The relationship between root growth, soil resources, and productivity in an apple–soybean irrigated agroforestry system in northwest China

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Abstract

Background and aims Understanding the relationship between roots, soil moisture, and nutrients in agroforestry systems in irrigated orchards is critical for optimizing orchard management in arid regions. However, there are still many knowledge gaps in this area. Our goals were to (i) explore the spatiotemporal distribution of fine roots for two species under irrigated conditions; (ii) investigate the relationship between fine roots, soil moisture, and nutrients; and (iii) evaluate the productivity of irrigated agroforestry systems.

Methods An orchard with soybeans and apples as intercropping materials was established, including single-cropping soybean, single-cropping apple, and apple–soybean intercropping treatments. Data were collected on the spatiotemporal distribution of fine roots and soil resources under apple monocropping and soybean–apple intercropping treatments in 2020–2021, soybean and apple yield, and yield components.

Results Compared with apple monocropping, apple–soybean intercropping increased the richness of fine roots in the field. Apple fine roots decreased in the shallow layer and increased in the deep layer in the area where the species overlapped, which increased the soil water content, decreased the nitrate nitrogen content, decreased the effects of soil moisture and nitrate nitrogen on fine roots, increased soybean plant height and leaf area, decreased stem diameter, increased the number of pods per plant and grains per pod, and decreased the 100-grain weight. The LER (land equivalent ratio) = 1.41.

Conclusions Irrigated agroforestry increased the richness of fine roots under soybean–apple intercropping, reduced the dependence of root growth on soil resources, eased competition among species, and achieved higher productivity.

Introduction

The large-scale single planting of crops is important in agricultural production. However, this agricultural practice has led to many environmental problems, such as soil erosion and degradation, chemical contamination, and biodiversity loss (Malézieux et al., 2009). Modern orchards usually adopt clean cultivation and management practices to reduce the competition for water and nutrients by eradicating weeds. In this system, large areas of soil are exposed to the air, causing susceptibility to erosion and the loss of soil moisture and nutrients, thereby reducing soil quality and productivity (Gao et al., 2014; Zhao et al., 2014). Therefore, it is necessary to design a soil management system that supports the sustainable development of orchards, such as mixed cropping. Agroforestry, or the combination of crops and woody components in the same field, can achieve both good productivity and sustainable land use (Lehmann et al., 2020). Agroforestry systems are a very popular agricultural practice worldwide, including in China (Yang et al., 2019), France (Forey et al., 2017), America (Fletcher et al., 2012), Iran (Abbasi Surki et al., 2020), and Canada (Bouttier et al., 2014). Agroforestry not only improves land use efficiency (Paul et al., 2017) and nutrient use efficiency (Zhu et al., 2019), but also enhances crop yields and profits (Abbas et

al., 2021; Pratiwi and Suzuki, 2018). There are two interaction interfaces in agroforestry systems: the above-ground interface, where species compete for light and heat, and the below-ground interface, where interspecific roots compete for soil, water, and nutrients (Gao et al., 2013; Kubo et al., 2017). In agroforestry systems, interspecific competition occurs predominately below-ground (Sun et al., 2018). This competition depends largely on the spatial distribution of roots, which is modified if competition is high (Mulia and Dupraz, 2006). The spatial distribution of roots and their density in the soil determine the ability of a crop to acquire the nutrients and water necessary to sustain plant growth. This acquisition function is mainly performed by fine roots (diameter ≤ 2 mm) (Xia et al., 2013). The vertical stratification of the root system, that is, the use of the subsoil below the roots of the crop by the root systems of the trees, is an advantage of agroforestry (Forey et al., 2017). In response to underground competition for soil moisture and nutrients, the fine roots of trees move to deeper soil (Gao et al., 2013) or to shallower soil (Jose et al., 2006), while the fine roots of crop species move to shallower soil (Sun et al., 2018). In this case, it is particularly important to study the effect of the spatial distribution of the fine roots of each component of a crop-agroforestry system on the overall system (Sun et al., 2018).

