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Root distribution and interactions in jujube tree/wheat agroforestry system

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Abstract Even though agronomists have considered the spatial root distribution of plants to be important for interspecific interactions in agricultural intercropping, few experimental studies have quantified patterns of root distribution and their impacts on interspecific interactions in agroforestry systems. A field experiment was conducted to investigate the relationship between root distribution and interspecific interactions between intercropped jujube tree (*Zizyphus jujuba* Mill.) and wheat (*Triticum aestivum* Linn.) in Hetian, south Xinjiang province, northwest China. Roots were sampled by auger in 2-, 4- and 6-year-old jujube tree/wheat intercropping and in sole wheat and 2-, 4- and 6-year-old sole jujube down to 100 cm depth in the soil profile. The roots of both intercropped wheat and jujube had less root length density (RLD) at all soil depths than those of sole wheat and jujube trees. The RLD of 6-year-old jujube intercropped with wheat at different soil depths was influenced by intercropping to a smaller extent than in other jujube/wheat intercropping combinations. 6-year-old jujube exhibited a stronger negative effect on the productivity of wheat than did 2- or 4-year-old jujube and there was less effect on productivity of jujube in the 6-year-old system than in the 2- or 4-year-old jujube trees grown in monoculture. These findings may partly explain the interspecific competition effects in jujube tree/wheat agroforestry systems.

Keywords Intercropping · Interspecific interactions · Jujube tree · Wheat · Root length density (RLD)

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Introduction

Jujube tree (*Zizyphus jujuba* Mill.)/wheat (*Triticum aestivum* L.) agroforestry systems play an important role in agricultural production in Southern Xinjiang Uygur Autonomous Region, northwest China and are of increasing interest because they offer potential advantages for resource utilization (land, light and temperature), higher economic returns to farmers (with fresh jujube prices averaging USD 3–6 kg^{-1}) and increased sustainability in crop production. The estimated area under jujube tree and wheat in Hetian was 32,000 ha in 2011 (Liu et al. 2012). The jujube tree is the main cash crop and wheat is a primary food crop and both are harvested once a year in south Xinjiang. In this agroforestry system the jujube trees are grown simultaneously with wheat for 240–260 days. When the two plant species grow together interspecific interactions between them inevitably occur. Although it is well known that the jujube/wheat system improves tree establishment and growth in the plantation forests of northwest China (Lin et al. 2000) there is lack of data on tree–crop interactions that can be used to elucidate intercropping advantages. To provide farmers with scientific advice and management techniques it is necessary to study the competitive ability of intercropping plant components and to examine optimum jujube tree/wheat intercropping patterns.

Studies of tree-crop interactions have produced two very different patterns of results. For example, Rao et al. (1991) and Chamshama et al. (1998) reported that the concentration of roots in the upper soil profile caused intense belowground competition for resources which, in turn, resulted in decreased crop productivity. Livesley et al. (2000) observed that greater proximity to a tree row reduced maize root length and therefore reduced its ability to compete for resources. Schroth and Zech (1995) concluded that trees can compete with associated crops through their root systems and this may lead to yield depressions and may contribute to the economic failure of land-use systems. Gillespie et al. (2000) reported crop yield reductions of up to 40 % due to severe competition when trees were 11 years old. Other investigators have found benefits to crops from multipurpose farm trees, *Grevillea robusta*, and dinitrogen fixing trees, such as *Gliricidia sepium* and *Leucaena leucocephala* (Maghembe et al. 1986; Young 1997; Reyes et al. 2009). Imo and Timmer (2002) considered that tree-crop interactions are not always competitive and may be affected by several factors including component combinations, total planting densities, and management regimes. Systematic methods are therefore required to quantify the overall interaction effects in different agroforestry systems.

Although many of the competitive vectors of alley cropping systems have been identified, not all have been adequately quantified. In the present study we experimentally compared three ages of jujube tree grown with a wheat crop systematically to examine the competitive interactions between the two species and the likely response mechanisms in order to guide policy decisions in tree-crop system management. Jujube trees and wheat were selected for the study because of their importance as the main economic and food crops, respectively, in south Xinjiang.

Considering the growing interest in jujube trees and wheat for alley cropping systems in northwest China and the limited information on their root distribution and yields, specifically in response to the belowground competition, our study was conducted to test the following hypotheses. Firstly, the yield and biomass will decrease with interspecific competition underground in the tree-wheat associations. Secondly, the root length density will be adversely affected by belowground competition. Thirdly, the older the jujube trees the greater the decrease in RLD and the stronger the inhibition of wheat root growth in response to competition in the subsoil.

