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Competitive interaction in a jujube tree/wheat agroforestry system in northwest China's Xinjiang Province

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Abstract The jujube tree (*Zizyphus jujuba* Mill.)/ wheat (*Triticum aestivum* L.) agroforestry system is frequently used in China's Xinjiang Province. The system improves land-use efficiency and increases economic returns. A field experiment was conducted at the Hetian oasis in southern Xinjiang Province to investigate the relationship between root distribution and interspecific interaction between the two intercropped species. The study included seven treatments: sole-cropped 5, 7, or 9-year-old jujube trees (treatments 1–3); 5, 7, or 9-year-old jujube trees intercropped with wheat (treatments 4–6); and sole-cropped wheat (treatment 7). To determine vertical root distribution, soil cores were collected in 20-cm increments from the 0 to 100-cm soil depth. The cores were collected at horizontal distances of 30, 60, 90, 120, and 150 cm from the jujube rows. The results showed that the land equivalent ratios were >1 for the three jujube/wheat intercropping systems. This indicated that these systems were advantageous compared with sole cropping. Tree height, breast height diameter, and mean crown radius were less in the intercropped treatments than in the corresponding sole-cropped treatments. Intercropping reduced the root length densities (RLDs) and root diameters (RDs) of both jujube and wheat at all soil depths. The RLD and RD of 9-year-old jujube trees were greater than those of the 5- and 7-year-old trees, which indicated that the root systems of the 9-year-old trees were more developed. Wheat root growth was inhibited more by older jujube trees than by younger ones. In conclusion, jujube tree/wheat intercropping can be practical and beneficial in the region. However, the mechanisms involved in the belowground interspecific interactions are still unknown. Additional research is needed to provide optimal management strategies and technologies for jujube/wheat intercropping.

Keywords Intercropping · Interspecific interactions · Jujube tree · Wheat · Land equivalent ratio (LER) · Root length density (RLD) · Root diameter (RD)

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Introduction

Demand for jujube (*Zizyphus jujuba* Mill.) fruit is increasing for both food and medicinal purposes (Qing et al. 2013). In the southern part of China's Xinjiang

Province, farmers are growing an increasing amount of jujube intercropped with wheat (*Triticum aestivum* L.). The jujube trees are grown as a cash crop, whereas wheat is grown primarily for food. This agroforestry system improves resource utilization (e.g., land, light, and temperature), economic return, and sustainability. Jujube/wheat intercropping at the Hetian oasis, where this study took place, covered 32,000 ha in 2011 (Zhang et al. 2013).

Knowledge about root distribution, interspecific interaction, competitive abilities, and growth strategies is fundamental to understanding the optimal combination of jujube and wheat. It is important to study the root's competitive abilities of both species and to compare different intercropping patterns in order to attain the maximum yield and stability. Based on this information, researchers can provide farmers with scientific advice and management techniques about jujube/wheat intercropping. Therefore, it is important to know how much interspecific competition influences root development and productivity.

Because of their morphological and physiological plasticity, crop root systems have inherent capability to adjust to complex soil environmental conditions (Zamora et al. 2007) This plasticity allows plants to avoid excessive intra- and interspecific competition (Schroth 1999). Competition for light, water, and nutrients exists at the interface between trees and crops in most agroforestry systems. This competition can reduce yield (Singh et al. 1989; Schroth 1999; Ong and Huxley 1996). The competition between perennial tree species and annual crop species exists not only aboveground (e.g., competition for light) but also belowground (e.g., competition for water and nutrients). This can lead to reductions in aboveground biomass and yield (i.e., fruit yield for trees and grain yield for crops) (Jose et al. 2000a, 2001; Zamora et al. 2007). Jose et al. (2004, 2006) noted that the spatial distribution of roots in tree/crop mixtures plays an important role in the competition for belowground resources. In a long-term experiment at the Hetian oasis, the root length densities (RLDs) of both trees and crops were reduced when wheat was intercropped with either jujube trees (Zhang et al. 2013) or walnut trees (*Juglans regia* L.) (Zhang et al. 2015). Zamora et al. (2007) measured the RLD of cotton (*Gossypium hirsutum* L.) alley cropped with pecan (*Carya illinoensis* K. Koch). They reported that the RLD of cotton was less in the nonbarrier treatment than in either the barrier or the sole-cropped treatments. Teklehaimanot and Quedraogo (2004) noted that the RLD of sorghum was reduced due to competition for water in a sorghum/néré (*Parkia biglobosa* Benth) alley cropping system. In a field study in western Kenya, Livesley et al. (2000) observed that the root lengths of trees and crops were both reduced when maize (*Zea mays* L.) was intercropped either grevillea (*Grevillea robusta*) or senna (*Senna spectabilis*).

Productivity, which is central to agroforestry systems, is affected by belowground root interactions (Schroth 1999; Jose et al. 2001). Rao et al. (1991) and Chamshama et al. (1998) concluded that tree-crop interactions reduced annual crop yields. Jose et al. (2000b) observed that maize yields were reduced by 35 % when alley cropped with black walnut, and by 33 % when alley cropped with red oak (*Quercus* spp.). Wang et al. (2014) reported that both fruit and crop yields were reduced when either 3-, 5-, or 7-year-old jujube trees were intercropped with wheat. Chamshama et al. (1998) noted that maize height was reduced by 43 % and maize biomass by 75 % in a Leucaena/maize mixture.

Because of growing interest in tree–wheat intercropping in northwest China, a long-term trial was established in 2006 to learn more about jujube tree–wheat (Zhang et al. 2013). This study, which focuses on the jujube tree–wheat system, was conducted with three questions in mind. The first question was how does interspecific competition affect productivity in jujube tree/wheat systems. We hypothesized that belowground interspecific competition would reduce the aboveground biomass and yield of the both crop species; however, total yield would be greater in the intercropped systems. The second question was how does interspecific competition affect root growth in this system. We predicted that the RLD and root density (RD) of both species would be adversely affected by belowground competition. The third question was what is the relative competitive ability of the crops in the intercropping systems. We hypothesized that older jujube trees would inhibit wheat root growth more than younger jujube trees.

