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ORIGINAL ARTICLE

Root distribution chronosequence of a dense dwarfed jujube plantation in the semiarid hilly region of the Chinese Loess Plateau

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Abstract Dense jujube (*Ziziphus jujube* Mill. CV. Lizao) plantations with a spacing of 2 m between trees and 3 m between tree rows have been established in the semiarid hilly region of the Chinese Loess Plateau since 1999. Our objective was to assess differences in the vertical and horizontal root distribution with stand age based on a trench wall analysis of the roots. The stands were 4, 8, and 11 years old. We investigated three root diameter classes for each stand, which consisted of fine (< 1 mm), medium (1–3 mm), and coarse (> 3 mm) roots. Our main findings were as follows. (1) All diameter classes of root intersects increased significantly with stand age ($P < 0.01$). However, the proportion of the three diameter classes in the total roots remained about the same, regardless of stand age. (2) Root intersects decreased significantly with soil depth ($P < 0.001$). (3) There were no significant differences in root intersects with distance from the trunk ($P > 0.05$) in this dense planting pattern. These root distribution patterns may enhance our understanding of the dense jujube plantation belowground root ecology and provide a basis for jujube plantation management practices in this semiarid hilly region.

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Introduction

The conservation of soil and water in the semiarid hilly region of Chinese Loess Plateau has become a huge challenge in this deteriorating environment. The annual soil erosion modulus are very high ca 2,000–7,000 t km^{-2} (Zhu 1989). A promising method for conserving the soil and water in this hilly region is the development of sustainable management systems that convert farmland to economic woodland, which protects vulnerable environments and provides economic benefits for local farmers (Yang et al. 2006). However, a major difficulty of sustained management is maintaining a suitable fruit yield while balancing the ecological and economic effectiveness (Shi and Shao 2000).

Jujube (*Ziziphus jujube* Mill. CV. Lizao) is a drought-tolerant economically important deciduous Chinese native tree species, which bears fruit early and has a long life. Jujube has been cultivated for thousands of years in the semiarid hilly region of the Chinese Loess Plateau. Jujube fruit is full of nutrients and has high economic value, so it has become a leading industry and a major source of income for local farmers. By 2010, 122,376 ha of land area were cultivated with jujube trees in the Yulin District Shaanxi Province, China. Wu et al. (2008) reported that the average fresh fruit yield in this region was only 2,250 kg ha^{-1} year^{-1}, which was a low production level. This was achieved without irrigation or fertilizer using a plant spacing of 4 m between trees and 5 m between tree rows (500 trees ha^{-1}) where most of the trees exceeded 5 m in height. In 1999, a pilot study was undertaken to increase the jujube fruit yield by improving the planting density and water and nutrient uptake management. Jujube trees were planted at a spacing of 2 m between trees and 3 m between tree rows (1,665 trees ha^{-1}), while the tree height was kept at <2 m by manual pruning. The jujube fruit yield increased 8.8-fold under the densely planted regime when compared with the traditional plant spacing (Wu et al. 2008). In order to obtain a sustainable high yield, it is imperative to determine how to apply water and nutrients effectively in this semiarid region and ensure that high jujube yields are sustained.

Studies suggest that the economical yield is influenced by the ability of the root system to absorb water and nutrients from the greatest possible volume of soil (Lynch 1995; Lynch and Brown 2001; Lehmann 2003). The root system is the main organ of water uptake for the plant. The horizontal and vertical fine root distribution in the soil has a direct influence on the ability of plants to extract water and solutes from the soil (Fitter 1996). Thus, the effective water and nutrient utilization in orchards requires a more detailed knowledge of the root distribution, and especially the fine root distribution and the relationships between fine root distribution and soil environments. Previous research has shown that root systems can vary in their vertical and horizontal distributions with tree age (Vogt et al. 1987; Vanninen and Makela 1999; Claus and George 2005; Fujimaki et al. 2007). The root intersect numbers are known to increase with stand age (Bouillet et al. 2002) and to decrease with soil depth, with a marked horizontal anisotropy (Laclau et al. 2001). However, the vertical root distribution pattern of apple trees did not change with age (Gan et al. 2010).