Materials and methods

Experimental site

The field experiment was conducted in 2011 at Hetian Agricultural Scientific Research Institute, Agro-Tech Extension and Service Center of Hetian Prefecture, Xinjiang Uygur Autonomous Region, China. Hetian Agricultural Scientific Research Institute (73°37′N, 34°20′E) is located 6 km north of Hetian City and is 1,380 m above sea level. Annual mean temperature is 13.7 °C. Cumulative temperatures above 0 and 10 °C are 4,646 and 4,064 °C, respectively. The frost-free period is 200–220 days. Total solar radiation is 6,627 MJ m^{-2} $year^{-1}$. Annual precipitation is 37.1 mm, potential evaporation is 2,636 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. Some chemical properties of the soil are presented in Table 1 (Soil Survey Office in Hetian, 2003).

Experimental design

The experimental design was a single factor field experiment with three replicates, comprising sole wheat (*T. aestivum* Linn.) and sole 2-, 4- and 6-year-old jujube

Table 1 Nutrient status of the experimental soil

Soil depth (cm)	pH (H_2O) (2.5:1)	Organic matter (g kg^{-1})	Total N (g kg^{-1})	Alkali-hydrolyzable N (mg kg^{-1})	Olsen P (mg kg^{-1})	NH_4OAc-extractable K (mg kg^{-1})
0–30	8.51	19.23	5.8	54.2	21.2	51.3
30–60	8.46	10.46	5.7	44.9	2.6	29.7
60–100	8.45	6.27	5.1	41.6	1.0	27.8

trees (*Z. jujuba* Mill.) and wheat intercropped with 2-, 4- and 6-year-old jujube trees. The intercropping was designed as a replacement series. Wheat and 2-year-old jujube tree intercropping involved planting in 2-m-wide strips (wheat plus two rows of 2-year-old jujube trees) which included a 0.9-m-wide wheat strip (six rows of wheat with 0.15 m inter-row distance) and 1.10 m between the 2-year-old jujube tree stems within rows. The distance between the 2-year-old jujube trees and the nearest wheat row was 0.55 m. The jujube trees occupied 55 % of the intercropped area and wheat 45 %. Wheat and 4-year-old jujube tree intercropping involved planting in 6-m-wide strips (wheat plus two rows of 4-year-old jujube trees) which included a 4.50-m-wide wheat strip (30 rows of wheat with 0.15 m inter-row distance) and 1 m between 4-year-old jujube tree stems within rows. The distance between 4-year-old jujube trees and the nearest wheat row was 0.75 m. 4-year-old jujube trees occupied 25 % of the intercropped area and wheat 75 %. Wheat and 6-year-old jujube tree intercropping involved planting in 3-m-wide strips (wheat plus two rows of 6-year-old jujube trees) which included a 1.80 m wide wheat strip (12 rows of wheat with 0.15 m inter-row distance) and 2 m between 6-year-old jujube tree stems within rows. The distance between 6-year-old jujube trees and the nearest wheat row was 0.60 m. 6-year-old jujube tree occupied 40 % of the intercropped area and wheat 60 %. The density of intercropped wheat was 11,250,000 plants ha^{-1}.

One strip comprising two rows of jujube trees and 12 rows of wheat (or thirty rows of wheat intercropped with 4-year-old jujube trees or 12 rows of wheat intercropped with 6-year-old jujube trees) constituted an intercropping plot, and three rows of jujube trees comprised a sole jujube tree plot. The individual plot area was 10×2 m^2 for sole 2-year-old jujube trees and wheat/2-year-old jujube tree intercropping, 10×6 m^2 for sole 4-year-old jujube trees and wheat/4-year-old jujube tree intercropping, and 10×3 m^2 for sole 6-year-old jujube trees and wheat/6-year-old jujube tree intercropping.

All plots were given identical applications of N at 450 kg ha^{-1} as urea and diammonium phosphate (N), and of phosphorus (P) at 30 kg ha^{-1} as diammonium phosphate. All the P fertilizer and a half of the N were broadcast evenly and incorporated into the top 20 cm of the soil prior to sowing. The remaining half of the N fertilizer was applied at the elongation stage in the intercropping systems, sole jujube trees and sole wheat.