Materials and methods

Experimental site

The study was conducted in 2014 at the Hetian Agricultural Scientific Research Institute(73°37′N, 34°20′E), the Agro-Tech Extension and Service Center of Hetian Prefecture, Xinjiang Uygur Autonomous Region, China. Annual mean temperature is 13.7 °C. Cumulative temperatures above 0 and 10 °C are 4646 and 4064 °C, respectively. Annual precipitation is 37.1 mm, potential evaporation is 2636 mm, and the region has a typical arid climate. The soil at the site is classified as an Arenosol in the classification system of the Food and Agriculture Organization (FAO). Arenosols are sandy, textured soils that lack any significant soil profile development. They exhibit only a partially formed surface horizon (uppermost layer) that is low in humus, and they are bereft of subsurface clay accumulation. The study consisted of a randomized complete block design with 27 plots of jujube tree–wheat alley cropping (Zhang et al. 2013). The characteristics of the physical and chemical properties of the soil have been described in a previous paper (Zhang et al. 2013). The intercropping was designed as a replacement series.

The following seven treatments were compared in this study: sole-cropped jujube trees (5-, 7-, or 9 years old), intercropped jujube/wheat (the jujube trees were 5-, 7-, or 9 years old), and sole-cropped wheat. The planting patterns are shown in Fig. 1. In plots with 5-year-old jujube, the row spacing was 200-cm and there was 110-cm between trees within a row. When wheat was planted between the jujube rows, the wheat strip was 90 cm wide (6 rows) and there was a 55-cm-wide bare strip between the wheat and the jujube trees. The jujube trees occupied 55 % of the intercropped area and wheat occupied 45 %. In plots with 7-year-old jujube, the row spacing was 600-cm, and there was 100 cm between trees within a row. When wheat was planted between the jujube rows, the wheat strip was 450-cm-wide (30 rows) and there a 75-cm-wide bare strip between the wheat and the jujube trees. The jujube trees occupied 25 % of the intercropped area and wheat occupied 75 %. In plots with 9-year-old jujube, the row spacing was 300 cm and there was 200 cm between trees within a row. When wheat was planted between the jujube rows, the wheat strip was 180-cm-wide (12 rows) and there a 60-cm-wide bare strip between the wheat and the jujube trees. The jujube trees occupied 40 % of the intercropped area and wheat occupied 60 %. The wheat planting density was 11.25 million plants ha^{-1}. There was 15 cm between wheat rows. Each plot included two 10-m-long rows of jujube. Thus, the 5-year-old jujube plots were 2 m × 10 m, the 7-year-old jujube plots were 6 m × 10 m, and the 9-year-old jujube plots were 3 m × 10 m. Each treatment was replicated three times.

The wheat (cv. Xindong 20) was sown on October 28, 2013. All plots were fertilized with urea and diammonium phosphate at rates of 450 kg N ha^{-1} and 30 kg P ha^{-1}. Half the N fertilizer and all the P fertilizer were broadcast evenly across the soil surface and then incorporated into the 0–20-cm depth before sowing wheat. The remaining half of the N fertilizer was applied to the plots when wheat reached the stem elongation stage. The plots were irrigated six times (March 24, April 16, May 4, May 29, July 26, and September 3, 2014). Each irrigation application consisted of 90 mm (900 m^3 ha^{-1}). These irrigation practices were recommended to farmers by local agronomists.

Collection of root samples

Vertical root distribution was determined using the method of Böhm (1979). Soil cores were collected with an auger (5.5-cm diam) on June 15, 2014. The wheat was nearly mature, and the jujube trees were flowering. The soil cores were collected in 20-cm increments to a maximum depth of 100 cm. The cores were collected 30, 60, 90, 120, and 150 cm from the tree row in each plot so that spatial changes in the horizontal distribution of the roots could be determined (Fig. 1). Specific sampling and measuring method for root have been described in a previous paper (Zhang et al. 2013).

Collection of plant samples

The wheat was harvested on June 26, 2014. Just before harvesting, the stunting and mortality rates of wheat plants were determined in a 5-m-long portion of each wheat strip. The plants were then cut at ground level. The samples were air dried, threshed by hand, and then weighed to determine grain yield and total above-ground biomass (i.e., straw + grain).

The height, diameter at breast height, and mean crown radius of the jujube trees was determined on October 2, 2014. Immediately afterward, the jujube fruit were harvested. The fruit were air dried and then weighed.

Calculation of Land equivalent ratio (LER)

The LER is the ratio of the area under a pure stand to the area under intercropping needed to produce an equal amount of yield at the same management level (Vandermeet 1989; Rao et al. 1990, 1991; Cao et al. 2012). The LER indicates the environmental resource use efficiency of intercropping compared with sole cropping (Mead and Willey 1980; Dhima et al. 2007). The LER is calculated using the following equation:

$$LER = Y_{jw}/Y_{j} + Y_{wj}/Y_{w},$$

where Y_j and Y_w are the yields of sole-cropped jujube and sole-cropped wheat, respectively; and Y_{jw} and Y_{wj} are the yields of jujube and wheat in the intercropped systems, respectively. A ratio greater than 1.0 indicates that intercropping is advantageous whereas a ratio less than 1.0 indicates that intercropping is disadvantageous (Zhang et al. 2013, 2015; Wang et al. 2014).

Statistical analysis

Analysis of variance (ANOVA) was conducted using SPSS Version 19.0 for Windows. Mean ($n = 3$) were compared using least significant difference (LSD) tests at the 5 % level.

Results

Land equivalent ratio

Based on yield, the LER values were >1 for all intercropping treatments. The LER values decreased in the order 7-year-old jujube tree/wheat (1.28) > 5-year-old jujube tree/wheat (1.20) > 9-year-old jujube tree/wheat (1.15) (Table 1).