In the current study, jujube plantations were established on a sandy loam soil. Previous work has shownd that the available nutrient and organic matter content was poor, while the soil water retention capacity was very low for this type of soil (Qiao 2008). The root distribution of a single jujube tree under the traditional spaced planting pattern has shown that the maximum vertical rooting depth and the maximum horizontal distance of lateral roots can extend deeper and wider, i.e., about 4 and 10 m, respectively (Liu and Liu 1998). Wei and Li (2009) reported jujube plantation root distribution under a sparse planting pattern. Wei et al. (2010) analyzed jujube plantation root distribution under drip irrigation. The spatial root distribution in dense jujube plantation is poorly documented and it remains unknown whether it is affected by tree age.

The jujube tree stands that we examined were 4, 8, and 11 years old. We hypothesized that the root distributions would vary among these stands. The root intersect number would increase with stand age, decrease with the soil depth concentrating on the top soil layer vertically, and uniformly distributed in the same soil layer horizontally based on the dwarfed densely jujube plantation. We investigated the vertical and horizontal root distribution with different stand ages by recording the fine, medium, and coarse root intersects throughout the entire 1 m depth soil profiles. This study would enhance our understanding of the belowground root ecology in artificial jujube plantations.

Materials and methods

Study area

The jujube tree stands were situated in the Loess Hilly region of Mizhi County, North Shaanxi Province (37°5′N, 119°49′E). The study area was about 1,212 km^2. The climate was typical for a temperate semiarid zone with high seasonal variations. The mean annual rainfall was about 490 mm with more than 50 % of the total annual rainfall occurring in July, August, and September. The maximum natural rainfall infiltration depth was about 1.2 m (Zhang and Wang 2010) with no deep seepage in this region. The mean annual air temperature was 8.5 °C, relative humidity was 55.4 %, the mean potential annual evaporation was 1,574 mm, and the wind speed was 2.1 m s^{-1} from 1956 to 2005, according to meteorological data. The soil texture was a sandy loam with an average soil bulk density of 1.30 g cm^{-3} in the 0–1 m soil layer, field water capacity of 23.4 %, and saturated water capacity of 39.8 %. The texture of the soil was as follows: clay, silt, and sand particles accounted for 5.5, 27.4, and 67.1 % respectively. The topography was steep with slope gradients ranging from 23° to 45°. Fertilizer urea (containing 50 % N), ordinary super phosphate (containing 12 % P_2O_5), and potassium sulfate (containing 50 % K_2O) were applied annually to 30 cm soil depth and 50 cm uphill from the trunk perpendicular to the tree rows at the end of April. The soil chemical characteristics at a 0–1 m soil depth using conventional analytical method are shown in Table 1 for August 2010. Soil organic matter was determined by potassium bichromate sulfuric acid oxidation method. Available K was determined by ammonium acetate extraction followed by flame photometry method. Available P was determined by $NaHCO_3$ solution extraction

Table 1 Soil chemical properties in 0–1 m soil layer of a jujube (*Ziziphus jujube*) plantation with various stand ages

Stand age	Available N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})	Organic matter (g kg^{-1})	pH value
4	12.71	4.96	120.5	4.12	8.5
8	13.24	4.83	117.3	4.89	8.5
11	13.73	4.76	116.1	4.72	8.3

followed by antimony molybdenum scandium colorimetric method. Available N was determined by KCl solution extraction and ammonium nitrogen and nitrate nitrogen were analyzed by continuous flow analyzer. pH value was determined with potentiometry method.

Stand characteristics

The three stands formed a chronosequence, i.e., F1 = 4 years, F2 = 8 years, and F3 = 11 years old at the time of sampling in 2010 (Table 2). The plot areas were 6, 20, and 25 ha for the F1, F2, and F3 stands, respectively, which were all located at the middle of south face slope. The jujube trees had been planted along contour lines with a spacing of 2 m between trees and 3 m between tree rows since 1999. Studies using a chronosequence approach assumed that the stands represented the main development stages of the dense plantations found in the region. All the stands were pruned twice a year to keep the jujube trees dwarfed (about 2 m tree height), control tree canopy size in March (before leaf growth), and prevent over-strong growth, limit transpiration, and enhance fruit production in June (flowering period) (Zhao et al. 2010). Stands were not irrigated. We measured the tree height from the ground to the top of the tree using a standard tape measure. A diameter tape was used to measure the diameter 0.1 m above the ground. We also measured the crown diameter using a standard tape measure from aspects parallel to the tree (length) and perpendicular to the tree (width).

