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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

Xiaolin Song[a,c,d], Xiaodong Gao[b,c,d], Miles Dyck[e], Wei Zhang[c,d,f], Pute Wu[a,b,c,d], Jie Yao[g], Xining Zhao[b,c,d,*]

[a] *College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling, Shaanxi 712100, China*
[b] *Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China*
[c] *Institute of Water Saving Agriculture in Arid Areas of China, Northwest A&F University, Yangling, Shaanxi 712100, China*
[d] *National Engineering Research Center for Water Saving Irrigation at Yangling, Yangling, Shaanxi 712100, China*
[e] *Department of Renewable Resources, University of Alberta, Canada*
[f] *Institute of Water Conservancy and Architectural Engineering, Northwest A&F University, Yangling 712100, China*
[g] *Baota District Fruit Bureau in Yanan City, Yanan 716000, 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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[*] Corresponding author at: Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China.
E-mail address: zxn@nwafu.edu.cn (X. Zhao).

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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

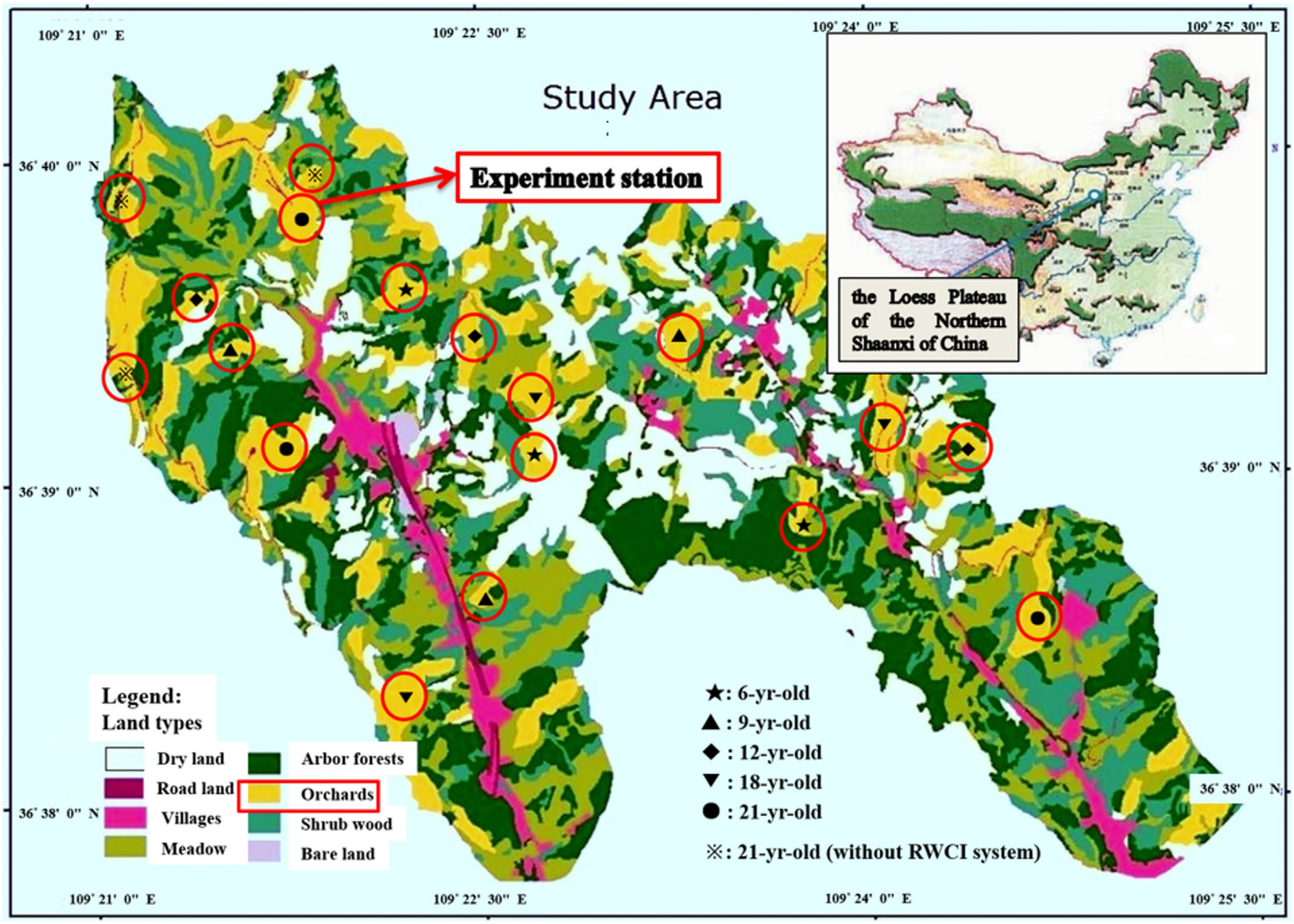

Fig. 1. Location of the study area and sampling sites in the rain-fed apple orchards of the Tianhe watershed on the Loess Plateau of the Northern Shaanxi of China.

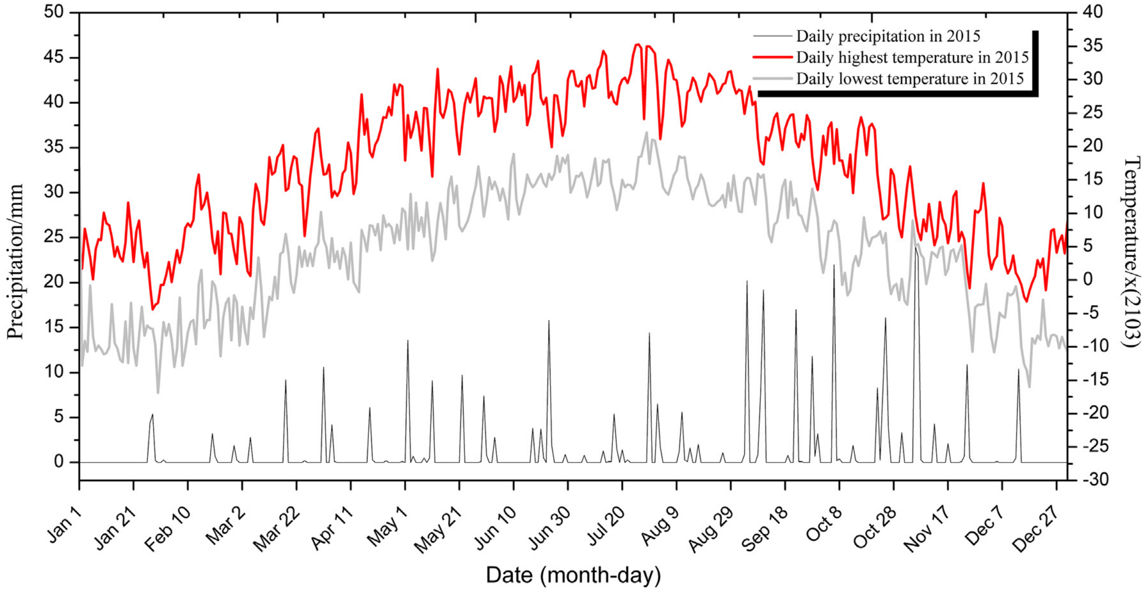

Fig. 2. Dynamics of daily precipitation and daily highest and lowest temperature in the testing year (2015) at sampling area and experimental site.

the wall. The collected rainfall can then move laterally and downward pit into the soil surrounding the pit. This configuration slows the flow of runoff and thus minimizes sedimentation and loss of storage capacity of the pit.

On flat sites, the RWCI ridges were rectangular in shape (Fig. 1b). The in-situ RWCI system was constructed between the two trees. A soil pit 80 cm × 80 cm × 60 cm deep was dug between the two trees in line with the tree trunk. The following implementation steps were the same

Table 1
Average physical properties of the Loess soil.

Depth (cm)	Soil bulk density (g/cm^3)	Soil parent material	Saturated water content (% vol)	Field capacity (% vol)	Wilting point (% vol)	Organic carbon (%)
0–40	1.13	Loess	29.24	16.85	6.31	1.5
40–80	1.25	Loess	28.77	17.65	6.42	
80–120	1.26	Loess	28.31	17.76	6.11	
120–160	1.33	Loess	28.87	18.15	6.50	
160–200	1.23	Loess	29.41	18.89	6.73	
Mean value	1.24	Loess	28.92	17.86	6.41	

as above. The plastic film would collect rainwater or irrigation water which would flow into the rhizosphere for ensuring a sustainable water supply through the RWCI system.