Intercropping with 5-, 7-, and 9-year-old jujube trees significantly reduced wheat grain yield on a net area basis by 24 % ($p = 0.042$), 39 % ($p = 0.007$), and 54 % ($p = 0.001$), respectively (Table 1). Aboveground biomass was significantly reduced by 5-, 7-, and 9-year-old jujube trees by 23 % ($p = 0.015$), 37 % ($p = 0.002$), and 54 % ($p = 0.001$), respectively. Intercropping significantly reduced the yield of 5- and 7-year-old jujube trees by 20 % ($p = 0.012$ and 0.008, respectively). Intercropping reduced the yield of 9-year-old trees by 15 %; however, the difference was not significant ($p = 0.055$).

Intercropping had no significant effect on tree height ($p = 0.103$), diameter at breast height ($p = 0.286$), and mean crown radius ($p = 0.165$); however, these values were all generally less in intercropped tree than in sole-cropped trees (Table 2).

Fig. 1 Schematic diagram showing the planting patterns for ▶ **a** sole-cropped 5-year-old jujube trees, **b** sole-cropped 7-year-old jujube trees, **c** sole-cropped 9-year-old jujube trees, **d** 5-year-old jujube/wheat, **e** 7-year-old jujube/wheat and **f** 9-year-old jujube/wheat in intercropped plots. Distances between rows and gap sizes (cm) are indicated. There was a distance of 30 cm between adjacent root sampling sites

Spatial distribution of wheat root length density

Intercropping reduced the RLD of wheat at all distances from the trees (Fig. 2a–d). Averaging all soil depths (0–100 cm), the RLD of wheat intercropped with 5-year-old jujube was 58, 60, 65, 69, and 71 % that of sole-cropped wheat at distances of 30, 60, 90, 120, and 150 cm from the trees (Fig. 2a, b, $p < 0.05$). The same pattern was observed in wheat intercropped with 7- and 9-year-old jujube ($p < 0.05$). The RLD of intercropped wheat (Fig. 2b–d) was reduced more at the edge of the wheat strip (i.e., near the trees) than it was in the center of the wheat strip (i.e., far from the trees). The horizontal distribution of wheat RLD in plots with 9-year-old trees was different from that in plots with either 5- or 7-year-old trees (Fig. 2b–d). The RLD of intercropped wheat was reduced by trees at the majority of soil depths. The largest reductions in the RLD of intercropped wheat were 0–60 cm from the tree row (Fig. 2b–d). The roots of intercropped wheat tended to be distributed more shallowly than those of sole-croppped wheat.

Spatial distribution of root length density of jujube

The distribution of jujube RLD is presented as contour diagrams in Fig. 3a–f. The RLD of jujube was less in the intercropped treatments than in the sole-cropped

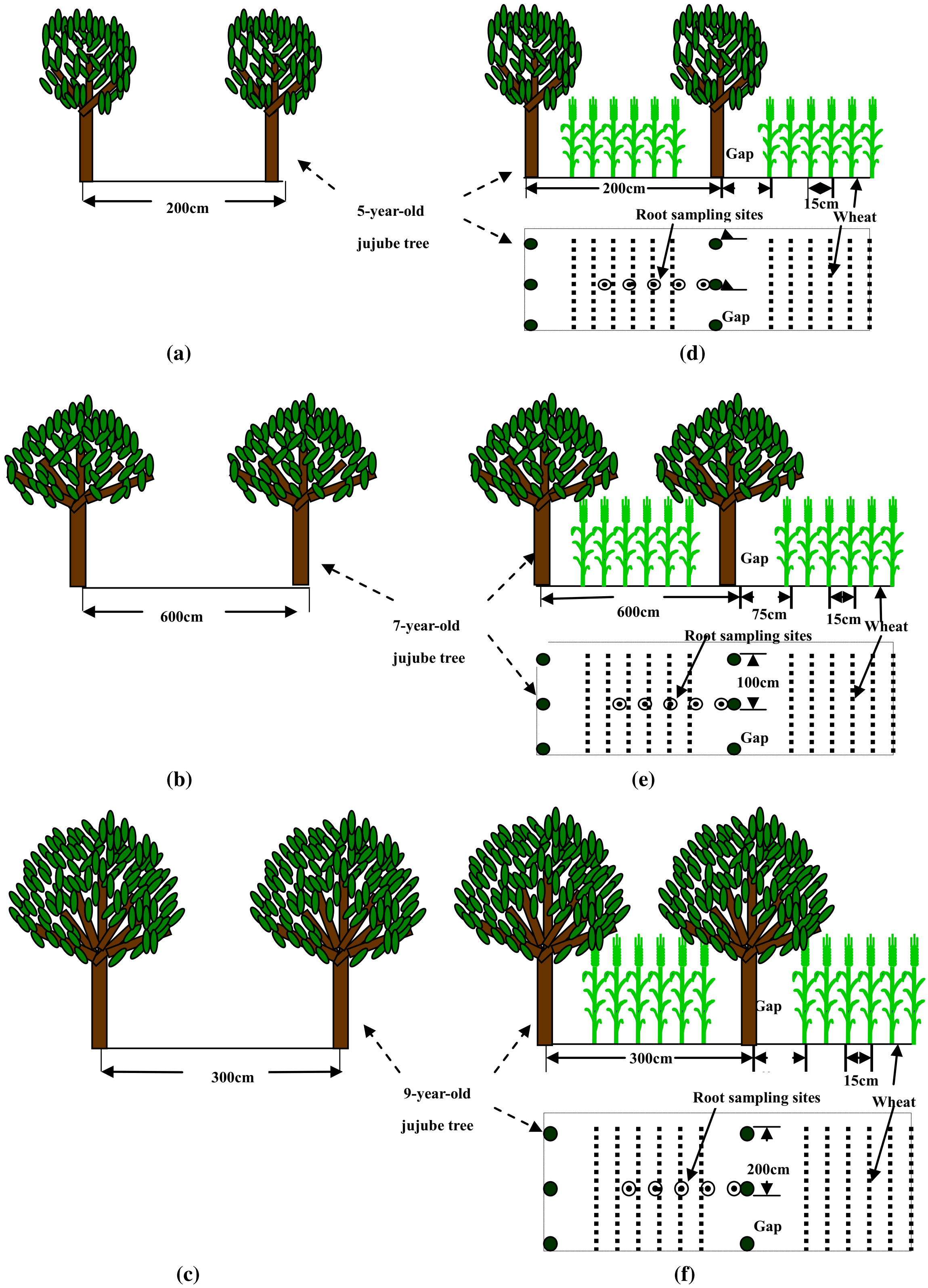
200cm
5-year-old
jujube tree
(a)
Gap
200cm
15cm
Root sampling sites
Wheat
Gap
(d)
600cm
7-year-old
jujube tree
(b)
Gap
600cm
75cm
15cm
Wheat
Root sampling sites
100cm
Gap
(e)
300cm
9-year-old
jujube tree
(c)
Gap
300cm
15cm
Root sampling sites
Wheat
200cm
Gap
(f)