Tree root distribution

The method used to study the jujube tree root distribution was based on the trench profile method described by Smit et al. (2000). In August 2010 (the jujube tree fruit setting period), shovels were used to excavate one trench for each age of stand, measuring 6 m length (three consecutive tree spacing) × 1.0 m depth × 0.8 m width. The trenches were excavated in rows located on a south-facing slope and we prepared a vertical wall on one side of the trench, which was used for sampling. The excavation was performed at the lower position (downhill) of the trunk. The trench was parallel to a tree row. The sampling profile (the closest trench side to the trunk) was 0.15 m away from the trunk. Each trench sampling profile was flattened and smoothed using a scraper and spade. Four neighboring trees were selected in the same age stands at a similar growth stage for each trench (6 m). Each sampling profile length was defined from the tree trunk to the inter-tree horizontal distance (0–1 m). Thus, there were six replicates ($n = 6$) per age stand (Fig. 1). All weeds were removed inside the area at 30, 20, and 10 days before trench excavation, so as to minimize any interference from other plant roots. Root intersects were defined as live roots and jujube fine roots were identified as white-colored, whereas weed roots were dark in color. Dead weed roots were wrinkled, broke easily, and smelled strongly. The differentiation of root color and morphology was achieved by a visual inspection. Root intersects were defined as live roots that intersected with the sampling profile after surface cleaning.

A 5 × 5 grid system that contained 25 squares was placed against the trench sampling profile, where each cell measured 0.2 × 0.2 m in area (Sokalska et al. 2009) ($n = 6$ grid frames per age stand, $n = 30$ observations per 0.2 m soil depth layer per stand age). Pin-fixed labels were used to mark the root positions on the exposed soil profile for each individual cell of the grid system, before photographing the marked profile using a Canon DSLR-A350 digital camera (4,592 × 3,056 pixels). Note that each grid cell (0.2 × 0.2 m) was photographed while using a black umbrella to provide a dark background and reduce leaf shadows. Photographs were then imported into the R2V

Table 2 Site characteristics of the jujube stands (records from 2010)

Characteristic	F1	F2	F3
Stand age (year)	4	8	11
Trunk diameter (mm)	62.2 ± 0.698 c	72.3 ± 0.54 b	84.0 ± 0.54 b
Tree height (m)	1.82 ± 0.0089 a	2.2 ± 0.0733 b	2.3 ± 0.0399 b
Crown diameter (m)[a]	1.71 ± 0.0192 a	1.86 ± 0.0115 b	2.2 ± 0.0759 b
Stand area (ha)	6	20	25

Values presented are means ± SE, SE indicating standard error for all the trees in each plot area per stand age

Different letters denote significant differences among stands ($P < 0.05$, Duncan's test)

[a] The average crown length and width

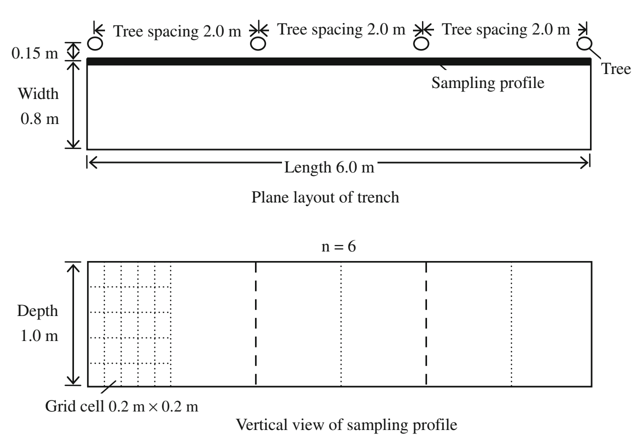

Fig. 1 Trench excavation layout (continuous three tree spacing) in a jujube (*Ziziphus jujube*) plantation