2.4. Field sampling and measurement

Nine trees with similar canopy area, growing conditions and diameter, were selected in the A1–A5 stands (under RWCI). In the A1–A4 stands (flat land), the soil sampling locations were located at distance of 100 cm away from the trunk. All soil sampling locations in A5 and A6 (slope land) were located in the same direction and distance of 55 cm and away from the trunk.

Soil moisture and fine roots were sampled and tested on September 2015 (the apple fruit maturation period). In order to minimize interference from other plant roots systems, we removed all other vegetation around the sampling point before sampling. Each soil sample was sampled using a Luo Yang shovel (it had an internal diameter of 0.16 m) in 20 cm increments to the depth of 8 m in each stand apple orchard (Ma et al., 2013).

We sampled soil from each 20 cm soil layer to 8 m depth. We transferred a small part of the soil samples of each soil layer without roots to an aluminum specimen box for SMC using the oven-drying method. The rest of the soil samples were spread out on a plate, then the fine roots were collected one-by-one by tweezers from the soil sample. Firstly, we washed the root samples thoroughly, and then oven-dried those to determine the dry root weight (Gravimetric) (Song et al., 2017). The root biomass was converted to the dry root weight density (RWD, g dry roots m^{-3} of soil) (Ma et al., 2013; Song et al., 2017). We used the values of D_{50} and D_{95}, which represented the depth reached by 50% and 95% of the total amount of root system, respectively, to describe the depth profiles (Schenk and Jackson, 2002; Ma et al., 2013). The RWD and cumulative RWD were also calculated in each special soil depth ranges.

2.5. Statistical analysis

The data were analyzed with a one-way analysis of variance (ANOVA) using SPSS v. 18.0 (IBM Company). Duncan's multiple range test with $P < 0.05$ was performed to test the significance of difference between the treatments on the soil moisture, soil water storage (SWS: soil water storage within a certain depth) and the RWD in stands A1–A4 on the flat land. In A5 and A6 both on the hill slope, a *t*-test was performed to analyze the data on the soil moisture and fine root dry weight density.

Calculation of SWS: SWS was calculated on the basis of soil water and soil bulk density. SWS is a key component of the soil water balance and allows the evaluation of infiltration efficiency. SWS_i (mm) for a given soil layer *i* was calculated using the following equation:

$$SWS_i = 0.1\rho D_i h_i \tag{1}$$

where ρ is soil moisture content (%), D_i is soil bulk density (g cm^{-3}), and h_i is the depth of the layer *i* (cm). In our study, total SWS in the first 2 m soil layer [the maximum rainfall infiltration depth (MRID) = 2 m], the second soil layer [from 2 m to the maximum rooting depth (MRD)] and the third soil layer (from the MRD to 8 m) was calculated as the sum of each 0.2 m soil layer in the corresponding soil layer, respectively. SWS of each 0.2 m soil layer was calculated according to Eq. (1).

3. Results

3.1. Soil moisture distribution with stand ages

The vertical soil moisture distribution is presented in Fig. 4 for stands A1, A2, A3 and A4 with RWCI systems in 2015. We found that the deep soil moisture content (SMC; > 2 m) was mostly higher than shallow soil layer (< 2 m) in rain-fed apple orchards. The average SMC in the top 2 m (MRID) in A1, A2, A3 and A4 was 7.99%, 7.46%, 7.35% and 6.25%, respectively, showing a decreasing trend in shallow SMC (< 2 m) with the increase of stand age. The SMC below the MRID (> 2 m) was mostly higher than the shallow soil layers (0–2 m).

The soil water storage (SWS) is presented in Table 4 for stands A1, A2, A3, A4, A5 and A6 (Table 4). In the top 2 m, the SWS in A1, A2, A3 and A4 was 245.81 mm, 229.37 mm, 226.14 mm and 192.09 mm, respectively, and it decreased with increasing stand age. From 2 m to the MRD and the MRD to 8 m, the SWS in A1, A2 and A3 was 424.93 mm (2–4.6 m), 707.92 mm (2–6.4 m) and 1004.76 mm (2–7.6 m), and 688.38 mm, 219.95 mm and 84.30 mm, respectively. In A4, the SWS was 950.73 mm in the 2–8 m soil layer.

Fig. 4 also shows that the SMC coefficient of variation (CV) differed with increasing soil depth and with stand age. The CV of SMC in A1, A2, A3 and A4 ranged from 10% to 28%, 5% to 28%, 5% to 25% and 7% to 25%, respectively. All SMC CVs in A1, A2, A3 and A4 were within 10%–20% in which the soil layers were defined the sub-active layer on the Loess Plateau of China (Huang et al., 2001; Chen and Shao, 2003).

Overall, the SMC increased with increasing soil depth and the variations of SMC in the deep soil layer (< 2 m) were higher than in the top 2 m. The lowest SMCs in A1, A2, A3 and A4 were observed in the 0–2 m soil layer (MRID) which also had the greatest root densities (Fig. 5). The mean SMC in MRID was 7.99%, 7.24%, 6.88% and 5.74% for A1, A2, A3 and A4, respectively and the content presented a decreasing trend with stand age.

3.2. Root distribution with stand ages

The spatial distribution of root system in stands A1–A4 under RWCI varied among soil layers and treatments (Fig. 5). The dry root weight density (RWD) increased with the increase of stand age and decreased sharply with the increase of soil depth. The total RWDs were 539.93, 761.19, 808.17 and 1104.93 g m^{-3} in the A1, A2, A3 and A4, stands, respectively. Thus, the apple tree stand age had a remarkable effect on the total RWDs. Fine roots were most abundant in the top 2-m of soil (83.9%, 60.06%, 69.05%, 65.46% and 63.09% of the total roots in A1, A2, A3 and A4, respectively), and the maximum RWD appeared at a depth of 0–0.4 m in A1, A2, A3 and A4 (35%, 14.06%, 16.36% and 12.22% of the total roots, respectively). Significant differences in RWD

Table 2
The multi-year (2003–2008) means water consumption of apple tree on the rain-fed apple orchards in Yanan.

Month	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Des.	Total
Water consumption/mm	13.82	13.08	36.32	41.45	81.92	124.52	123.97	97.07	68.68	38.23	26.47	10.95	676.47

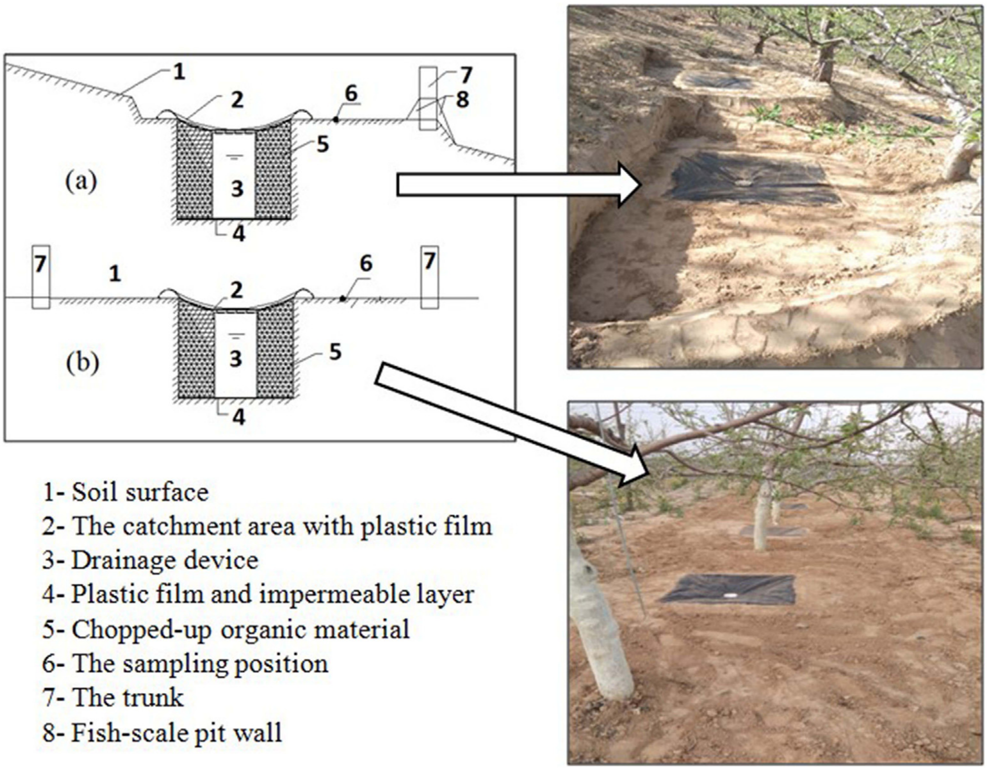

Fig. 3. Field engineering schematic diagram of Rain Collecting and Infiltration (RWCI) systems set-up, (a) A hill-slope and (b) Flat land.

were shown in the 4.4–8 m soil layers with stand age.