Table 1 Land equivalent ratio, grain yield (kg ha^{-1}), and biomass (kg ha^{-1}) of sole-cropped wheat, intercropped wheat, sole-cropped jujube trees, and intercropped jujube trees

Age of trees (years)	Wheat				Jujube			LER
	Sole	Intercropped (Net area)	Intercropped (Gross area)	Significance	Sole	Intercropped	Significance	
Grain yield (fruit yield)								
5	4753	3601	1891	*	7129	5703	*	1.20
7	4753	2922	2294	*	1,1081	8868	*	1.28
9	4753	2168	1409	*	1,3698	1,1689	ns	1.15
Abovegroundbiomass								
5	9158	7047	3457	*	–	–	–	–
7	9158	5728	4297	*	–	–	–	–
9	9158	4197	2518	*	–	–	–	–

Wheat yield and aboveground biomass were measured when plants reached maturity on June 26, 2014. Jujube yield was measured on October 2, 2014

Values for net area grain yield and aboveground biomass are averages of sole- and three intercropped wheat, and with three replicates ($n = 12$); values for fruit yield are averages of sole-cropped 5-, 7-, and 9-year-old jujube trees and intercropped 5-, 7-, and 9-year-old jujube trees, and with three replicates ($n = 6$)

* indicates significant difference between the sole and intercropping treatments at $p < 0.05$; ns, no significant difference ($p > 0.05$)

Table 2 Selected characteristics of the jujube trees on October 2, 2014

Age of trees (years)	TH			DBH			MRC		
	5	7	9	5	7	9	5	7	9
Sole-cropped	211a	243a	265a	42a	46a	54a	145a	167a	188a
Intercropped	197a	235a	258a	40a	46a	52a	136a	159a	173a

Treatment values followed by the same lower case letter (within a column) refers to no significant difference between the sole and intercropping treatments at the 0.05 level by paired *t* test

TH tree height (cm), *DBH* diameter at breast height (cm), *MRC* Mean crown radius (cm)

treatments. Averaging the 0–100-cm depth, the RLDs of the 5- or 7-, and 9-year-old intercropped trees were 19, 15, and 11 % less, respectively, than those of sole-cropped jujube trees of corresponding age. In general, there was little difference in the horizontal distribution of jujube roots between the intercropped treatments and the sole-cropped treatments (Fig. 3a–f). In the intercropped treatments, the jujube roots grew under the wheat rows; however the RLD beneath the wheat was less than that in the corresponding position in the sole-cropped jujube treatments (Fig. 3b, d, f).

Intercropping reduced the rooting depth of jujube, and there were significant vertical differences in the RLD of jujube between the intercropping treatment and the sole-cropped treatment. Specifically, the RLDs of intercropped trees were less than those of sole-cropped trees (Fig. 3). For example, the 20 cm/125 cm^3 contour of 5-year-old jujube trees was below the 80-cm depth in the sole-cropped treatment but above the 80-cm soil depth in the intercropped treatment (Fig. 3a, b). The same patterns were observed for 7- and 9-year-old jujube trees. The 60 cm/125 cm^3 RLD contour of 7-year-old trees was below the 40-cm depth in the sole-cropped treatment but above the 40-cm depth in the intercropped treatment (Fig. 3c, d). For 9-year-old trees, the 30 cm/125 cm^3 RLD contour was within the 80–100-cm depth in the sole-cropped treatment whereas in the intercropped treatments it was within the 60–80-cm depth (Fig. 3e, f). The RLD of 9-year-old trees was less affected by intercropping than the 5- and 7-year old trees. For instance, the 50, 60, and