image processing program. Images were calibrated and corrected to a square referenced to the framework grid lines of a cell and saved as jpeg files. The jpeg files were imported sequentially into AutoCAD 2006 (Autodest, San Rafael, USA) and a scale was set, where 1 U represented 1 mm. Root intersects were classified into three size categories, i.e., < 1 mm (fine), 1–3 mm (medium), and greater than 3 mm (coarse). There were a total of eighteen 5 × 5 grids ($n = 6$ for each stand). The number of root intersects was counted using a statistical attribute of the software. The actual diameter of the roots in the soil profile was measured with a micrometer caliper while the diameter of root intersects was measured in images using AutoCAD. We then compared the differences of part of root intersects statistically. This method allowed root diameters to be measured with an error of < 0.03 mm (Ma et al. 2011).

Soil water measurement

In order to analyze the effect of soil water dynamic on root distribution, nine positions located in the centre of two trees along tree row were selected randomly from the 11-year-old jujube stand to represent jujube plantation soil water content ($n = 9$). The soil core method was used to collect soil sampling at 0.1-m increments between 0 and 1 m soil depth in each position. The oven-drying method was used to measure soil water content twice a month from July 25 to September 25 during the rainy season in 2010.

Statistical analysis

Statistical calculations were performed with SPSS v.17.0 (IBM, NY, USA). We confirmed the assumption of normality. In our study, the trench profile method was used to determine the number of root intersects at various depths and various distances from the trunks, which were not independent. Thus, a general linear mixed model was used to test the effects on the root intersects numbers with three diameter classes of stand age, soil depth, distance from trunk, and stand age × distance from trunk. We set the three root diameter classes as dependant variables, while stand age was the fixed factor, soil depth was the covariate, and the horizontal distance was the random factor. Duncan's test was used to assess any differences between stands per soil depth layer and any differences between depth layers within stands. The values are expressed as the means for each grid cell (0.2 m × 0.2 m) ($n = 6$ replicates per age stand, from tree trunk to inter-tree horizontal distance 0–1 m. Horizontal distances from the tree were classed as distances to the nearest tree. The statistical analysis used a $P < 0.05$ level of significance.

Results

The number of intersects of fine, medium, and coarse roots was significantly affected by stand age and soil depth (Table 3). However, the root intersect number was not significantly affected by the distance from the trunk in any of the stands ($P > 0.05$). The interaction between stand age and horizontal distance was not significant.

Variation in the jujube tree size and abundance of root intersects (coarse, medium and fine) among the three stands

The jujube trees grew larger with stand age, there was a significant difference in trunk diameter among the three stands, but no significant difference in tree height and maximum crown diameter (Table 2). All root classes intersects increased significantly with stand age (Table 4). In the three stands, the total number of fine root intersects at depths of 0–1 m ranged from 3,562 m^{-2} in the youngest stand to 6,632 m^{-2} in the oldest stand, medium root intersects ranged from 90 to 219 m^{-2}, and coarse root intersects ranged from 60 to 117 m^{-2}. However, the proportion of the three root intersect classes was always similar relative to the total roots with no significant differences, regardless of the stand age (Table 5). The average percentages of coarse root, medium root, and fine root

Table 3 General effects of stand, soil depth, and distance from the trunk on root intersects according to a mixed model, with distance from the trunk as a random variable

	Diameter								
	<1 mm			1–3 mm			>3 mm		
	df	*F* value	*P* value	*df*	*F* value	*P* value	*df*	*F* value	*P* value
Stand age	2	8.545	0.010	2	320.772	<0.001	2	6.402	0.022
Soil depth	1	175.401	<0.001	1	93.901	<0.001	1	12.827	<0.001
Distance from trunk	4	1.495	0.291	4	1.410	0.314	4	1.554	0.276
Stand age × distance from trunk	8	1.233	0.278	8	0.339	0.951	8	0.844	0.564

df degrees of freedom

Table 4 Percentage of roots confined to top 0.2 m, 0.4 m, or 0.6 m and the total number of root intersects