In A1, A2 and A3, the MRD extended to 4.6, 6.4 and 7.6 m, respectively (Fig. 5). It can be seen that the root system extends deeper into the soil with the increase of stand age, almost extending to 8 m when the apple tree reached 12 years of age and over 8 m soil depth when stand age exceeded 12 years in the RWCI system plantation area.

Fig. 6 shows the cumulate RWD. The cumulative RWD was higher in the upper layer of soil than the deeper soil layer which was also observed in jujube plantations (*cv. Lizao* on *Ziziphus* rootstock) by Ma et al. (2013). Fig. 6a shows that the trend of the D_{50} soil depth increased with the increase of stand age. D_{95} extend deeper into the soil with the increase of stand age. In A1, the MRD reached to 4.6 m depth, while D_{50} and D_{95} were located at 1 m and 2.8 m soil depth, respectively. In A2, the MRD was 6.4 m and D_{50} and D_{95} were located at 1.2 m and 5.4 m soil depth, respectively. In A3 and A4, the MRD was about 8 m soil depth even, and there was no significant difference in D_{50} and in D_{95}, respectively. D_{50} and D_{95} were located at 1.4 m and 6.2 m soil depth, respectively.

3.3. Comparison of soil moisture and roots at sites with and without RWCI systems

Fig. 7 shows the soil moisture distribution with and without RWCI systems (A5 and A6) in the old rain-fed apple tree orchards. A low SMC zone was found within the MRID (0–2 m) in A6 (without RWCI), and the lowest volumetric water content (5.84% in A6) was in the 0.6–1 m soil layers. The SMC in A5 (with RWCI) was significantly higher than that in A6 in the MRID (< 2 m) ($P < 0.05$). The mean SMC in A5 and A6 was 9.79% and 7.45%, respectively, in the MRID (< 2 m). We found no significant difference in the mean SMC between A5 (12.10%) and A6 (12.43%) below the MRID (> 2 m), and the SMC below MRID (> 2 m) in this both treatments (A5 and A6) was higher than that in the MRID (< 2 m). The SMC between A5 and A6 presented the similar trends with increasing soil depth below 2 m (an increasing followed by a decreasing trend), with the greatest values of SMC appearing in the 3.6–5 m soil layers. According to our observations (Table 4), in the 0–2 m soil layer (MRID), SWS in A5 was 31.38% higher than that in A6 in the surface 2 m, and no significant difference was shown in SWS between A5 (1116.24 mm) and A6 (1146.63 mm) below the MRID (> 2 m).

Fig. 8 shows the vertical distribution of root systems in A5 and A6. The total RWDs in A5 and A6 were 2002.96 and 1373.60 $g\,m^{-3}$, respectively, and the MRD exceeded 8 m in A5, significantly higher than A6 (Fig. 8). In A5, the RWD was concentrated at a depth of 0–3 m from the surface, but in A6, it was most abundant in the 0–1 m soil layers (Fig. 8). Fig. 6b showed that the D_{50} soil depth was located at 2 m and 0.6 m and D_{95} at 7.4 m and 6.4 m for A5 and A6, respectively.

Table 3
Site characteristics of the apple tree stands (records from 2015).

Characteristic	A1	A2	A3	A4	A5	A6
Stand age (year)	6	9	12	18	21	21
Trunk diameter (cm)	$11.00^{d} \pm 0.58$	$14.44^{c} \pm 0.40$	$15.94^{c} \pm 0.34$	$16.98^{c} \pm 0.58$	$24.20^{a} \pm 1.16$	$20.30^{b} \pm 1.83$
Tree height (m)	$3.03^{b} \pm 0.08$	$3.83^{a} \pm 0.04$	$3.73^{a} \pm 0.07$	$2.86^{b} \pm 0.14$	$3.45^{a} \pm 0.17$	$3.59^{a} \pm 0.16$
Crown diameter (m)^{e}	$4.59^{c} \pm 0.05$	$4.65^{c} \pm 0.07$	$6.07^{a} \pm 0.29$	$5.66^{a} \pm 0.10$	$5.19^{b} \pm 0.07$	$4.97^{bc} \pm 0.05$
Stand area (ha)	6.67×10^{-2}	4.67×10^{-2}	2.00×10^{-1}	2.00×10^{-1}	6.67×10^{-1}	6.67×10^{-1}

Values are means ± SE where SE indicates the standard error for all trees in each plot area per stand age.
[a,b,c,d] Different letters denote significant differences among stands ($P < 0.05$, Duncan's multiple range test).
[e] Average crown length and width.