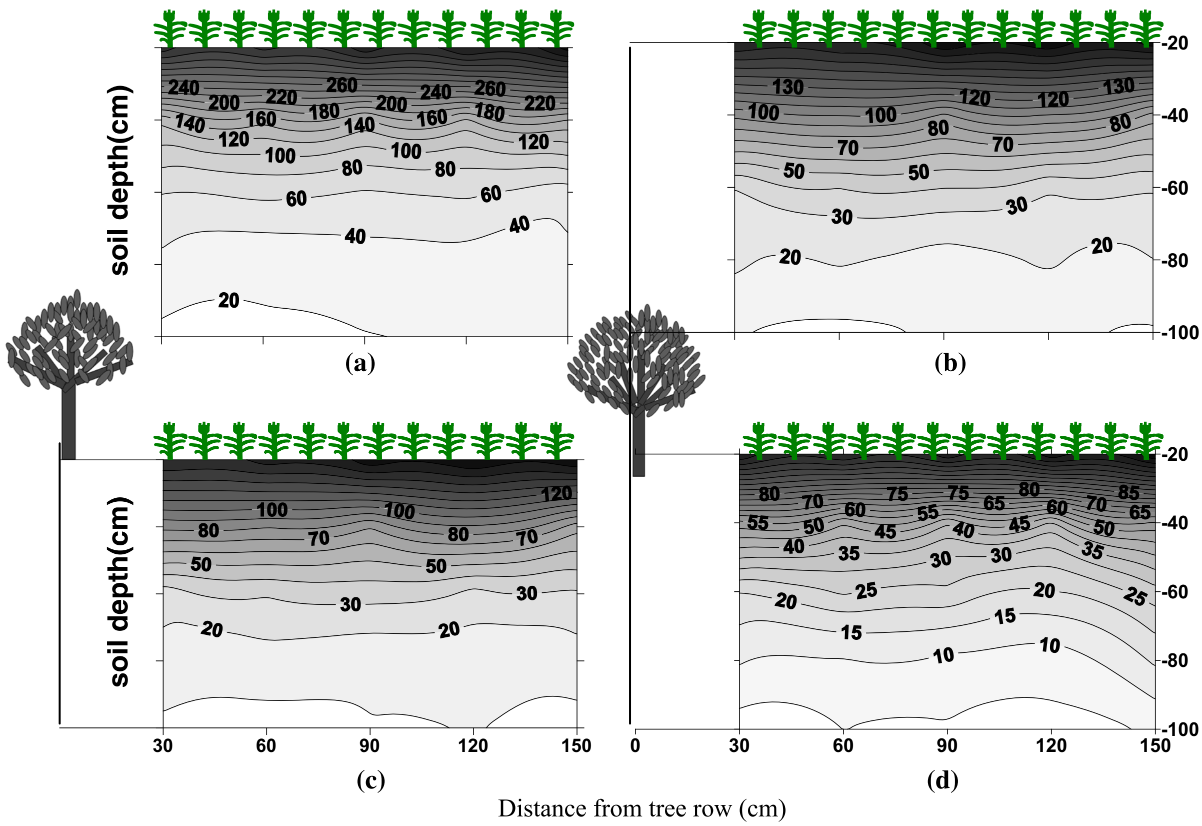

Fig. 2 Spatial distributions of wheat root length density (RLD, cm 125 cm^{-3}) in **a** sole-cropped wheat, **b** wheat intercropped with 5-year-old jujube trees, **c** wheat intercropped with 7-year-old jujube trees, and **d** wheat intercropped with 9-year-old jujube trees

70 cm/125 cm^3 RLD contours were within the 40–60-cm soil depth in both the sole-cropped and intercropped treatments.

Spatial distribution of wheat root density

The spatial distribution of wheat RD in the sole- and intercropped treatments is shown in Fig. 4. Averaging the 0–100-cm depth, the RD of sole-cropped wheat was 0.34 mm. In comparison, the RDs of wheat intercropped with 5-, 7-, and 9-year-old jujube trees were 0.24, 0.22 and 0.19 mm, respectively. The RD of wheat was less in the intercropped treatments than that in the sole-cropped treatments at all depths, and especially in the 0–60-cm depth. (Figure 4a–d). Specifically, compared with sole-cropped wheat, intercropping with 5-, 7-, and 9-year-old jujube trees reduced the RDs of wheat by 23.8, 28.4, and 30.1 %, respectively (Fig. 4a–d). This indicated that the 9-year-old trees reduced the RD of wheat more than the 5- and 7-year old trees did.

Spatial distribution of jujube root density

In the intercropped treatments, the average RD of jujube trees was much larger than that of wheat at all depths (Fig. 5). However, intercropping reduced the RDs of the jujube trees (Fig. 5a–f). Averaging all depths (0-100 cm), the RDs of 5-, 7-, and 9-year-old jujube trees were, respectively, 2.63, 3.31, and 4.69 mm in the sole-cropped treatments compared with 2.31, 2.65, and 3.28 mm in the intercropped treatment. Averaging the 0–60-cm depth, the RDs of 5-, 7-, and 9-year-old jujube trees were, respectively, 3.91, 4.49, and 5.39 mm in the sole-cropped treatments compared with 3.19, 4.11, and 4.58 mm, in the intercropped treatments. Overall, the RD of intercropped trees was less than that of sole-cropped trees at the majority of soil depths, especially at 0–60-cm soil depth (Fig. 5a–f).

There were also significant differences in the vertical distribution of RD among treatments. For example, the 3.6-mm contour of 5-year-old trees was