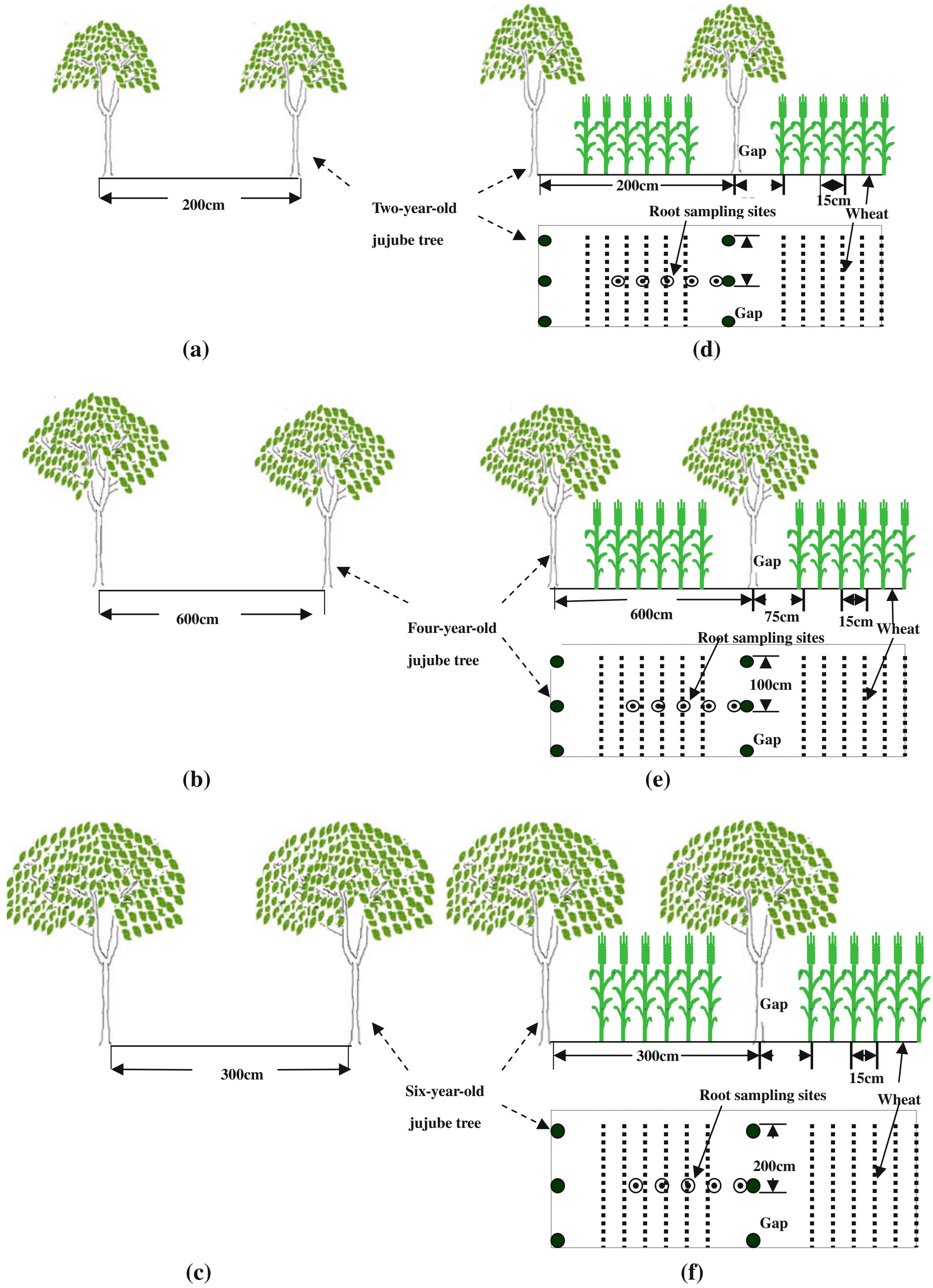
Wheat was sown on October 25, 2010. Dates of harvesting were June 25, 2011 for wheat and October 5, 2011 for jujube. Irrigation was carried out on six occasions on March 25, April 14, May 2, and May 23, 2011. Each irrigation application consisted of 90 mm (900 m^3 ha^{-1}). The irrigation practice followed that recommended to farmers by local agronomists. The fruit yield of jujube trees and grain and straw yields of wheat were measured at maturity.

Plant sample collection

Grain, fruit and straw yields of wheat and jujube trees were determined at maturity of the individual crops. Wheat grain yield and biomass were determined by harvesting 5 m of each strip in intercropped wheat at maturity. After harvest, plant samples were air-dried and the grain was threshed by hand. Nitrogen, P, and K concentrations in the grain and straw were determined on ground subsamples of oven-dried plant material after digestion in a mixture of concentrated H_2SO_4 and H_2O_2. Nitrogen was measured by the micro-Kjeldahl procedure, P by the vanadomolybdate method, and K by flame photometry.