	F1	F2	F3	*P* value
Tree roots (<1 mm) confined to top 0.2 m, 0.4 m, or 0.6 m of the total 1 m profile examined				
Top 0.2 m (%)	22 (3.3) b	28 (3.2) b	40 (6.4) a	<0.0001
Top 0.4 m (%)	45 (4.2) c	55 (2.0) b	63 (3.1) a	<0.0001
Top 0.6 m (%)	67 (3.5) b	80 (3.5) a	77 (3.7) a	<0.0001
Total intersects (number m^{-2})	3,562 (479.5) b	4,698 (797.5) ab	6,632 (369.7) a	0.008
Tree roots (1–3 mm) confined to top 0.2 m, 0.4 m or 0.6 m relative to 1 m				
Top 0.2 m (%)	26 (9.3) b	36 (4.7) ab	40 (4.7) a	0.017
Top 0.4 m (%)	45 (9.0) b	64 (14.1) a	68 (8.1) a	0.011
Top 0.6 m (%)	69 (13.1) b	87 (9.7) a	83 (5.6) ab	0.033
Total intersects (number m^{-2})	90 (16.9) b	133 (23.5) b	219 (35.4) a	<0.0001
Tree roots (>3 mm) confined to top 0.2 m, 0.4 m or 0.6 m relative to 1 m				
Top 0.2 m (%)	18 (14.8) a	9 (7.1) a	29 (13.4) a	0.067
Top 0.4 m (%)	47 (25.3) a	46 (13.3) a	60 (13.7) a	0.429
Top 0.6 m (%)	68 (15.1) a	68 (12.2) a	83 (8.5) a	0.125
Total intersects (number m^{-2})	60 (28.4) b	82 (26.6) ab	117 (11.3) a	0.021

Values presented are means followed by standard deviations in parentheses. Different letters denote significant differences among stands at $P < 0.05$, Duncan's test

intersects in the total roots for all three stands were 1.7, 2.7, and 95.6 % respectively.

Vertical distribution of root intersect classes in the three stands

We found 67, 80, and 77 % of the fine root intersects, 69, 87, and 83 % of the medium root intersects and 68, 68, and 83 % of the coarse root intersects in the top 0.6 m in the F1, F2, and F3 stands, respectively. There were significant differences in the proportions of the different root classes in the 0–0.2, 0–0.4, and 0–0.6 m soil depth intervals among the stand ages, except for the coarse roots (Table 4).

Stand age effects were significant for fine and coarse root intersects in the three soil depth intervals (Fig. 2a, c) and for medium root intersects in the top two depth intervals (Fig. 2b). Fine and medium root intersect numbers dropped sharply below the 0.6 m soil depth (Fig. 2a, b). The maximum abundance of coarse root intersects was found in the 0.2–0.4 m layer and the curve dropped sharply below 0.4 m (Fig. 2c).

Table 5 Percentage of different root intersect classes of the total root intersects in stands of the same age

	F1	F2	F3	Mean
Tree roots (<1 mm) (%)	96.0 a	95.6 a	95.2 a	95.6
Tree roots (1–3 mm) (%)	2.4 a	2.7 a	3.1 a	2.7
Tree roots (>3 mm) (%)	1.6 a	1.7 a	1.7 a	1.7
Total	100.0	100.0	100.0	100.0

Values presented are percentages of different root classes in the total root intersects for stands of the same age. Different letters denote significant differences between treatments at $P < 0.05$, Duncan's test

Horizontal distribution of root intersect classes in the three stands

The horizontal distribution of root intersect numbers tended to be similar with each stand age (Fig. 3). The oldest stand was always at the top and the youngest stand was at the bottom of the curves, there was no significant difference in the root intersect numbers with the same stand age (Table 3). Stand age effect were significant for fine root in the 0–0.2 and 0.2–0.4 m horizontal distances (Fig. 3a), for medium root in all the five horizontal distance intervals (Fig. 3b) and for coarse root in he 0.4–0.6 m horizontal distance (Fig. 3c).