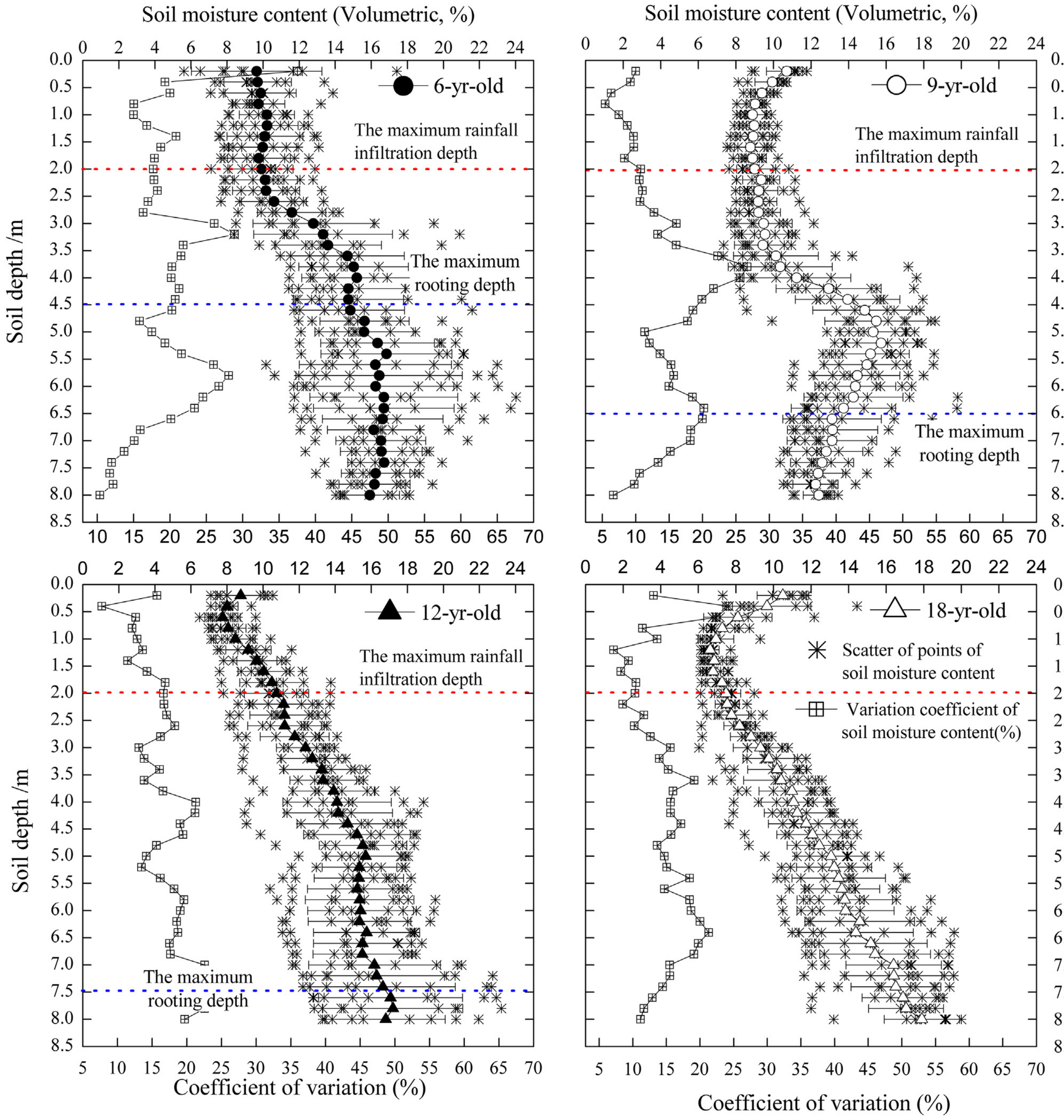

Fig. 4. Soil moisture content profile in the rhizosphere of apple trees in rain-fed orchards of different ages following implementation of RWCI. Solid circles, empty circles solid triangles and empty triangles represent average water content at each depth (n = 9 with 95% CI error bars) in 6-year, 9-year, 12-year and 18-yearl old orchards, respectively. The asterisks, *, represent the individual soil moisture measurements under the 9 trees and solid squares represent the coefficient of variation. Dotted lines represent the maximum rainfall infiltration depth and dashed lines represent the maximum observed rooting depth.

4. Discussion

Viewed broadly, space-for-time substitution uses the contemporary spatial distribution of biological attributes to understand temporal process that are otherwise unobservable, most notably past and future events (Blois et al., 2013). Generally, the soil water status and root distribution patterns of apple orchards with a variety of ages were assumed to represent the soil water dynamics and consumption of apple trees over time. The greatest uncertainty associated with space-for-time substitution is that spatial variability is small enough such that differences in the stands are actually a result of age differences rather than geographical differences. In our case, all of the stands were within average 0.86 km of each other and occurred on Loess soils and experienced similar climatic conditions, suggesting spatial variability is relatively small. Thus, the space-for-time substitution design can be used to investigate the effect of RWCI on soil water dynamics and consumption of apple trees.

4.1. *Soil moisture profile*

Soil water is the key factor which limits vegetative growth in semiarid ecosystems (Talon and Si, 2004). Trees first absorb water from the area closest to the trunk and the degree of water uptake from different soil layers depends on the water accessibility in the soil profile

Table 4
Soil water storage (mm) in rain-fed orchards of different ages.

Stand age (year)	Samples	First layer (0–2 m)	Second layer (from 2 m to MRD)	Third layer (from MRD to 8 m)
A1 (6)	9	245.81 ± 36.24	424.93 ± 56.17 (2–4.6 m)	688.38 ± 101.10 (4.6–8 m)
A2 (9)	9	229.37 ± 13.58	707.92 ± 60.73 (2–6.4 m)	219.95 ± 27.91 (6.4–8 m)
A3 (12)	9	226.14 ± 27.60	1004.76 ± 149.65 (2–7.6 m)	84.30 ± 17.62 (7.6–8 m)
A4 (18)	9	192.09 ± 13.57	950.73–115.74 (2–8 m)	
A5 (21)	9	301.12 ± 51.80	1116.24 ± 134.74 (2–8 m)	
A6 (21)	9	229.19 ± 20.86	1146.63 ± 29.58 (2–8 m)	

Values are means ± SE where SE indicates the standard error for all trees in each plot area per stand age.
Maximum rainfall infiltration depth = 2 m.
The maximum rooting depth = MRD.

(Green et al., 1997; Koumanov et al., 2006. The main source of available water was in the 0–2 m soil layer which was usually the MRID for rain-fed apple orchards in this region (Chen et al., 2005; Chen et al., 2008; Zhao et al., 2009; Chen et al., 2011; Yang et al., 2012; Song et al., 2017; Wang et al., 2009). However, the soil moisture in the deeper soil layers (> 2 m) also contributes to plant available water (Yang et al., 2012; Fang et al., 2016). The soil moisture in the 0–2 m soil layer, which was mainly affected by precipitation and root system, reflected the soil water status when soil samples were collected from the field. Therefore, soil samples allowed us to investigate the soil water regime

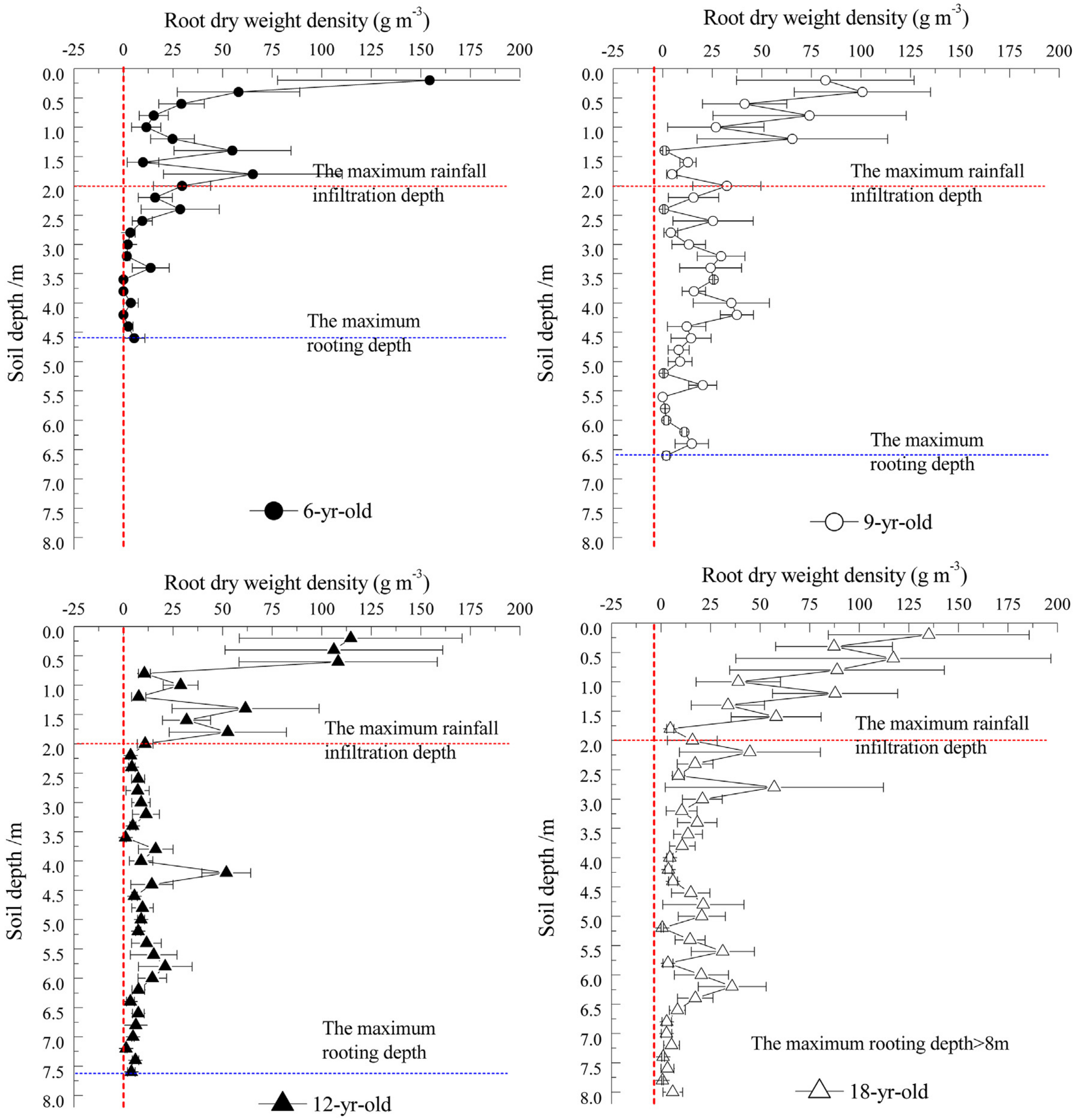

Fig. 5. Root distribution with stand ages in rain-fed apple orchards following implementation of RWCI. Solid circles represent 6-year-old apple trees sites, empty circles represent 9-year-old apple trees sites, solid triangles represent 12-year-old apple trees sites and empty triangles represent 18-year-old apple trees sites. Each point represents an average of nine soil samples in the same soil layer (n = 9). Error bars represent 95% confidence intervals.