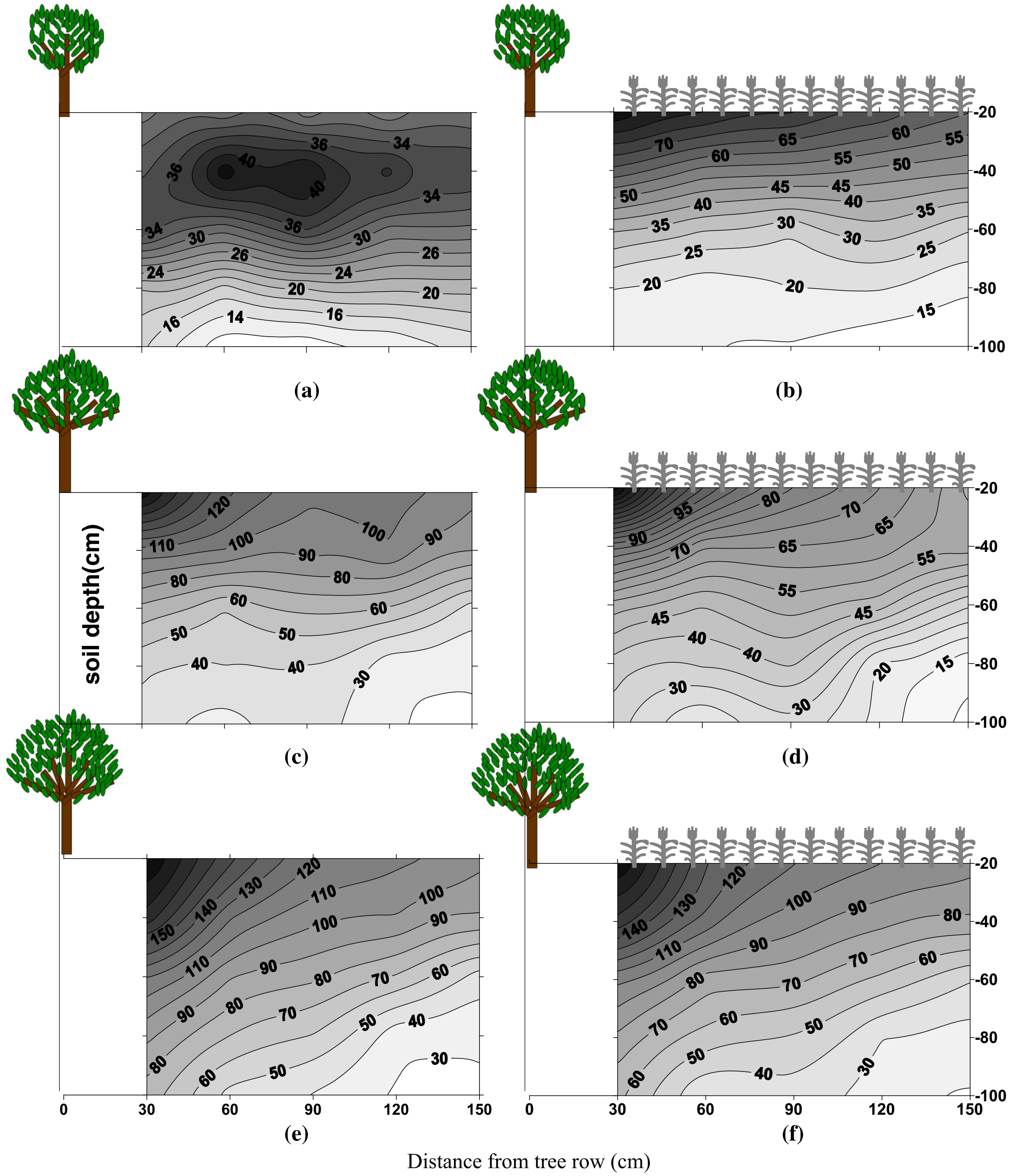

Fig. 3 Spatial distribution of root length density (RLD, cm 125 cm^{-3}) in **a** jujube trees grown alone for 5 years, **b** 5-year-old jujube trees intercropped with wheat, **c** jujube tree grown alone for 7 years, **d** 7-year-old jujube trees intercropped with wheat, **e** jujube trees grown alone for 9 years, and **f** 9-year-old jujube trees intercropped with wheat

below the 40-cm depth in the sole-cropped treatment, but above the 40-cm depth in the intercropped treatment (Fig. 5a, b). In 7-year-old trees, the 3-mm RD contour was in the 40–60-cm soil depth in the sole-cropped treatment, but below the 60-cm depth in the intercropped treatments (Fig. 5c, d). In 9-year-old

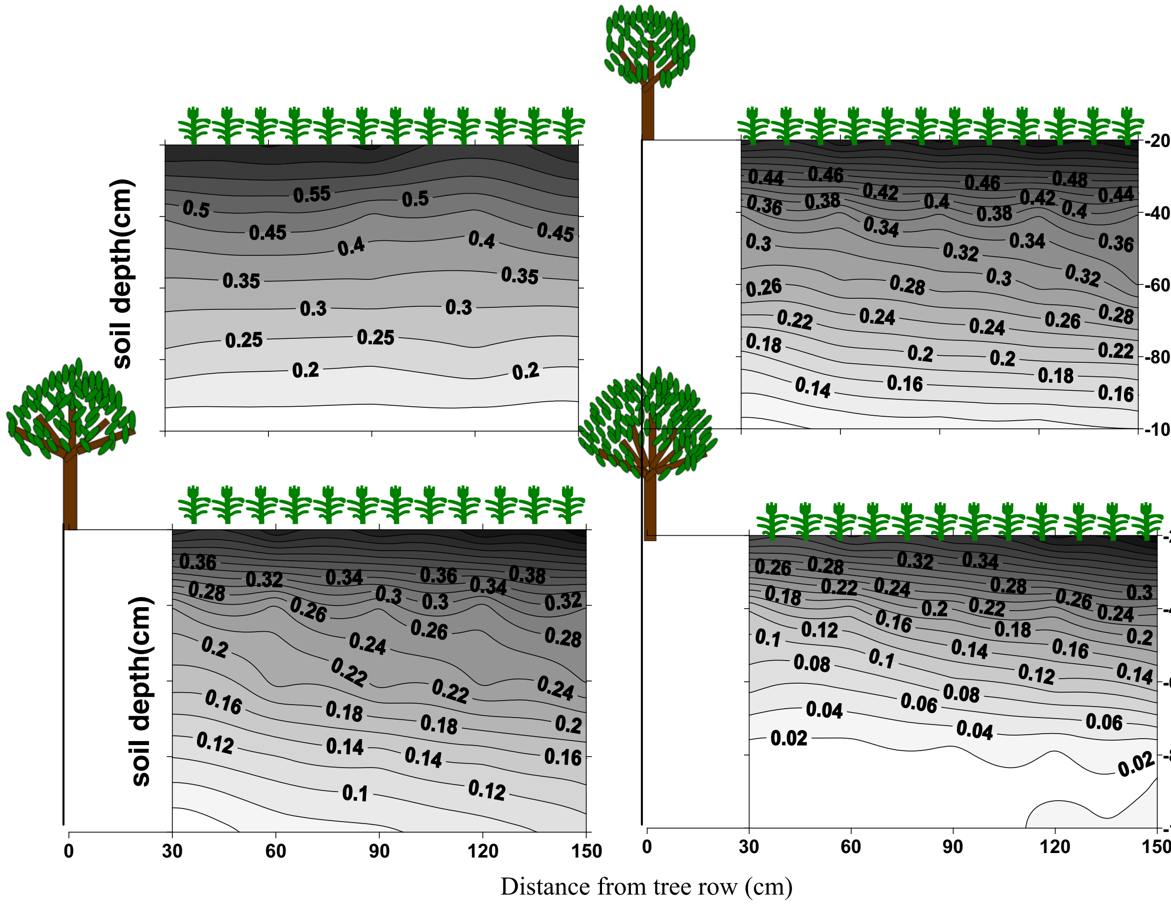

Fig. 4 Spatial distribution of root diameter (RD, mm) in **a** sole-cropped wheat, **b** wheat intercropped with 5-year-old jujube trees, **c** wheat intercropped with 7-year-old jujube trees, and **d** wheat intercropped with 9-year-old jujube trees

trees, the 4-mm RD contour was located at the 40-cm depth in the sole-cropped treatment, whereas it was at the 20–40-cm depth in the intercropped treatment (Fig. 5e, f).