Soil water patterns

Soil water contents in the 0–1 m layer of the soil profile during the period of jujube plantation root sampling are shown in Fig. 4. In the sampling period, the soil water content declined with increasing soil depth, higher soil water contents were present in the top 0.6 m with large variation, while soil water contents in the 0.6–1 m were lower and tended to be relatively stable.

Discussion

This is the first systematic investigation of the spatial distribution of different diameter classes roots chronosequence

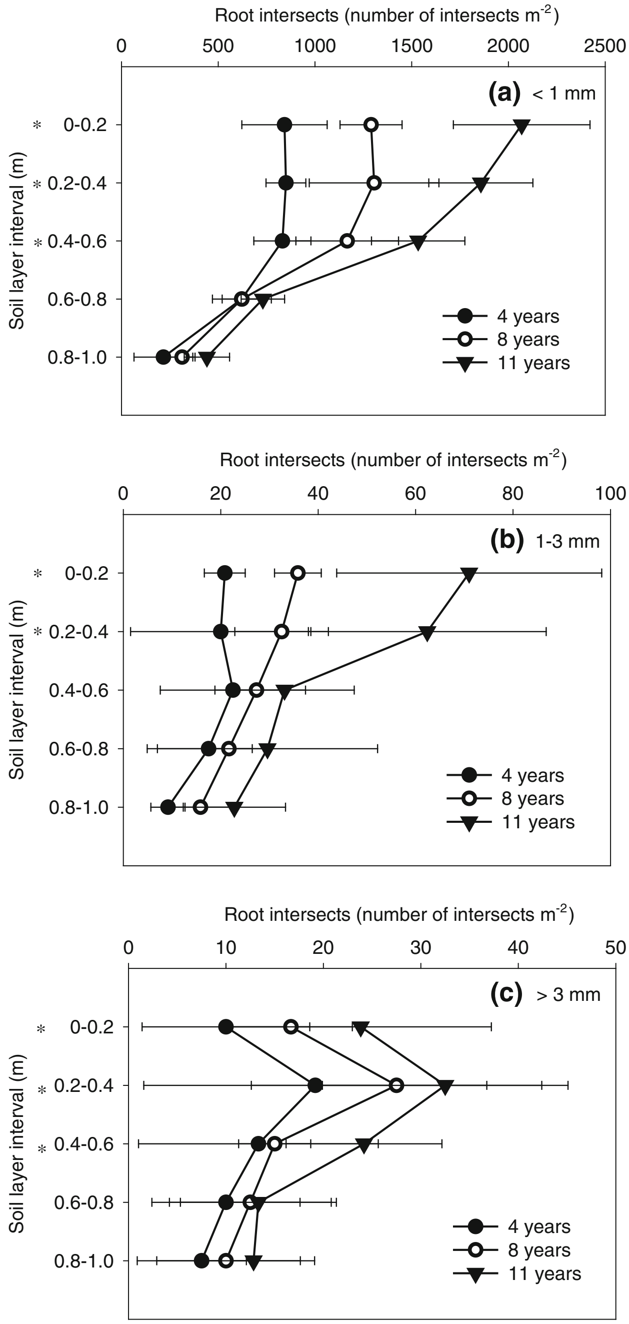

Fig. 2 Number of root intersects in each soil layer for fine roots (**a**), medium roots (**b**) and coarse roots (**c**) in the three stands F1–F3, represented as mean values and SD. Values presented are means of five different horizontal positions from the tree trunk to the inter-tree horizontal distance (0–1 m). Horizontal distances from the tree were classed as distances from the nearest trees. Each horizontal position value is the mean ($n = 6$ per age stand per soil layer). *Asterisks* denote significant differences in the number of intersects among stands at the given soil layer ($P < 0.05$, Duncan's test)

for a densely planted jujube species. This chronosequence study showed that different diameter class root intersects increased with stand age, fine root intersect number increased more than the coarse and medium roots in

