-slope. Stands A1 through A4 and A6 were in privately-owned orchards. Stand A5 was part of a long-term public funded research field trial (Fig. 1). The mean study area of each stand apple orchards was 6.67×10^{-2}, 4.67×10^{-2}, 2.00×10^{-1}, 2.00×10^{-1}, 6.67×10^{-1} and 6.67×10^{-1} ha in A1 to A6, respectively (Table 3).

2.3. The RWCI system

The RWCI system on the hill-slope consisted of a semi-circular ridge of radius 1.7 m and height 0.15 m and was constructed upslope of individual trees. The ridge was constructed by excavating and moving soil such that the tree trunk was at the apex of the semi-circular ridge and to make the soil surface within the semi-circle area relatively flat. Viewed from above, these ridges formed an upslope ‘fish scale’ pattern along each row in the orchard (Fig. 1a). A soil pit 80 cm × 80 cm × 60 cm deep was dug within the semi-circular ridge in line with the tree trunk. The down-slope wall of this pit was 90 cm from the tree trunk. The bottom of this storage pit is lined with impermeable plastic film. A section of PVC pipe 50 cm long and 15 cm diameter was placed vertically in the center of each pit. Holes 0.1 cm diameter and placed 2 cm apart were drilled in the wall of the tube at 11 locations along the circumference. The surrounding space around this tube was filled with a mixture of soil, plant residues (straw, weeds, branches), and organic fertilizer. The surface of this space was then covered with plastic film. The ‘fish-scale’ ridges would collect rainfall runoff which would flow into the PVC pipe and infiltrate into the fill material though the holes in

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