Discussion

Land equivalent ratio (LER), growth, biomass, and yield

The LERs of all three jujube tree/wheat treatments were >1, indicating that the land-use advantages of intercropping were significantly greater than those of sole cropping. These findings agreed with the results of previous studies in Hetian which showed that the LER of jujube tree–wheat systems was >1 (Zhang et al. 2013; Wang et al. 2014). The LER values indicate that there is complementarity in resource use between the jujube and the wheat. The results also support the idea that agroforestry systems have greater productivity, and potentially greater sustainability, compared with monocultures (Ong et al. 2004; Zhang et al. 2013, 2015; Wang et al. 2014). Similar results were observed in two agroforestry systems in semiarid Machakos, Kenya: Leucaena (*Leucaena leucocephala*)/maize and senna (*Senna siamea* syn. *Cassia siamea*)/maize (Jama et al. 1995).

Interspecific competition with jujube significantly reduced wheat yield and aboveground biomass. The negative effect of jujube on wheat increased as the jujube trees matured. This agrees with Yin and He (1997) who reported that crop yields were lower when intercropped with old paulownia (*Paulownia*

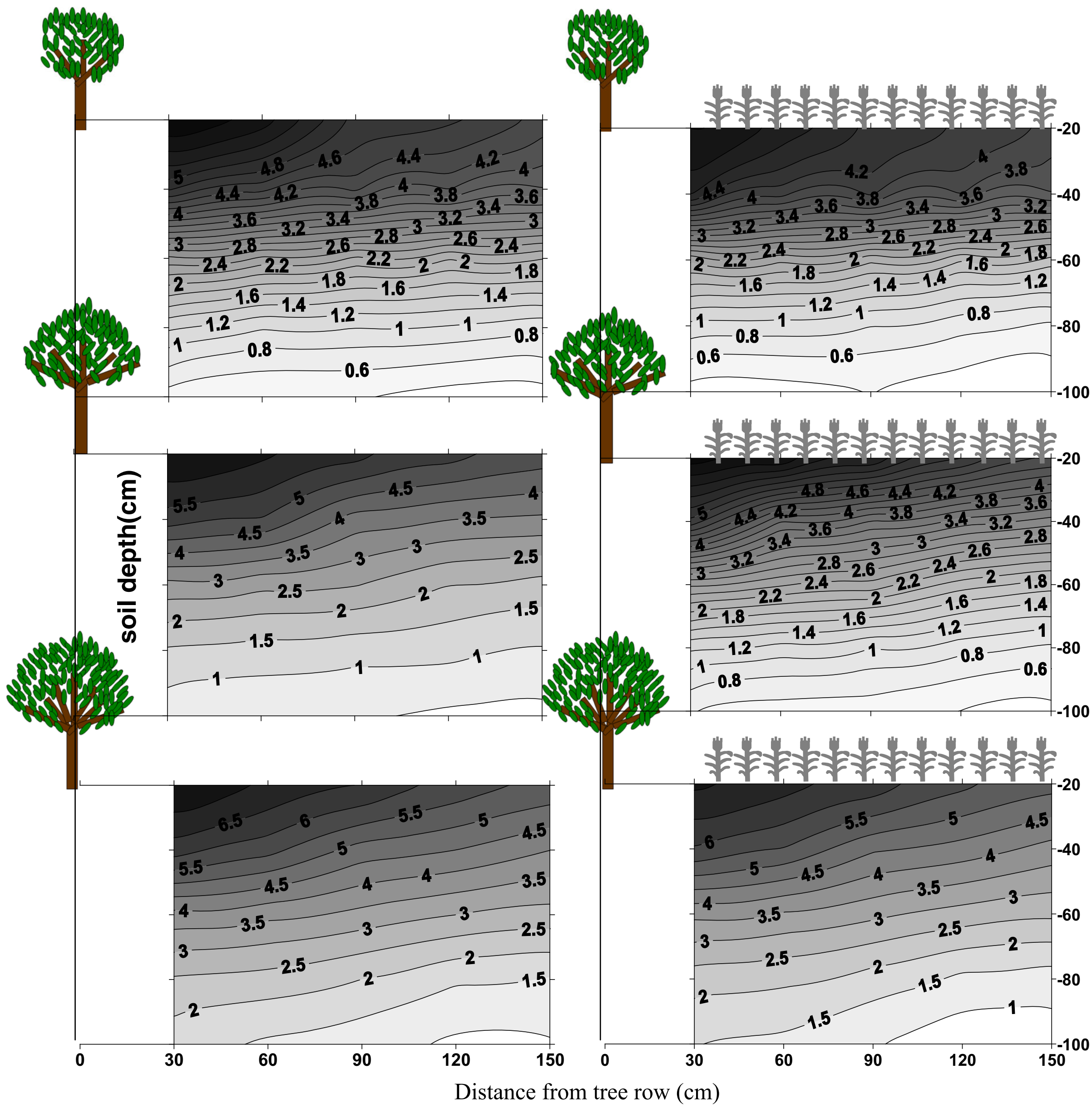

Fig. 5 Spatial distribution of root diameter (RD, mm) in **a** jujube trees grown alone for 5 years, **b** 5-year-old jujube trees intercropped with wheat, **c** jujube tree grown alone for 7 years, **d** 7-year-old jujube trees intercropped with wheat, **e** jujube trees grown alone for 9 years, and **f** 9-year-old jujube trees intercropped with wheat

elongata) trees than with young ones. In the present study, the fruit yields of 5- and 7-year-old jujube trees were less in the intercropped treatments than those in the sole-cropped treatments. This result supports our first hypothesis that yield and biomass will decrease because of belowground interspecific competition in the tree/crop mixtures. Similar yield declines have been observed in the following agroforestry systems: *L. leucocephala* Lam hedgerow/crop (Singh et al. 1989); pecan (*C. illinoensis*)/cotton (*G. hirsutum*) (Wanvestraut et al. 2004); and apple/soybean or apple/peanut (Gao et al. 2013). Our results are also similar to previous reports about jujube/wheat intercropping systems (Zhang et al. 2013; Wang et al.