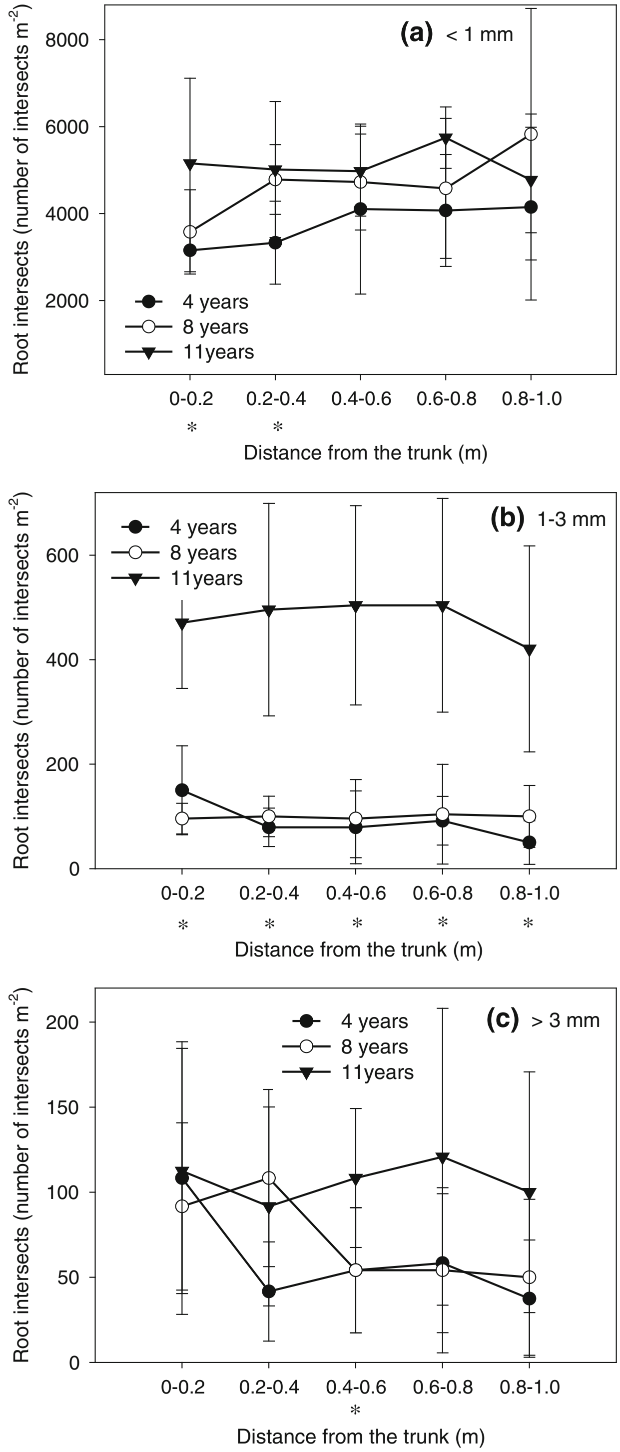

Fig. 3 Number of horizontal root intersects among trees throughout the soil profile (1 m) for fine roots (**a**), medium roots (**b**) and coarse roots (**c**) in the three stands F1–F3, represented as mean values and SD. Values presented are means of five different horizontal positions from tree trunk to inter-tree horizontal distance (0–1 m) ($n = 6$ per age stand). Horizontal distances from the tree were classed as distances in the nearest trees. Each horizontal position value is the sum of five soil layer per age stand 0–1 m soil depth. *Asterisks* denote significant differences in the number of intersects among stands at the given horizontal distance ($P < 0.05$, Duncan's test)

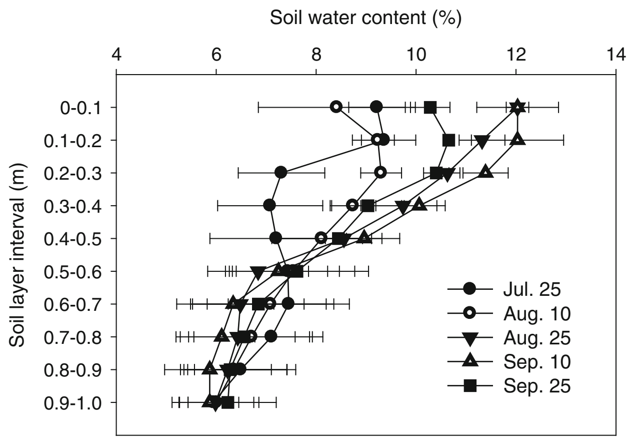

Fig. 4 Soil water dynamics in the soil profile from 0 to 1 m. Values presented are means of nine different position in 11 years old jujube plantation ($n = 9$)