Vegetation cover can reduce soil evaporation and erosion and facilitate soil water infiltration (Baptista et al., 2015; Yao et al., 2005). Planting crops between rows of trees can enhance the amount of soil water infiltration and reduce soil evaporation, thereby increasing soil water availability (Ling et al., 2017). Moreover, agroforestry systems can alleviate both point and non-point agricultural pollution because they are able to reduce leaching to groundwater aquifers and absorb pollutants from both unsaturated and saturated low-depth zones through their tree roots (Pavlidis and Tsihrintzis, 2017). Leguminous crops are used as ground cover in agroforestry systems. Their main benefits include the biological fixation of atmospheric nitrogen through symbiosis with soil bacteria, which increases the soil nitrogen content (Rodriguez et al., 2020). When the root systems of two species cross in an intercropping system, soil nutrients or soil moisture become uneven (Chen et al., 2019), and the spatial distribution of roots responds differently to differences in soil nutrients and soil moisture. In agroforestry systems, the distribution of soil water and nutrients is complex due to the diversity of species and the existence of interspecific root systems. Therefore, it is important to explore the relationships among soil moisture, nutrients, and roots in agroforestry systems.

At present, most of the research on agroforestry root systems, soil water content, and soil nutrient distribution in China has focused on rainfed agriculture, while few studies have been conducted on irrigated agroforestry systems. Xinjiang is the birthplace of wild apples in China, and apple–crop intercropping systems constitute one of the most widely applied agroforestry systems in China. However, the root traits of the two species and their relationships with soil moisture and nutrients in agroforestry systems remain unclear. The purpose of this study was to characterize the temporal and spatial distribution of fine roots, rhizosphere soil water content, and soil nitrate nitrogen content in mixed apple and soybean agroforestry systems in northwest China. The temporal and spatial distributions of fine roots, rhizosphere soil water content, and soil nitrate nitrogen in apple–soybean intercropping and apple monocropping systems were measured. In addition, the relative indicators of growth and yield in intercropping soybeans and monocropping soybeans were determined. It was assumed that (i) in areas

where the root systems of the two species overlapped, the growth of the superficial (0–20 cm) fine roots of apples would be inhibited and the growth in the deep (40–60 cm) layers would be promoted; (ii) irrigation and fertilization through drip irrigation belts in forests could help reduce the impact of soil resources on root growth; and (iii) soybean–apple intercropping would exhibit advantages and increased system productivity compared to monoculture.

Materials And Methods

Study site and experimental design

The study was conducted in Yining County, Yili Kazak Autonomous Prefecture, Xinjiang Uygur Autonomous Region, China (81.86, 43.76) (Fig. 1). The study site is 903 m above sea level and the climate is a temperate continental climate with a mean annual temperature of 9.3°C. The total rainfall amounts from June to October during the study periods in 2020 and 2021 were 170.92 mm and 196.44 mm, respectively. Over the past five years, the annual rainfall was 525.41 mm.

A randomized block design was set up during 2020 and 2021. The three blocks consisted of monocropping apples, apple and soybean intercropping, and monocropping soybeans. There were 6 × 10 apple trees per plot, with tree spacing of 3 m and row spacing of 5 m. The planting of intercropping soybeans was divided into wide and narrow rows. The row spacing of wide rows was 40 cm, and the row spacing of narrow rows was 30 cm. Drip irrigation tape was laid in the middle of narrow rows, and soybean plant spacing was 10 cm. The single-cropped apple had a drip irrigation belt on each side of the tree row, while the soybean single-crop had a drip irrigation belt to manage four rows, with a row spacing of 30 cm and a plant spacing of 10 cm, and no difference between wide and narrow lines. The row spacing between apples and soybeans was 1.2 m, with a 60-cm open space in the middle of the tree row. This was done to facilitate the mechanized management of the field. Apple trees were planted in autumn 2019, and soybeans were sown on June 8, 2020 and June 10, 2021. Base fertilizer was applied 4–5 days before sowing each year. During fertilization, 300 kg·hm⁻² of diammonium phosphate and 105 kg·hm⁻² K were applied 1 m from the apple tree rows. Drip irrigation was adopted for soybeans and apples. The apple trees were irrigated five times a year, with topdressing two times a year. Each irrigation amount was 750 m³·hm⁻², and each application of fertilizer consisted of 225 kg·hm⁻² water-soluble fertilizer. During the whole growth period, soybean irrigation was performed six times and topdressing was performed two times. For soybeans, each irrigation amount was 600 m³·hm⁻², and each fertilizer application consisted of 150 kg·hm⁻² urea and 125 kg·hm⁻² water-soluble fertilizer.