2014). It should be noted that the height, DBH, and mean crown radius of intercropped jujube trees were not significantly different from those of the mono-cropped trees. This might be related to the well-developed root systems of jujube trees.

Interspecific competition and root spatial distribution

Belowground competition is most likely to occur when two or more species attempt to capture resources from the same soil strata or at the same time (spatial or temporal) (Jose et al. 2004). Belowground competition between jujube and wheat is reflected by decreases in RLD and RD. The RLDs and RDs of both species were less in the intercropped treatments than in the sole-cropped treatments. However, the wheat was much less competitive than the jujube. The decrease in the RLD and RD of wheat and the inhibition of wheat root growth was greater when the jujube trees were older. Schroth (1999) suggested that plants with high RLD are likely to be more competitive than those with low RLD. Overall, these results answer our second and third questions. Specifically, belowground competition adversely affected the RLD and RD of both species. Furthermore, older jujube trees suppressed wheat growth more than younger trees did. Similar outcomes have been observed in other agroforestry systems. For instance, in a pecan/cotton intercropping system, the RLD of cotton was lower at each soil depth in the nonbarrier treatment than in either a monoculture treatment or a barrier treatment (Zamora et al. 2007). Bolte and Villanueva (2006) noted that the sum of species fine root attributes was less in mixed stands rather than pure stands of European beech (*Fagus sylvatica* L.) and Norway spruce [*Picea abies* (L.) Karst.]. Other authors have also suggested that interspecific interactions in tree/crop systems may lead to increased capture of a limiting growth resource (Ashton 2000; Teklehaimanot and Quedraogo 2004; Wanvestraut et al. 2004) and lower RLD of crops. The results of the present study are consistent with those of Hendriks and Bianchi (1993) who reported that the RD of Douglas fir decreased more gradually with depth in a mixed forestry system than in pure stands. In addition, we also observed that in the intercropped treatments, jujube roots spread under the wheat (Figs. 2b–d, 3f, h, j) and were generally more shallow than those in the sole-cropped treatments. We think that intercropped jujube trees expanded their effective space in order to increase absorption of a limiting growth resource. Many authors have held similar views regarding tree/crop systems (Ong and Huxley 1996; Ashton 2000; García-Barrios and Ong 2004). It should be noted that shallower fine root systems of intercropped trees may increase drought vulnerability (Schmid 2002). Thus, we recommend that more irrigation may help intercropped jujube/wheat to grow.

A problem that needs to be solved

In general, perennial plants have a longer life-span and larger root system than annuals. Interspecific interaction such as root competition inevitably occurs when perennials and annuals are grown together (Zhang et al. 2013). In many intercropping systems, belowground competition may be more important than aboveground competition (Remison and Snaydon 1980). This kind of root competition may be an asymmetric interaction, especially when the intercropped trees are old and when the tree density is high (Yin and He 1997). In addition, Jackson and Caldwell (1992) reported that in agroforestry systems, trees reduce the availability of both light and CO_2 to the annual plants, thus weakening the root system of the annuals and making them less able to respond to fertile soil. The interspecific root competition mentioned above is an urgent problem that must be solved at our experimental site. In southern Xinjiang, jujube is the main cash crop, with fresh jujube prices averaging between 3 and 6 USD kg^{-1} (Zhang et al. 2013). In contrast, wheat is primarily grown for food (wheat grain prices average between 0.3 and 0.4 USD kg^{-1}) and for livestock feed (Wheat straw is favored by farmers as livestock feed, especially in oasis of Hetian). The negative effect of jujube on wheat increases as jujube trees grow larger and reach their phase of maximum production. This results in substantially less wheat yield (Wang et al. 2014). At the same time, intercropping also reduces the fruit yield of jujube trees to some extent (Zhang et al. 2013). Therefore, farmers are reluctant to intercrop wheat with jujube once the jujube trees have reached maturity. The farmers can earn more money when mature jujube trees are sole-cropped. They can then use their additional income to buy wheat that has been grown in another location. Expanding the planting space may be reduce both above- and belowground interspecific competition (Zhang et al. 2013); however, lower tree densities would mean less fruit output per unit area. Tree pruning is another means of reducing interspecific competition; however, excessive shoot pruning may affect photosynthesis, thus reducing fruit yield (Zhang et al. 2013). Furthermore, Fernandes et al. (1993) suggested that as trees age, the efficiency of shoot pruning in controlling belowground competition may decrease. Given this situation, some local officials have proposed the following systems to guarantee food and fodder supplies: (1) only interplanting wheat between lines of young fruit trees or (2) only planting food crops. The officials believe that this is the best way to maintain high yield of jujube and improve economic benefit. However, the Hetian oasis has a large population and little arable land. Any method which simply secures the economic benefit of jujube fruit at the expense of food and fodder does not benefit the steady and healthy development of the local production structure. Understanding the balance of these interactions and relations across time is important for farmers and local officials to evaluate their management options. Thus, a long-term study should be established to examine how to minimize the interspecific competition in jujube tree/wheat mixtures in order to maximize the benefit to local farmers. We hope that the results of this study can be used in the future for policy decisions in the old oasis of Hetian.

Conclusions

Wheat roots tended to be shallower in the intercropped treatments than in the sole-cropped treatments. Jujube roots spread under the wheat in the intercropped treatments but occupied a comparatively smaller soil space than in the sole-cropped treatments. Consequently, the RLDs and RDs of both jujube and wheat were less in the intercropped treatments than in the sole-cropped treatments. These results support the hypothesis that interspecific competition in the intercropped treatments affects root growth, biomass accumulation, and yield. Jujube tree/wheat intercropping can achieve greater combined production than sole cropping. In addition, wheat root growth is inhibited more by older jujube trees than by younger ones.

Successive years of study have clearly shown that the root morphologies of both crops are significantly altered in the jujube tree–wheat alley cropping system. The mechanisms involved in the belowground interspecific interactions are still unknown. Further research is needed about these interspecific interactions and the mechanisms behind these interactions. The outcomes of such studies would be useful for arriving at suitable future policy decisions by the local government in Hetian.

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