absolute values, which were much more abundant at all stages, and this was consistent with previous studies for other forest species (Vogt et al. 1995; Li et al. 1998; Wen et al. 1999). This fine root distribution pattern agreed with Gwenzi et al. (2011), who reported on nutrient- and water-limited artificial ecosystems dominated by woody vegetation species, where a high proportion of fine roots represented an effective strategy for increasing the root surface area and resource uptake. Our study found that the proportions of root intersect in different diameter classes were similar, regardless of stand age. Studies have shown that jujube trees can survive for more than 100 years with a traditional planting pattern in this region (unpublished data). However, the oldest stand was only 11 years old in this densely planted jujube plantation, so the similar proportions of different diameter classes roots were probably attributable to site- and species-specific differences and the relative young age of stands in this study.

The vertical distribution of fine roots is of crucial importance for ecosystem water and nutrient use and productivity. In arid and semiarid environments, the root attributes determine plant access to the subsoil or shallow groundwater during periods of low water availability and high evaporative demand (Eamus et al. 2006). Root intersects were most abundant in the upper soil horizons (about 0–0.3 m) and this abundance declined with increasing soil depth, which is a generally observed pattern (Jackson et al. 1996; Parker and van Lear 1996). In our research, the majority of the total roots were concentrated in the top 0.6 m of the soil layer and all root diameter classes were significantly affected by soil depth (Table 3), especially in the 0–0.2, 0.2–0.4, and 0.4–0.6 m soil depth intervals (Fig. 2). This was because the roots in the top soil layer were exposed to soil water content with great fluctuations (Fig. 4). The high water and heat exchanges that occur in surface soil were beneficial to root growth and development (Cheng et al. 2006). The root distribution observed in our study agreed with Chen et al. (2009), who reported a close relationship between soil moisture and the fine root distribution, with a suitable soil water environment promoting the growth of fine roots.

In contrast to the variable lateral root distribution that is often observed in sparse woody stands (Nambiar 1983; Sudmeyer et al. 2004; Gwenzi et al. 2011), our results showed that the horizontal distance from the nearest tree did not significantly affect the fine root abundance and that the fine roots extended uniformly. This observation was attributed to the dense planting of the jujube stands. These results agreed with previous trench wall studies by Bouillet et al. (2002) and soil core studies by Chen et al. (2005). However, these studies addressed the horizontal root distribution of trees planted with greater spacing than our study. Nambiar (1983) reported that root closure occurred in radiata pine plantations in southeast Australia after 2–3 years due to rapid root development as the stand approached canopy closure. In our study, the site appeared to be fully occupied with this dense spacing pattern where root closure analogous to canopy closure probably would have occurred. Sandy loam soils with low mechanical impedance and low moisture retention also tend to promote extensive lateral root spreading (Schenk and Jackson 2002). Liedgens and Richner (2001) reported that uniformly distributed maize root systems increased the root water uptake compared with those with high lateral variability root systems at the stand scale. In our work, the uniformly distributed horizontal fine roots might absorb water and nutrient effectively.

Our study only analyzed the root distribution in the first meter of soil, while the root system expanded more in depth. In view of this limitation, the results do not provide a description of the root distribution for an entire jujube tree. Nutrient uptake may also occur for eucalypts in deep soil layers at a depth of 3 m in sandy soil when gravitational solutions reach that depth (da Silva et al. 2011). Sharp and Davies (1985) reported that high soil water depletion rates correlated with high root densities. In our study, a major component of the root intersects appeared in the top 0.6 m, which could provide optimal application position for water and nutrient management practices. Further study will focus on the relationships of root distribution and soil water and root distribution and nutrient distribution in varied stand age jujube plantations.

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