Root sample collection

On 12 June, 2011, when the wheat was at maturity and the jujube trees were flowering, an auger sampling method (Böhm 1979) was employed to minimize damage to the plots and allow detailed examination of root distribution at later growth stages (see below).


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

◀ **Fig. 1** Diagrammatic representation of the planting of strips of **a** sole-cropped 2-year-old jujube trees, **b** sole-cropped 4-year-old jujube trees, **c** sole-cropped 6-year-old jujube trees, **d** 2-year-old jujube/wheat, **e** 4-year-old jujube/wheat and **f** 6-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

Soil cores (5.5 cm diameter × 5.0 cm deep) were collected at 20-cm intervals to a maximum depth of 100 cm to determine the vertical root distribution. To determine the horizontal distribution of jujube tree roots, soil cores were collected from under the centers of the jujube trees and 30 cm from the row in sole-cropped jujube trees under the center of the wheat rows, and 30 cm from the row in sole-cropped wheat. Five sampling sites were used in all three intercropping systems as shown in Fig. 1a, b. Soil cores were stored in plastic bags until the roots were washed out. Soil moisture contents at different soil depths were determined using auger samples.

Root length density measurement

All the auger (12 June, 2011) samples were weighed and then soaked in water for at least 1 h. The samples were stirred vigorously and poured through a sieve (0.2 mm^2 mesh, 20 cm diameter and 4 cm height). The sieves were suspended in a large water bath and shaken continuously by hand until the roots were washed free of soil. Soil material remaining on the sieves was removed manually. In jujube/wheat intercropping some auger samples contained the roots of both species and therefore one crop had to be distinguished from the other based on visual appearance. The roots of wheat and jujube were distinguished by their different colors, textures and rooting patterns. For example, the roots of wheat were yellowish and hairy compared to those of jujube which had smooth surfaces and a dark brown color and had a larger diameter than the wheat roots. Wheat and jujube root samples were scanned by specialized scanner and corresponding images were gotten. Using the WinRHIZO™ (Régent Instruments Inc., Québec, Canada) image analysis system we identified the morphological parameters of roots, such as root length, surface area and average diameter from the scanned images. Root biomass was recorded after oven-dried for 72 h at 70 °C (Zamora et al. 2007). The separated root fractions were weighed. The data from the auger samples represent the whole population of jujube tree and wheat roots in each soil profile, respectively. Results are presented as contour diagrams made by WinSURFER v. 5.01 (Surfer Mapping System). Root distribution maps were created where rooting depth and lateral growth of roots could be determined by locating the given contour value in the soil profile.

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. LER is the most widely accepted index for evaluating the effectiveness of all forms of mixed cropping and has been extended to agroforestry by some workers (Vandermeer 1989; Rao et al. 1990, 1991; Cao et al. 2012). In particular, LER indicates the efficiency of intercropping for using the resources of the environment compared with monoculture (Mead and Willey 1980; Dhima et al. 2007). LER is calculated according to:

$$\mathrm{LER} = \mathrm{Yjw}/\mathrm{Yj} + \mathrm{Ywj}/\mathrm{Yw}$$

where Yj and Yw are the yields of jujube and wheat in pure culture, respectively, and Yjw and Ywj are the yields of jujube and wheat, respectively, as mixtures. If the ratio is greater than 1.0, intercropping is advantageous and a ratio less than 1.0 indicates a disadvantage.

Statistical analysis

All data were submitted to analysis of variance (ANOVA) using the SAS software package (SAS Institute 2001) and mean values ($n = 3$) were compared by least significant difference (LSD) at the 5 % level.

Results

Land equivalent ratio (LER), plant growth and yields

All land equivalent ratios (LERs) of tree/wheat intercropping were greater than one regardless of whether the jujube trees were 2-, 4- or 6-year-old. The highest efficiency of land use in this experiment was obtained for wheat/4-year-old jujube tree intercropping with LER values of 1.45 (grain yield) and 1.67 (biomass), and wheat/2-year-old jujube intercropping had LER values of 1.44 (grain yield) and 1.38 (biomass), and 6-year-old jujube tree intercropping had LER values of 1.24 (grain yield) and 1.51 (biomass) (Table 2).

The grain yield of intercropped wheat was not significantly ($p = 0.063$) reduced by 7.55 % by 2-year-old jujube trees but was reduced significantly ($p = 0.008$) by 17.7 % by 4-year-old jujube trees or by 30.4 % ($p = 0.002$) by 6-year-old jujube trees at maturity (wheat) compared with sole wheat (Table 2). Fruit yields of intercropped jujube trees were reduced by 6.95 % ($p = 0.031$) or 21.9 % ($p = 0.01$) or 23.1 % ($p = 0.008$) by 2- or 4- or 6-year-old trees compared to monocropped jujube trees. These results show interspecific competition between intercropped wheat and jujube in which both crops showed declining yield when intercropped and the older the jujube trees the lower the yield of wheat.