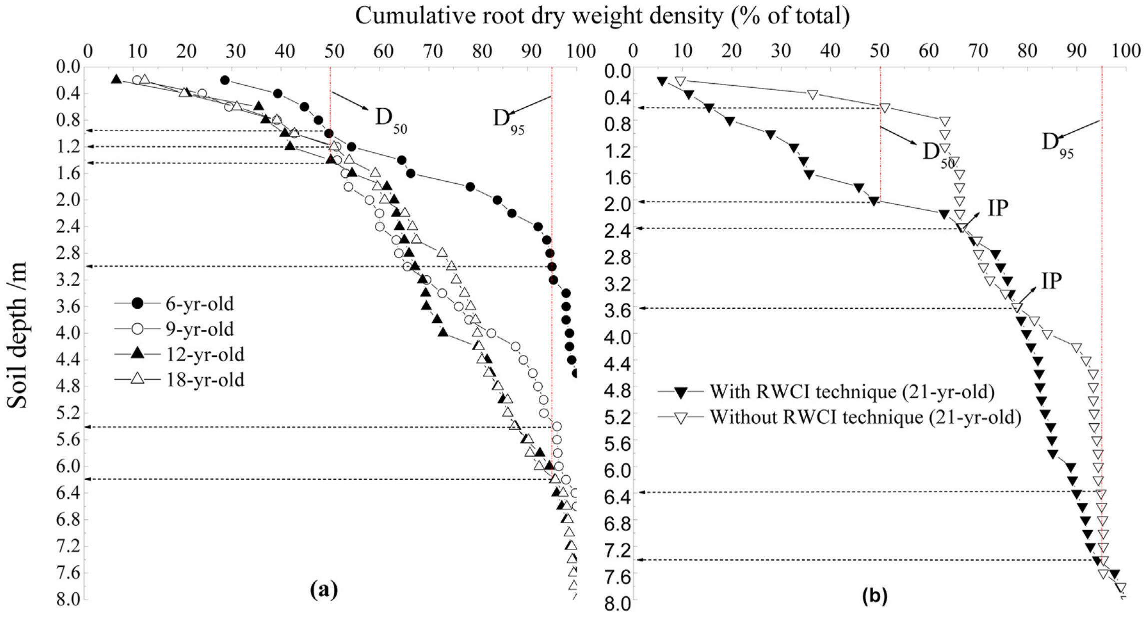

Fig. 6. Cumulative root dry weight density with stand ages in rain-fed apple orchards following implementation of RWCI. D_{50} and D_{95} represent the soil depth reached by 50% and 95% of the total root dry weight, respectively. Dotted arrows indicate the D_{50} and D_{95} thresholds for the specific proportions of roots with different stand ages and with and without RWCI system. IP (Interaction Point) in the right figure represents the same value for the specific proportions of roots in 21-year-old trees with and without RWCI systems.

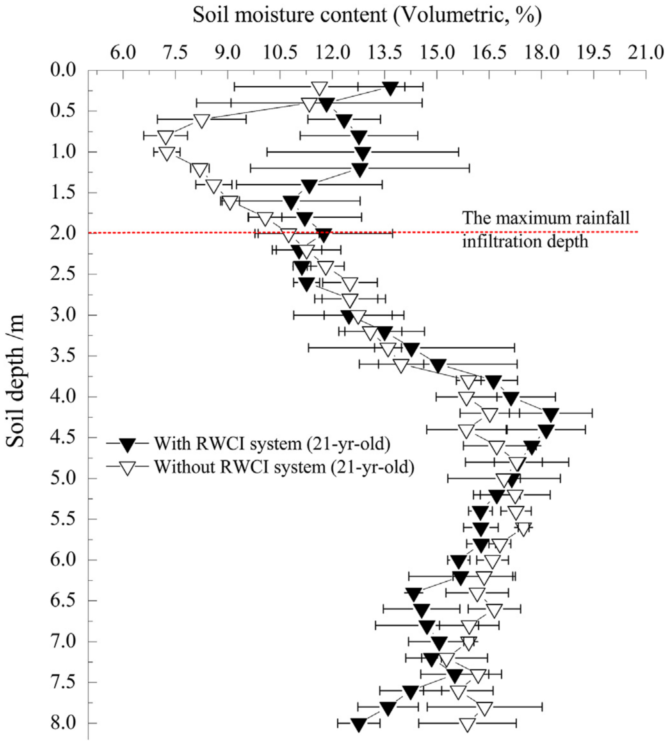

Fig. 7. Comparison of soil moisture profile content of 21-year-old trees with and without RWCI system. Solid triangles represent apple trees sites with RWCI system and empty triangles represent apple trees sites without RWCI system. Dashed lines represent the maximum rainfall infiltration depth. Each point represents an average of nine soil samples located in the same soil layer with and without RWCI systems (n = 9). Error bars represent 95% confidence intervals.

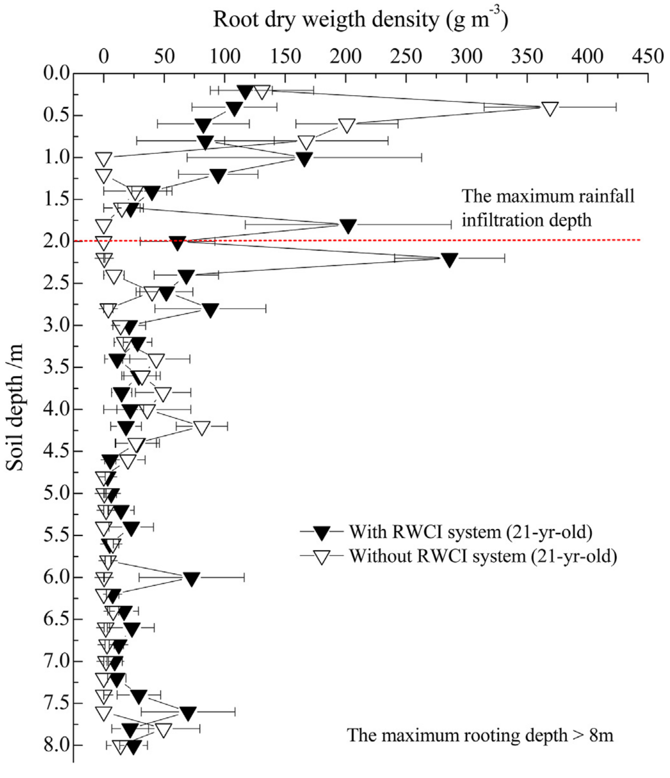

Fig. 8. Comparison of root distribution of mature apple trees in 21-year-old with and without RWCI system. Solid triangles represent root distribution with RWCI system and empty triangles represent root distribution without RWCI system. Each point represents an average of nine soil samples located in the same soil layer with and without RWCI system (n = 9). Error bars represent 95% confidence intervals.

in A1, A2, A3, A4, A5 and A6 in the apple fruit-ripening period.

Cao et al. (2006) reported that the minimum SMC occurred at soil depths where maximum root absorption of water for plant growth and transpiration occurred. A low SMC zone between depths of 40 cm and 80 am was reported by Song et al. (2016). In our study, we also found that there was a low SMC zone around the MRID without RWCI and the mean SMC and the SWS (0–2 m) decreased with increasing stand age. This indicates that the root system had completely extracted moisture stored in these soil layers. According to the root distribution pattern of apple trees, we suggest that the water consumption increase along with the increasing stand age and that the root system tended to grow deeper to meet plant water requirements. Since the rainwater collection and infiltration system (RWCI) was used in our study, the soil water availability of the rhizosphere (0–2 m) has been greatly improved. Thus, we will focus on discussing the effect of RWCI system on the soil moisture content and fine roots in Section 4.4.