Collection of root and soil samples

Sampling was conducted every year in mid-June, late July, and mid-September. Soil cores were taken with a cylindrical steel soil corer with an internal diameter of 4.5 cm (volume was 141 cm³) driven into the soil by a sledgehammer. Each treatment had four sampling positions 50 cm, 100 cm, 150 cm, and 200 cm away from the tree row. At each sampling position, cores were collected at depths of 0–20, 20–40 and

40–60 cm. For the convenience of data analysis, the 12 points sampled were replaced with the coordinate axis, with the trunk as the origin, the horizontal distance as the x-axis, and the vertical distance as the y-axis, and the positions were arranged according to the distance from the tree as follows: (50, 20), (50, 40), (50, 60), (100, 20), (100, 40), (100, 60), (150, 20), (150, 40), (150, 60), (200, 20), (200, 40), and (200, 60).

Fine root analysis

Roots were removed from soil samples using forceps passed through sequential sieving with water. The fine roots were separated by species through visual inspection. Apple fine roots were distinctly reddish-brown, whereas the soybeans roots were off-white. Fine roots (≤ 2 mm) were then scanned using a flatbed scanner (STD4800; Regent Instruments Inc., Canada) at 600 dpi. From these images, the fine root lengths from each core sample were measured using WinRhizo (Reg. 2020a; Regent Instruments, Canada). These data were used to calculate the fine root length density (FRLD; $\text{cm}\cdot\text{cm}^{-3}$).

$$FRLD = \frac{FRL}{V}$$

1

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In the formula: FRL is the fine root length; and V is the volume of the core (141 cm^3).

Soil analysis

For each soil sample, the nitrate nitrogen content in soil was determined by colorimetry. Five grams of soil sample was added to 50 ml of 2 mol/L KCL solution and shaken for 1 hour before the suspension was filtered for 3–5 min. Then, the absorbance A_{220} and A_{275} of the extract was measured at 220 nm and 275 nm, respectively. The corrected absorbance was calculated according to the following formula A:

$$A = A_{220} - 2A_{275},$$

2

By establishing the correlation curve between A and the concentration of nitrate nitrogen, the concentration of nitrate nitrogen in the leaching solution could be calculated. Nitrate nitrogen was calculated as follows:

$$\text{Nitratennitrogencontent} = C * V * \frac{D}{m},$$

3

In the above formula, C is the NO_3^- -N content obtained from the standard curve; V is the total volume of the colorimetric assay solution (ml); D is the fractionation multiple; and m is the fresh soil sample mass (g).

The soil water content was determined using the drying method. The soil samples were placed in an aluminum box and the soil samples were dried in an oven. Then, the soil water content was calculated by comparing the soil weights before and after drying. The formula is as follows:

$$\text{Soilmoisturecontent} = \frac{m_1 - m}{m_2 - m},$$

4

where m is the weight of the aluminum box (g); m_1 is the weight of the fresh soil sample and the aluminum box (g); and m_2 is the weight of soil dry sample and aluminum box (g).

Statistical analyses

Microsoft Excel 2010 and SPSS 19.0 (SPSS, Chicago, USA) were used for data processing and one-way analysis of variance (ANOVA), respectively. The significant differences between the treatments means were compared by Duncan's multiple range test at the 5% probability level. Different letters in the same period represent significant differences. Bars represent the standard deviation (n = 3).

Results

Fine root length density distribution in the intercropping system

The two-dimensional distribution characteristics of the root length density of apples and soybeans showed that as the soil depth increased in the vertical direction, the root length density of single-cropped apples first increased and then decreased. In 2020, as the soil depth increased, the root length density of intercropped apples mostly increased first and then decreased. In 2021, with the increase of soil depth, the root length density of intercropped apples mostly showed a continuous upward trend, while for intercropping soybeans, the soybean fine roots were concentrated in the 0–20-cm soil layer. As the depth of the soil layer increased, the root length density of the fine roots continued to decrease. In the horizontal direction, the root length density of single-cropped and intercropped apples decreased with the increase of distance from the tree row, while the density of soybean fine roots increased with the increase of the distance from the tree row.

By comparing the root systems of monocropping and intercropping apples, it was found that in the 2020 soybean branching stage, intercropping significantly reduced the root length density of apples at the (150, 20) site by 25.07% (Fig. 3A). In 2021, intercropping significantly decreased the root length density of apples at the (50, 20), (50, 40), and (150, 40) sites by 19.47%, 9.69%, and 32.28%, respectively, and