Spatial distribution of root length density (RLD) of sole-cropped and intercropped wheat

Intercropped wheat had a lower RLD than sole-cropped wheat (Fig. 2a–d). Specifically, in the wheat/2-year-old jujube intercropping system the RLD of wheat (Fig. 2b) was much lower than that of sole-cropped wheat at all distances from the wheat row. The RLDs of wheat in the wheat/2-year-old jujube intercropping system at 12.5 and 25 cm from the trees were 76 and 87 % of RLDs in the sole-cropped wheat system at the row position (Fig. 2b). Similarly, wheat intercropped with 4-year-old jujube trees had a lower RLD at all depths than sole-cropped wheat under the wheat row (Fig. 2c). Generally, the wheat RLD decline by intercropping was greater deeper in the soil profile and under the row positions. Although absolute RLDs decreased, the pattern of horizontal root distribution changed little between the two above-mentioned intercropping systems (Fig. 2b, c). Similar to the previous two intercropping systems, intercropped wheat had less RLD than sole-cropped wheat at the majority of soil depths, especially in the top 0–30 cm of the soil profile (Fig. 2d). The RLD of intercropped wheat was lowered by associated jujube, especially below 40 cm soil depth (Fig. 2d). Furthermore, the roots of wheat intercropped with the trees tended to have a more shallow distribution compared to sole-cropped wheat. Compared to sole-cropped wheat, the RLDs of the wheat/6-year-old jujube tree intercropping system decreased by 46 % in wheat.

Spatial distribution of root length density (RLD) of sole-cropped and intercropped jujube

The RLD of intercropped jujube trees was lowered by associated wheat compared to sole-cropped jujube (Fig. 3a–f). For instance, the RLD of monocropped 2-year-old jujube was higher (Fig. 3e) than that of intercropped 2-year-old trees (Fig. 3a, b) at 0–80 cm depth. In the wheat/4-year-old jujube tree intercropping system a low density of the 4-year-old jujube tree roots extended up to and under wheat row (Figs. 2c, 3d). There was little change in the general patterns of distribution of roots of 4-year-old jujube trees with

Table 2 Land equivalent ratio, grain yield (kg ha^{-1}) and biomass (kg ha^{-1}) of sole wheat, intercropped wheat, sole jujube trees and intercropped jujube trees in wheat/jujube tree intercropping systems at maturation stage of wheat (23 June) and jujube trees (1 October)

	Age of trees (years)	Wheat				Jujube			LER
		Sole	Intercropped (net area)	Intercropped (gross area)	Significance	Sole	Intercropped	Significance	
Grain yield (fruit yield)	2	4,712	4,444	2,333	ns	2,128	1,980	*	1.44
	4	4,712	4,022	3,157	*	4,650	3,630	*	1.45
	6	4,712	3,444	2,239	*	8,943	6,880	*	1.24
Above-ground biomass	2	9,069	8,861	4,347	ns	9,720	8,345	*	1.38
	4	9,069	8,744	6,559	*	14,916	13,580	ns	1.67
	6	9,069	7,487	4,492	*	20,014	19,454	ns	1.51

ns No significant difference

* Refers to significant difference between the sole and intercropping at the 0.05 level by paired *t* test