4.2. Root distribution pattern

Fine roots are the main component of a tree root system, as they are the main link between plant and soil. Seasonal dynamics of fine root biomass and length are affected by tree age and species, as well as environmental conditions (Makkonen and Helmisaari, 1998). Generally, the fine root biomass increases with plant age (Vogt et al., 1983; Makkonen and Helmisaari, 2001; Bouillet et al., 2002; Ma et al., 2013). However, the opposite effect was reported in *Fagus svlvatica* and *Hevea brasiliensis* (Finér et al., 2007; Lin et al., 2011). Gan et al. (2010) reported that the age of apple trees does not affect the vertical distribution pattern but does affect the production of fine roots and the specific root length. Studies have shown that the total mass of the root system increased with the increase of stand age initially, and it decreased gradually, before stabilizing, after a specific period of time when maximum biomass was reached (Börja and Nilsen, 2009). Similar observations were made on the apple trees measured in our study.

In our study, the fine roots of apple trees were most abundant in the upper soil horizons (> 50% of total amount of root system were in the 0–1.5 m soil depth range) (see also Jiang, 1997; Jia et al., 1997; Wang and Fu, 2001; Meng, 2011; Ma et al., 2012; Song et al., 2016), but the vertical distribution pattern of fine root biomass for all age trees declined sharply with soil depth, as also observed by Konôpka et al. (2005), Gan et al. (2010) and Ma et al. (2013). D_{50} and D_{95} tended to extend deeper with increasing stand age and this was a general pattern (Jackson et al., 1996; Parker and Van Lear, 1996). Prior studies found that the maximum RWD appeared in the 0–2 m soil profile (Pùttsepp et al., 2006; Bakker et al., 2006; Meng, 2011; Song et al., 2016) and our study also uncovered a similar phenomenon. The root biomass was an indicator of the plant's ability to grow, and extract soil water and nutrients (Kang et al., 2010). In our study, the root system had a high capacity for absorbing soil water and nutrients in the 0–2 m soil layer, especially in the 0–1 m soil layer. Moreover, > 60% of the root biomass in A1, A2, A3, A4 and A5 was found in the surface 2-m - i.e., 83.9%, 60.06%, 69.05%, 65.46% and 63.09% of the total roots, respectively (see also Pùttsepp et al., 2006; Bakker et al., 2006; Gan et al., 2010). As the ages increased, the root system distribution of apple trees showed an overall decreasing trend in the surface 2 m. D_{50} and MRID (2 m) might be used to determine the depth parameters of RWCI system, the basic parameters of optimized irrigation scheme more effectively and the optimum wetness area for RWCI system. Ideally, the vertical range of RWCI-mediated infiltration should be in the main root distribution layer and the estimated maximum depth (the vertical infiltration front) should be less than the MRID. If implemented in the early stage of orchard establishment, RWCI systems could be used to encourage greater root development at shallower soil depths (< MRID), which may potentially decrease the development of apple tree roots very deep in the soil (> 5 m) and associated depletion of deep soil moisture.

4.3. Rooting depth

A deep root system is one of the main ways for the plant to adapt to arid and semiarid environments. Generally, rooting depth determines how much water stored in the soil can be accessed by plants for transpiration (Axel and Martin, 1998). There was a gradually increasing rooting depth and depth of soil water extraction by roots with increasing stand age reported by Zhang et al. (2011). Ma et al. (2013) found that the MRD generally increased with stand age of jujube, but it extended from 2 m at 2 years after planting to 4 m at 4 years after planting, and more slowly in older stands. Our study showed that the fine roots tended to occur in the deeper soil depths with increasing stand age and increased rapidly in relatively younger stands [from 4.6 m (A1) to 7.6 m (A3)] and more slowly in older trees. The MRD was 4.6 m, 6.4 m and 7.6 m, respectively, in A1, A2 and A3, and it was over 8 m when stand age exceeded 12 years (A4). We did not know whether the MRD was associated with exploration of deep soil layers to meet plant water requirements because of water stress in shallow layers or the deep roots are required to sustain the growth of plants on the ground. In general, the older apple trees had a larger tree crown and stem diameter (Table 1) so they demanded higher water consumption for the sustainable growth of trees obtaining water from the deeper soil. Based on this discussion, it appears that RWCI increased maximum rooting depth and density of roots with depth.

Ma et al. (2013) reported that no fine roots were found below 5 m (2 to 12 years stands) in the drip-irrigated plantation regions of jujube. However, in our study, we did not find fine roots below 8 m (A1 to A3) in the investigated non-irrigated plantation regions of apple. Our finding does not rule out the possibility that the fine roots might be found below 8 m after further sampling, but they are likely scarce.

4.4. Effect of rainwater collection and infiltration system

The rainwater collection and infiltration system (RWCI) is a rainwater catchment utilization system. It has been put forward to collect surface runoff during rainstorms to increase soil moisture and increase drought resistance and this system can be easily understood by local farmers. Irrigation water, rainfall or fertilizer solution is poured into or collected in the pits and can infiltrate into the rhizosphere soil rapidly and is available for tree uptake. The RWCI system has an advantage of saving water, increasing soil moisture storage, increasing drought resistance, and storing local rainfall runoff and it can provide sustainable water and nutrients for plant. A prior study by our group found that a low SMC zone appeared in the 0.4–0.8 m soil profile in natural conditions, and the water-fertilizer pit technique significantly promoted the increase of the SMC in the rain-fed apple orchards of the Loess Plateau of China (Song et al., 2016). In our study, we also found a low SMC zone which appeared in the MRID (0–2 m) in A6. We observed that the RWCI system greatly helped the soil water move deeper in the soil profile, increasing SWS, especially in the low SMC zone, as also reported by Song et al. (2016, 2017). Our study showed that, in the MRID (0–2 m), the SMC and SWS in A5 was significantly higher than that in A6 (Table 4 and Fig. 7).

In semi-arid areas, shallow soil moisture responds to precipitation events, transpiration, and surface evaporation (Meerveld and McDonnell, 2006; Seneviratne et al., 2010; Wang et al., 2012; Yang et al., 2014; Song et al., 2017). In our study, surface soil water (0–0.2 m) was usually greatly influenced by precipitation events. Our results showed that the water infiltration depth reached 2 m for the combined effect of RWCI system and precipitation (Fig. 7).

Understanding of root water uptake is the key for effective water management (Gong et al., 2006). Studies have shown that the soil from the surface to a depth of 3 m can be considered the active root zone of apple tree (Song et al., 2017). The total root biomass is an indicator of plant health and higher root biomass in specific soil layers is associated with a greater root water uptake (Kang et al., 2010) and the vertical distribution of fine roots was positively correlated with vertical changes in soil moisture (West et al., 2004; Powers et al., 2005; Cheng et al., 2005; Zhou and Shangguan, 2007; Shan et al., 2009), consistent with the observations in our study. Our study found that the A5 stand with RWCI system contained more fine roots than the A6 stand without RWCI system. In A5, the root system was mainly distributed in the 0–2 m soil layers, and A6 was in the 0–1 m soil layers (Fig. 6). We found that trees in locations with a high SMC resulted in a greater number of fine roots in the shallow soil layers (0–2 m) compared with those with lower SMC likely because the RWCI increased the SMC in the MRID (0–2 m). Thus, downward root extension and depletion in the deeper soil (> 2 m) would be reduced with the increasing SMC in the MRID (0–2 m), and the MRD was associated with the age of the tree but not with the SMC of the maximum rainfall infiltration soil layers. Overall, our results revealed that the capacity of water supply and recovery of RWCI system acted a critical role in the relations between soil water supply and the root system in the MRID (0–2 m). We suggest that the RWCI system may provide a sustainable water supply to the rhizosphere soil where the fine roots absorb more water from and improve the drought resistance in apple orchards of Loess Plateau. Also, the RWCI system can retain runoff, decrease soil wash and nutrient loss and increase utilization rate of water and fertilizer, meantime, it was an effective measure to realize the synchronous supply of water and fertilizer through irrigating fertilization liquid. However, the effect of RWCI systems on the mechanism of fertilizer transport has not been investigated, which may require further study. At the end of 2015, 1.5 million acres of the RWCI system had been established in rain-fed orchards in the study areas.

5. Conclusions

In the arid and semi-arid region, small household farmers were eager to obtain cheap but efficient rain-fed farming technology. The RWCI system proved to be an effective practice to improve soil water availability and ecological hydrological process by preventing evaporation and retarding water loss. Firstly, the vertical distribution of soil moisture and fine roots in different age apple tree orchards were investigated to provide the basis for applying the technology to practice. We found that, in the study area, the water storage in deep layers (> 2 m, especially > 4 m) was abundant in all orchards, and also found that, in the 0–2 m soil layer, the mean SMC and the SWS decreased with increasing plant age. However, fine roots were mainly distributed in the 0–2 m soil layer of all studied orchards (84%, 60%, 69%, 65% and 63% of the total amount of roots in A1, A2, A3, A4 and A5). Furthermore, the fine root system was significantly affected by the water regime in the MRID. The effective water management in this soil layer (0–2) promote root water uptake.