intercropping significantly increased the root length density of apples at the (150, 60) site by 56.45% (Fig. 3D). In 2020, during the soybean flower and pod stage, intercropping significantly reduced the root length density of apples at the (100, 20) and (150, 40) sites by 40.57% and 41.14%, respectively (Fig. 3B). In 2021, intercropping significantly decreased the root length density of apples at the (50, 20), (50, 40), (50, 60), and (150, 40) sites by 24.58%, 15.13%, 10.98%, and 25.89%, respectively (Fig. 3D), and intercropping significantly increased the root length density of apples at the (100, 40) and (150, 60) sites by 15.65% and 51.03%, respectively (Fig. 3D). In the 2021 soybean seed filling period, intercropping significantly decreased the root length density of apples at the (50, 20), (50, 40), (50, 60), and (150, 40) sites by 24.75%, 12.78%, 15.26%, and 33.01%, respectively (Fig. 3E), and intercropping significantly increased the root length density of apples at the (100, 40) and (150, 60) sites by 19.24% and 61.80%, respectively (Fig. 3E). Compared with apple monocropping, apple–soybean intercropping significantly increased the fine root length density at the flowering pod stage and the drum seed stage by 85.93% and 125.83%, respectively (Figs. 3B, C, D, E). As the growth period and years progressed, the root density of apple fine roots increased (except for at the (150, 20) and (200, 20) sites), and the root density increased from the soybean drumming period in 2020 to the soybean branching period in 2021, when it reached its maximum magnitude. With the advancement of the growth period, the long density of soybean fine roots also increased, and the growth rate of soybean fine roots was the highest from the soybean branching stage to the flowering pod stage.

In the apple–soybean intercropping system, intercropping inhibited the growth of apple fine roots closer to the trunk and the growth of apple fine roots overlapping with soybean fine roots. In contrast, apple fine roots in deep soil were more active, and intercropping significantly increased the total abundance of fine roots in the system.

Soil moisture content distribution

The two-dimensional distribution characteristics of soil moisture content showed that soil water content increased with the increase of soil depth and decreased with the increase of the distance from the tree row in both monocropping and intercropping apple systems. With the advancement of the growth period, the soil water content of monoculture apples at 50 cm from the tree continued to increase, while the soil water content of 100–200 cm from the tree continued to decline. In the soybean–apple intercropping treatment, the soil water content of 50–200 cm away from the tree increased continuously with the advancement of the growth period and reached the maximum at the soybean drumming stage.

Comparing the soil moisture content of monocropping and intercropping apple systems revealed that intercropping significantly increased the soil water content at the (50, 20), (50, 40), and (100, 40) sites at the branching period by 1.95%, 6.35%, and 21.68%, respectively (Figs. 4a, d, g, j). At the flower and pod period of soybeans, intercropping significantly increased the soil moisture content at the (100, 20), (100, 40), (100, 60), (150, 20), (150, 40), (150, 60), (200, 20), (200, 40), and (200, 60) sites by 82.57%, 58.92%, 31.07%, 67.75%, 58.63%, 30.91%, 46.85%, 54.05%, and 20.51%, respectively (Figs. 4b, e, h, k), and intercropping significantly decreased the soil water content at the (50, 20) and (50, 60) sites by 5.62% and

11.40%, respectively (Figs. 4b, e, h, k). At the seed-filling period in soybeans, intercropping significantly increased the soil water content at the (100, 20), (100, 40), (100, 60), (150, 20), (150, 40), (150, 60), (200, 20), (200, 40), and (200, 60) sites by 147.26%, 96.36%, 64.05%, 125.15%, 88.45%, 58.72%, 59.62%, 52.91%, and 26.98%, respectively (Figs. 4c, f, i, l), and intercropping significantly decreased the soil water content at the (50, 60) site by 10.77%

During soybean branching, soybean and apple intercropping increased the soil water content near the tree. Intercropping increased the soil moisture in soybean-covered areas during soybean branching and drumming.

Soil NO_3^- -N content distribution

The two-dimensional distribution characteristics of soil NO_3^- -N content showed that the soil NO_3^- -N content increased with the increase of soil depth and the distance from the tree row in the monoculture apple system. In the apple-soybean intercropping system, soil NO_3^- -N content increased with soil depth. With the advancement of the growth period, the nitrate nitrogen content at each soil depth decreased continuously in the single-cropping apple treatment and soybean-apple intercropping treatment.

Comparing the soil NO_3^- -N content of monocropping and intercropping apple systems showed that the intercropping of apple and soybean significantly decreased the soil NO_3^- -N content at the (100, 20), (100, 40), (150, 20), (150, 40), (200, 20), (200, 40), and (200, 60) sites at the branching period by 10.84%, 30.16%, 54.73%, 49.17%, 22.77%, 50.13%, 32.28%, and 52.54%, respectively (Figs. 5a, d, g, j). In 2021, the intercropping of apple and soybean significantly increased the soil NO_3^- -N content at the (50, 40) and (50, 60) sites at the branching period by 291.61% and 188.66%, respectively (Figs. 5g, j).