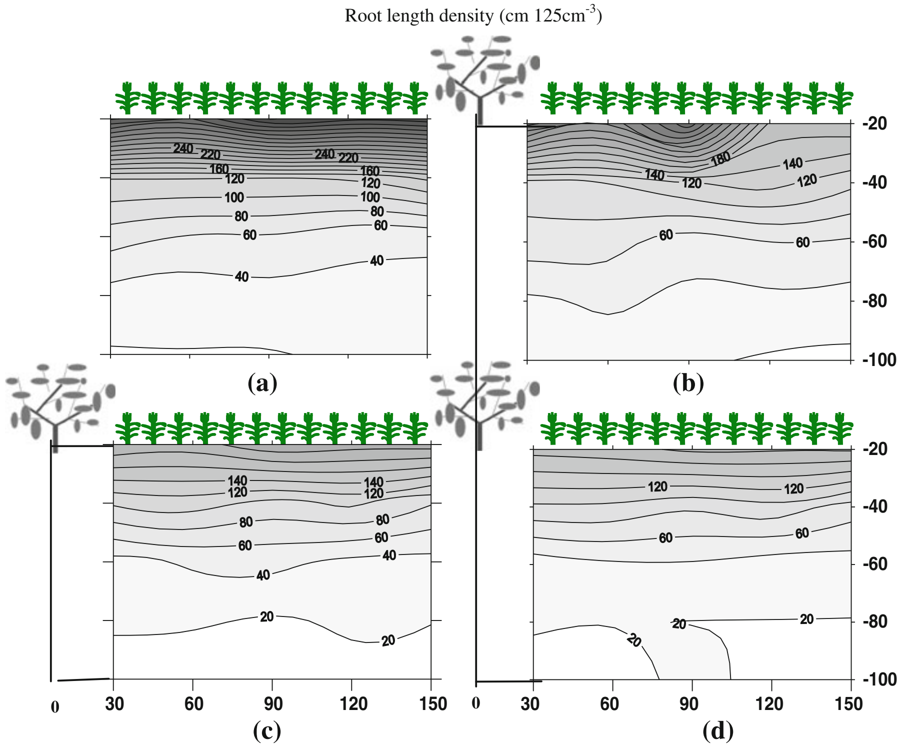


Fig. 2 Spatial distribution of wheat roots in the three intercropping systems: **a** wheat grown alone, **b** wheat intercropped with 2-year-old jujube trees, **c** wheat intercropped with 4-year-old jujube trees, and **d** wheat intercropped with 6-year-old jujube trees

increasing depth either grown alone or intercropped with wheat compared with wheat/2-year-old jujube intercropping (Figs. 2b, 3a, b). Generally, the reduction by intercropping was greater deeper in the soil and under the row positions. Although absolute RLDs decreased, the pattern of horizontal root distribution changed little between the two cropping systems. The RLDs of the wheat/4-year-old jujube intercropping system decreased by 35 % (wheat) and 21 % (jujube) compared to the monocrops. The data for 6-year-old jujube tree root distribution in the wheat/6-year-old jujube tree intercropping system are presented as contour diagrams (Fig. 3e, f) to demonstrate the integrated expression of the root distribution. As in the previous two intercropping systems, the RLD of 6-year-old jujube trees intercropped with wheat was also less than that of sole-cropped trees at most soil depths, and in this case especially below 60 cm (Fig. 3f). Horizontally, the roots of intercropped jujube trees spread under the wheat plants and maintained a higher RLD (Fig. 3b, d, f).

Rooting depths of intercropped jujube trees were decreased by associated wheat. Vertical differences in the RLD between jujube trees intercropped with wheat and sole-cropped trees were apparent. The roots of jujube intercropped with wheat decreased, especially below 40 cm soil depth, compared to corresponding sole jujube trees in the three intercropping systems (Fig. 3f). For instance, the 11 cm/125 cm^3 RLD contour was located below 80 cm soil depth in monocropped 2-year-old trees but the same contour was located above 80 cm soil depth in wheat/2-year-old jujube intercropping (Fig. 3 a, b). The difference in rooting depth was apparent in 4- and 6-year-old jujube trees. In the former the 11 cm/125 cm^3 RLD contour was distributed below 100 cm in the soil profile when jujube grew alone but was distributed only above 80 cm in intercropping (Fig. 3 c, d). In the latter the 29 cm/cm^3 RLD contour was located within 90–100 cm down the soil profile when jujube grew alone but was located at 80–90 cm soil depth when jujube trees were intercropped with wheat (Fig. 3 e, f).

Discussion

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

With all LERs more than one, intercropping of wheat/jujube trees, whatever 2-, 4- or 6-year-old trees, had