Thus, the selection and usage of RWCI system help improve water and fertilizer management for the sustainable development of rain-fed apple orchards on the Loess Plateau. The RWCI system had a significant effect on SMC and SWS in the 0–2 m soil layer, especially in the 0.2–1 m soil layer. The supplementation of the SMC in the 0–2 m soil layer with RWCI system could be used to improve the root distribution of apple trees. Therefore, the RWCI may be extended and applied as a promising approach to increase apple productivity, and hence to cope with drought and water shortage in Loess Plateau and other similar areas.

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References

Axel, K., Martin, H., 1998. Optimized rooting depth and its impacts on the simulated climate of an atmosphere general circulation model. Geophys. Res. Lett. 25 (3), 345–348.

Bakker, E.G., Stahl, E.A., Toomajian, C., Nordborg, M., Kreitman, M., Bergelson, J., 2006. Distribution of genetic variation within and among local populations of Arabidopsis thaliana over its species-range. Mol. Ecol. 15, 1405–1418.

Bao, X.J., Yin, S.Y., Peng, W.Y., 2012. Characteristics analysis of temporal-spatial change trends of highest and lowest temperature of past 50 years in Plateau of Northern Shannxi. Resour. Dev. Mark. 28 (1), 51–55.

Barron, J., Okwach, G., 2005. Run-off water harvesting for dry spell mitigation in maize (*Zea mays* L.): results from on-farm research in semi-arid Kenya. Agric. Water Manag. 74, 1–21.

Blois, J.L., Williams, J.W., Fitzpatrick, M.C., Jackson, S.T., Ferrier, S., 2013. Space can substitute for time in predicting climate-change effects on biodiversity. PNAS 110, 9374–9379.

Börja, I., Nilsen, P., 2009. Long term effect of liming and fertilization on ectomycorrhizal colonization and tree growth in old Scots pine (*Pinus sylvestris* L.) stands. Plant Soil 314, 109–119.

Bouillet, J.P., Laclau, J.P., Ardnaud, M., M'Bou, A.T., Saint-Andre, L., Jouedan, C., 2002. Changes with age in the spatial distribution of roots of Eucalyptus clone in Congo: impact of water and nutrient uptake. For. Ecol. Manag. 171, 43–57.

Cao, Y., Zhao, Z., Qu, M., Cheng, X.R., Wang, D.H., 2006. Effect of Robinia pseudoacacia roots on deep soil moisture status. Chin. J. Appl. Ecol. 17 (5), 765–768 (in Chinese with English abstract).

Cao, S., Chen, L., Yu, X., 2009. Impact of China's grain for green project on the landscape of vulnerable arid and semi-arid agricultural regions: a case study in northern Shaanxi Province. J. Appl. Ecol. 46, 536–543.

Chen, H.S., Shao, M.A., 2003. Review on hill-slope soil water movement and transformation mechanism on the Loess Plateau. Adv. Water Sci. 14 (4), 513–520 (in Chinese with English abstract).

Chen, H.S., Shao, M.A., Wang, K.L., 2005. Desiccation of deep soil layer and soil water cycle characteristics on the Loess Plateau. Acta Ecol. Sin. 25 (10), 2491–2498.

Chen, H., Shao, M., Li, Y., 2008. The characteristics of soil water cycle and water balance on steep grassland under natural and simulated rainfall conditions in the Loess Plateau of China. J. Hydrol. 360, 242–251.

Chen, X.B., Xu, W.G., Liu, X.P., 2011. Effect of rainfall infiltration on additional settlement and stability debasement of granular soil fillings embankment. J. Cent. S. Univ. (Sci. Technol.) 42 (3), 765–771 (in Chinese with English abstract).

Cheng, Y.H., Han, Y.Z., Wang, Q.C., Wang, Z.Q., 2005. Seasonal dynamics of fine root biomass, root length density, specific root length and soil resource availability in a Larix gmelini plantation. Front. Biol. China 29, 403–410 (in Chinese with English abstract).

Fang, X.N., Zhao, W.W., Wang, L.X., Feng, Q., Ding, J.Y., Liu, Y.X., Zhang, X., 2016. Spatial variations of deep soil moisture and the influencing factors in the Loess Plateau, China. Hydrol. Earth Syst. Sci. 19(1), 1–42.

Finér, L., Helmisaari, H.S.L., Majdi, K., Brunner, H., Borja, I., Eldhuset, I., et al., 2007. Variation in fine root biomass of three European tree species: beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* L. Karst), and Scots pine (*Pinus sylvestris* L.). Plant Biosyst. 141, 394–405.

Fox, P., Rockstrȍm, J., Barron, J., 2005. Risk analysis and economic viability of water harvesting for supplemental irrigation in semi-arid Burkina Faso and Kenya. Agric. Syst. 83, 231–250.

Gan, Z.T., Zhou, Z.C., Liu, W.Z., 2010. Vertical distribution and seasonal dynamics of fine root parameters for apple trees of different ages on the Loess Plateau of China. Agric. Sci. China 26 (4), 1–6.

Gao, X.D., Li, H.C., Zhao, X.N., Ma, W., Wu, P.T., 2018. Identifying a suitable revegetation technique for soil restoration on waterlimited and degraded land: considering both deep soil moisture deficit and soil organic carbon sequestration. Geoderma 319, 61–69.

Gong, D., Kang, S., Zhang, L., Du, T., Yao, L., 2006. A two-dimensional model of root water uptake for single apple tree and its vertification with sap flow and soil water content measurements. Agric. Water Manag. 83, 119–129.

Green, S., Clothier, B., McLeod, D.J., 1997. The response of sap flow of apple roots to localized irrigation. Agric. Water Manag. 33, 63–78.

Huang, M.B., Gallichand, J., 2006. Use of the SHAW model to access soil water recovery after apple trees in the gully region of the Loess Plateau, China. Agric. Water Manag. 85, 67–76.

Huang, M.B., Yang, X.M., Li, Y.H., 2001. Effect of apple base on regional water cycle in Weibei upland of the Loess Plateau. Acta Geograph. Sin. 56 (1), 7–13 (in Chinese with English abstract).

Huang, Y.L., Chen, L.D., Fu, B.J., Zhang, L.P., Wang, Y.L., 2005. Evapotranspiration and soil moisture balance for vegetative restoration in a gully catchment on the Loess Plateau, China. Pedosphere 15, 509–517d.

Jackson, R.B., Canadell, J.E., Hleringer, J.R., Mooney, H.A., Sala, O.A., Schulze, E.D., 1996. A global analysis of root distributions for terrestrial biomes. Oecologia 108 (389-41).

Jia, Z.Q., Song, G.P., Li, Q.H., Sun, B.P., Li, C.Z., 1997. Study on dynamic variation law of soil moisture in the typical watershed. J. Beijing For. Univ. 19 (3), 15–20 (in Chinese with English abstract).

Jiang, D.S., 1997. Mode of Soil Erosion Control in the Loess Plateau. China Water Power Press, Beijing, pp. 198–206 (in Chinese with English abstract).

Kang, B.W., Liu, J.J., Sun, J.H., Li, Y.F., 2010. Study on root distribution of Artemisa Ordosica in Mu Us sandy land. Res. Soil Water Conserv. 17 (4), 119–123 (in Chinese with English abstract).

Konôpka, B., Yuste, J.C., Janssens, I.A., Ceulemans, R., 2005. Comparison of fine root turnover in a Scots pine and Pedunculate oak in sandy soil. Plant Soil 276, 33–45.

Koumanov, K.S., Hopmans, J.W., Schwankl, L.W., 2006. Spatial and temporal distribution of root water uptake of an almond tree under micro-sprinkler irrigation. Irrig. Sci. 24, 267–278.