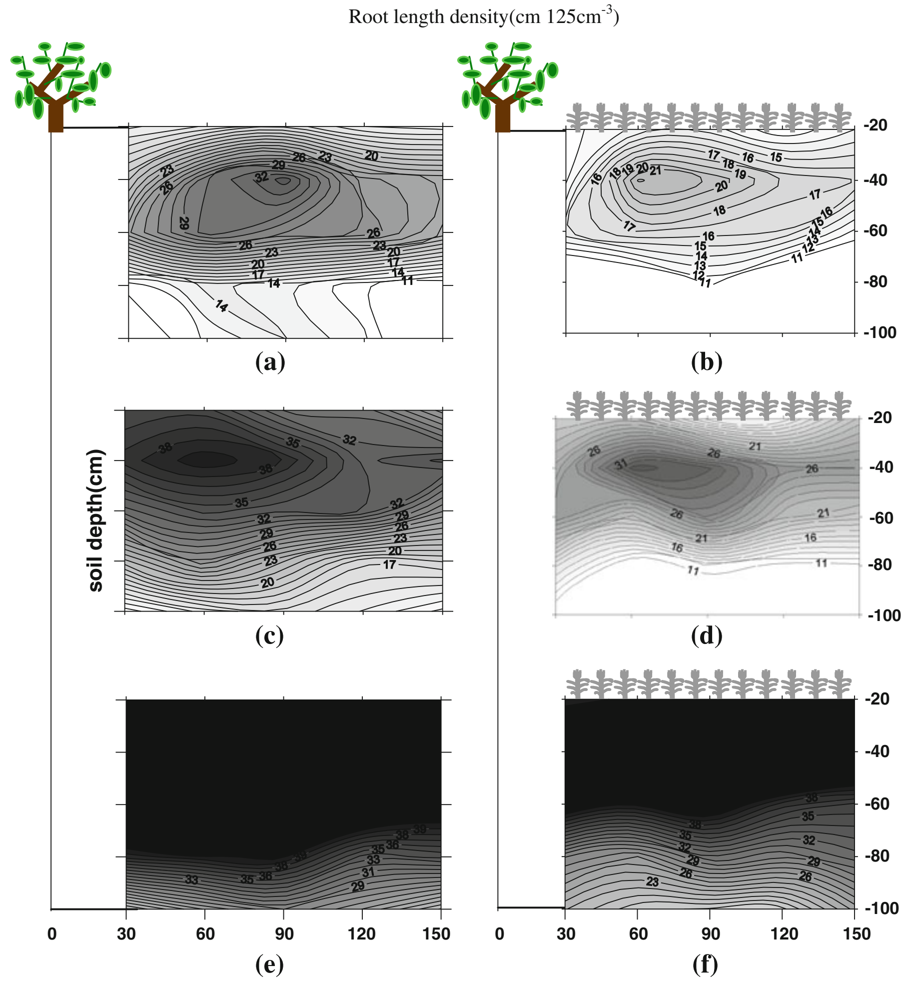


Fig. 3 Spatial distribution of jujube roots in the three intercropping systems: **a** jujube trees grown alone for 2 years, **b** 2-year-old jujube trees intercropped with wheat, **c** jujube tree grown alone for 4 years, **d** 4-year-old jujube trees intercropped with wheat, **e** jujube trees grown alone for 6 years, and **f** 6-year-old jujube trees intercropped with wheat

significant yield advantages of intercropping. Similar results were observed in *Acacia saligna* (Labill.)/sorghum (*Sorghum bicolor* L.) system in the Turkana district of northern Kenya (Droppelmann et al. 2000), in poplar (*Populus* spp.) or willow (*Salix viminalis* L.) tree *Acacia senegal*/crops (sorghum or sesame) systems in Sudan (Raddad and Luukkanen 2007), black locust (*Robinia pseudoacacia* L.) trees/crops (*Medicago sativa* L.) in Germany (Gruenewald et al. 2007), and in hybrid poplar (*Populus nigra* L. × *P. maximowiczii* A. Henry)/soybean system in southwestern Quebec, Canada (Rivest et al. 2010). The high values for LER in these agroforestry systems, including our wheat/jujube systems, indicate that there is complementarity in resource use between the different species.

The results indicate that there was a significant decrease in wheat growth and yield when the wheat was intercropped with jujube trees and the fruit yield of the jujube trees also decreased to some extent. Specifically, in wheat/6-year-old jujube tree intercropping systems, wheat growth, biomass and yield decreased mostly compared to sole-cropped wheat and the other two systems, whereas 6-year-old jujube tree growth, biomass and yield did not decrease significantly. However, in wheat/2-year-old jujube tree intercropping wheat growth, biomass and yield did not decrease significantly compared to sole-cropped wheat, the second system or the third system, but 2-year-old jujube tree yields did decrease to some extent. Yield decrease in wheat/4-year-old jujube tree intercropping is between the first and the third systems. This outcome supports our first hypothesis that yield and biomass will decrease with belowground interspecific competition in the tree-wheat associations. A similar phenomenon was observed in a maize and black walnut system in which maize and black walnut yields declined by 35 and 33 %, respectively (Jose et al. 2000b). Schroth et al. (1995) reported that trees can compete with associated crops through their root systems and this may lead to yield depressions. In a study of competition for water in an alley cropping system consisting of pecan (*Carya illinoensis*) and cotton (*Gossypium hirsutum*), a polyethylene barrier was installed in half of the plots. The barrier treatment had higher soil water content, better growth of cotton (height, leaf area, and fine root biomass) and higher cotton lint yield (677 kg ha^{-1}) than the non-barrier treatment (cotton lint yield was 502 kg ha^{-1}), which suggested that there was interspecific below-ground competition on cotton from pecan trees in the system (Wanvestraut et al. 2004).

Interspecific competition and root spatial distribution

The results also support our second and third hypotheses that root length density will be adversely affected by belowground competition and older jujube trees have greater ability to depress the RLD of wheat. Belowground interspecific interactions appear in response to strong competition. The RLDs of both intercropped species decreased to some extent compared to monocropping. The older the jujube trees the greater the decrease in RLD and the stronger the inhibition of wheat root growth. Although there appeared to be mutual competition in the root growth of the two crops the competitiveness of wheat was far below that of jujube, and especially the 6-year-old trees. Thus, plants with high fine root length densities are likely to be more competitive than those with lower root length density. Similar results were obtained by Schroth (1999). Most importantly, the roots of intercropped jujube trees spread into the root zone under wheat (Figs. 2b–d, 3f, h, j) and tend to have a more shallow distribution in the soil profile compared to monocropped jujube trees. The outcome was that the perennial plant roots occupied a greater soil volume. The interactions between tree and wheat species may lead to an increased capture of a limiting growth resource (Ong et al. 1996; Ashton 2000; García-Barrios and Ong 2004), and in a study to investigate how interspecific interactions between pecan (*C. illinoensis* K. Koch) and cotton (*G. hirsutum* L.), specific leaf area for barrier and nonbarrier plants was 61 and 47 % higher compared with the monoculture cotton (Zamora et al. 2006). After all, annual and perennial plants have different ecological niches in the soil. This type of competition can be derived from either mechanical forces or allelopathic effects but these still require further investigation.

Shade effects

In addition to belowground interspecific competition, yield depression derived from the aerial parts plants is another key factor. Several studies on Paulownia (*Paulownia* spp.)/wheat intercropping systems in China have shown that shading by Paulownia trees reduced wheat yields by 7 % (Chirko et al. 1996), 23 % (Yin and He 1997) to as much as 51 % (Li et al. 2008). Friday and Fownes (2002) indicated that competition for light is likely to be the most common negative tree-crop interaction in the humid tropics where maize yields have collapsed adjacent to hedgerows. Ding and Su (2010) also found that shading by poplar reduced maize crop yields in the Hexi Corridor desert oasis in China. However, Cao et al. (2012) found that belowground competition was more intense than aboveground competition. In our jujube/wheat system the jujube trees usually had a larger stem and crown and this made it very difficult for wheat to obtain solar energy when the two crops were grown together, especially at a high density. Moreover, the older the jujube tree the stronger the negative effects on wheat.

Possible methods for the solution of problems due to competition

Perennial plants have a longer life-span and larger roots than annuals and when the two types of plant are intercropped, one way to control root competition between shade trees and annual crops is manipulation of spacing. Expanding the planting space may be a suitable method to reduce interspecific competition both aboveground and belowground. Jose et al. (2004) reported that competition for light can be managed in design or maintenance of agroforestry systems. Atkinson et al. (1978) demonstrated that the spatial distribution of tree root activity is influenced by the spacing between trees and associated crops and Cao et al. (2012) suggested that trees were stronger competitors than crop species at high tree densities. If the ground cover starts near the trees there is more intermingling of the root systems and consequently more competition may occur (Schroth 1999). Another possible method to control shading is tree pruning, but excessive shoot pruning may affect the photosynthesis of the tree and then depress the fruit yield. Thus, through appropriate adjustment of management factors the farmer may be able to optimize grain production from wheat and economic benefits from the jujube tree.

Conclusions

In all three wheat/jujube intercropping systems examined the roots of the trees spread under the wheat plants and there were consequently relatively lower RLDs at all soil depths than in monocropped 2-year-old jujube plantations. The roots of wheat intercropped with jujube trended to have more shallow distribution in the soil profile and had a smaller RLD than monocropped wheat. In addition, the roots of intercropped jujube trees spread under associated wheat but occupied a comparatively smaller soil space than sole-cropped trees. Decreased soil exploration and apparent root competition led to decreases in yield and biomass. This provides direct evidence for the hypotheses that the lower growth in the tree-crop associations resulted from interspecific competition and less RLD in the soil. Furthermore, the older the jujube trees the stronger the inhibition of wheat root growth. Intercropping systems with high tree densities will lead to depression of yields of associated wheat crops. Further research is needed to examine the dynamic processes of species interactions in intercropping systems with trees of different ages.

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