Li, Y.S., Chen, B., Li, X.F., Zhao, Y.J., Ciren, Y.J., Jiang, B., Hu, W., Cheng, J.M., Shao, M.A., 2008. Effect of deep soil desiccation on artificial forestlands in different vegetation zones on the Loess Plateau of China. Acta Ecol. Sin. 28, 1429–1445.

Lin, X.H., Chen, Q.B., Hua, Y.G., Yang, L.F., Wang, Z.H., 2011. Soil moisture content and fine root biomass of rubber tree (Hevea brasiliensis) plantations at different ages. Chin. J. Appl. Ecol. 22 (2), 331–336 (in Chinese with English abstract).

Ma, L.H., Wu, P.T., Wang, Y.K., 2012. Spatial distribution of roots in a dense jujube plantation in the semiarid hilly region of the Chinese Loess Plateau. Plant Soil 354, 57–68.

Ma, L.H., Liu, X.L., Wang, Y.K., Wu, P.T., 2013. Effects of drip irrigation on deep root distribution, rooting depth, and soil water profile of jujube in a semiarid region. Plant Soil 373, 995–1006.

Makkonen, K., Helmisaari, H.S., 1998. Seasonal and yearly variations of fine root biomass and encompass in a Scots pine (*Pinus sylvestris* L.) stand. For. Ecol. Manag. 102, 283–290.

Makkonen, K., Helmisaari, H.S., 2001. Fine root biomass and production in Scots pine stands in relation to stand age. Tree Physiol. 21, 193–198.

Meerveld, H.J.T., McDonnell, J.J., 2006. On the interrelations between topography, soil depth, soil moisture, transpiration tates and species distribution at the hillslope scale. Adv. Water Resour. 29 (293-210).

Meng, Q.Q., 2011. Soil Moisture Consumption Pattern and Growth Response of Apple Orchard in the Loess Plateau. Northwest A & F Univ. Yangling, China (Ph.D. thesis, in Chinese with English abstract).

Mu, X.M., Xu, X.X., Wang, W.L., Wen, Z.M., Du, F., 2003. Impact of artificial forest on soil moisture of the deep soil layer on Loess Plateau. Acta Pedol. Sin. 40 (2), 210–217 (in Chinese with English abstract).

Oliveira, R.S., Bezerra, L., Davidson, E.A., Pinto, F., Klink, C.A., Nepstad, D.C., Moreira, A., 2005. Deep root function in soil water dynamics in cerrado savannas of central Brazil. Funct. Ecol. 19, 574–581.

Parker, M.M., Van Lear, D.H., 1996. Soil heterogeneity and root distribution of mature loblolly pine stands in piedmont soils. Soil Sci. Soc. Am. J. 60, 1920–1925.

Powers, J.S., Treseder, K.K., Lerdau, M.T., 2005. Fine root, arbuscular mycorrhizal hyphae and soil nutrients in four neotropical rain forests: patterns across large geographic distance. New Phytol. 165, 913–921.

Pǜttsepp, Ǜ., Lohmus, K., Persson, H.A., Ahlstrom, K., 2006. Fine-root distribution and morphology in an acidic Norway spruce (*Picea abies* (L.) Karst.) stand in SW Sweden in relation to granulated wood ash application. For. Ecol. Manag. 221, 291–298.

Ruiz-Sanchez, M.C., Plana, V., Fortuno, M.F., Tapia, L.M., Abrisqueta, J.M., 2005. Spatial root distribution of apricot trees in different soil tillage practices. Plant Soil 272 (1–2), 211–221.

Schenk, H.J., Jackson, R.B., 2002. Rooting depths, lateral root spreads and below-ground/above-ground algometry of plants in water-limited ecosystems. J. Ecol. 90 (3), 480–494.

Schulze, E.D., Mooney, H.A., Sala, O.E., Jobbagy, E., Buchmann, N., Bauer, G., et al., 1996. Rooting depth, water availability, and vegetation cover along an aridity gradient in Patagonia. Oecologia 108 (3), 503–511.

Schume, H., Jost, G., Hager, H., 2004. Soil water depletion and recharge patterns in mixed and pure forest stands of European beech and Norway spruce. J. Hydrol. 289, 258–274.

Seneviratne, S., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B., Teulingm, A.J., 2010. Investigating soil moisture-climate interactions in a changing climate: a reiew. Earth Sci. Rev. 99, 125–161.

Shan, L.S., Zhang, X.M., Hua, Y.H., Xie, T.T., Yan, H.L., Fan, H., 2009. Response of root distribution of Haloxylon ammodendron seedlings to irrigation amounts in the hinterlands of the Taklimakan Desert, China. Front. For. China 4, 60–67.

Song, X.L., Wu, P.T., Zhao, X.N., Gao, X.D., 2016. Distribution characteristic of apple tree root and soil moisture with hole application of both water and fertilizer in the Loess Plateau. Trans. CSAC 32 (7), 121–128 (in Chinese with English abstract).

Song, X.L., Gao, X.D., Zhao, X.N., Wu, P.T., Dyck, M., 2017. Spatial Distribution of Soil Moisture and Fine Roots in Rain-fed Apple Orchards Employing a Rainwater Collection and Infiltration (RWCI) System on the Loess Plateau of China. 184. pp. 170–177.

Talon, L.K., Si, B.C., 2004. Representative soil water benchmarking for environmental monitoring. J. Environ. Inf. 4, 28–36.

Vogt, K.A., Grier, C.C., Meier, C.K., 1983. Organic matter and nutrient dynamics in forest floors of young and mature *Abies amabilis* stands in western Washington, as affected by fine root input. Ecol. Monogr. 53, 139–157.

Wang, J., Fu, B.J., 2001. The impact of land use on spatial and temporal distribution of soil moisture on the Loess Plateau. Geogr. J. 55 (1), 84–91.

Wang, Z., Liu, B., Zhang, Y., 2009. Soil moisture of different vegetation types on the Loess Plateau. J. Geogr. Sci. 19, 707–718.

Wang, L., D'Odorico, P., Evans, J.P., Eldridge, D.J., McCable, M.F., Catlor, K.K., King, E.G., 2012. Dry land ecohydrology and climate change: issues and technical advances. Hydrol. Earth Syst. Sci. 16, 2585–2603. http://dx.doi.org/10.5194/hess-16-2585-2012.

Wang, Y.Q., Shao, M.A., Liu, Z.P., 2013. Vertical distribution and influencing factors of soil water content within 21-m profile on the Chinese Loess Plateau. Geoderma 193–194, 300–310.

West, J.B., Espeleta, J.F., Donovan, L.A., 2004. Fine root production and turnover across a complex edaphic gradient of a Pinus palustris-Aristida stricta savanna ecosystem. For. Ecol. Manag. 189, 397–406.

Yang, L., Wei, W., Chen, L., Jia, F., Mo, B., 2012. Spatial variations of shallow and deep soil moisture in the semi-arid Loess Plateau, China. Hydrol. Earth Syst. Sci. 16, 3199–3217.

Yang, L., Wei, W., Chen, L.D., Chen, W.L., Wang, J.L., 2014. Response of temporal variation of soil moisture to vegetation restoration in semi-arid Loess Plateau, China. Catena 115, 123–133.

Yao, X.L., Fu, B.J., Lü, Y.H., Chang, R.Y., Wang, S., Wang, Y.F., Su, C.H., 2012. The multi-scale spatial variance of soil moisture in the semi-arid Loess Plateau of China. J. Soils Sediments 12, 694–703.

Zhang, Y., Xie, Y.S., Hao, M.D., 2011. Study on characteristics of apple orchard soil moisture in gully region of Loess Plateau. Soil 43 (2), 293–298 (in Chinese with English abstract).

Zhao, X.N., Feng, H., Wu, P.T., Wang, W.Z., 2005. Study on integrated benefit of rainwater resources utilization in small watershed on the Loess Plateau. J. Nat. Resour. 20 (3), 354–360 (in Chinese with English abstract).

Zhao, Z., Li, J., Yuan, Z.F., Hu, X.N., Cao, Y., 2009. A model used to describe vertical change of soil moisture of Robiniapseudoacacia plantations growing in the Loess gully slope. Sci. Silvae Sin. 45 (10), 9–13.

Zhou, Z.C., Shangguan, Z.P., 2007. Vertical distribution of fine roots in relation to soil factors in *Pinus tabulaeformis* Carr. Forest of the Loess Plateau of China. Plant Soil 291, 119–129.