At the soybean flower and pod period, intercropping significantly decreased the soil NO_3^- -N content at the (100, 20), (100, 40), (150, 20), (150, 40), (200, 20), (200, 40), and (200, 60) sites by 24.50%, 30.40%, 59.81%, 66.14%, 79.88%, 66.09%, and 43.18%, respectively (Figs. 5b, e, h, k). At the seed-filling period, intercropping significantly decreased the soil NO_3^- -N content at the (50, 60), (200, 40), and (200, 60) sites by 43.73%, 53.15%, and 82.87%, respectively, in 2020 (Figs. 5c, f). Intercropping also increased the soil NO_3^- -N content at the (50, 20), (100, 20), (100, 40), (100, 60) and (150, 20) sites by 62.53%, 21.02%, 8.69%, 27.58%, and 32.15%, respectively, in 2020 (Figs. 5c, f). During the same period in 2021, intercropping significantly decreased the soil NO_3^- -N content at the (100, 20), (150, 40), (150, 60), (200, 40), and (200, 60) sites by 49.16%, 56.01%, 35.99%, 43.49%, and 73.62%, respectively (Figs. 5i, l). Intercropping also increased the soil NO_3^- -N content at the (100, 60) site by 24.06% (Figs. 5i, l). Soybean and apple intercropping decreased the soil nitrate nitrogen content in the range of 100–200 cm from the tree at the soybean branching and pod stages. However, the effect of intercropping on soil nitrate nitrogen varied greatly between the two years during the soybean drumming period.

The relationship between roots, soil water, and soil NO_3^- -N content

Correlation analysis showed that in the single-cropping apple treatment, the distribution of apple fine roots had very significant positive correlations with soil water content and soil nitrate nitrogen content. There was a significant negative correlation between soil water content and soil nitrate nitrogen content.

In the soybean and apple intercropping treatment, the distribution of apple fine roots was positively correlated with soil water content and had a significant negative correlation with soil nitrate nitrogen content. There was a negative correlation between soil water content and soil nitrate nitrogen content.

Linear regression analysis was performed with the fine root length density (y) of each treatment as the dependent variable, and soil nitrate nitrogen content (x_1) and soil water content (x_2) as independent variables. The results showed that the coefficient of determination (R^2) of the binary linear regression equation for each treatment was higher than that of the single-variable linear regression equation (Table 2). These findings showed that the two-factor linear model could better describe the relationship between the fine root length density and the soil nitrate nitrogen content and soil water content than the single-factor model.

Table 1

Correlations between fine root distribution, soil water content, and soil NO_3^- -N content in monocropping apple and apple-soybean intercropping systems

Treatments	Index	Fine root length density	Soil water content	Soil NO_3^- -N content
Monocropping apples	Fine root length density	1		
	Soil water content	0.506**	1	
	Soil NO_3^- -N content	-0.527**	-0.289*	1
Soybeans and apples intercropping	Fine root length density	1		
	Soil water content	-0.104	1	
	Soil NO_3^- -N content	-0.252*	-0.126	1
* Significant at 5% ($P < 0.05$).				
** Very significant at 1% ($P < 0.01$).				

Table 2
Regression analysis of root length density of fine roots, soil nitrate nitrogen content and soil water content

Treatments	Independent variable	Regression equation	R ²
Monocropping apples	Soil water content	$y = -0.056 + 0.018x_2$	0.264
	Soil NO ₃ ⁻ -N content	$y = 0.295 - 0.001x_1$	0.267
Soybeans and apples intercropping	Soil water content	$y = 0.385 - 0.009x_2$	-0.003
	Soil NO ₃ ⁻ -N content	$y = 0.362 - 0.001x_1$	0.05
Monocropping apples	Soil water content and soil NO ₃ ⁻ -N content	$y = 0.109 - 0.01x_1 + 0.014x_2$	0.397
Soybeans and apples intercropping	Soil water content and soil NO ₃ ⁻ -N content	$y = 0.531 - 0.01x_1 - 0.012x_2$	0.056
Note: x ₁ : soil NO ₃ ⁻ -N content, x ₂ : soil water content, y: fine root length density, n = 36			

The growth of soybeans

As shown in Fig. 6, the plant height, stem diameter, and leaf area of single-cropping soybean and intercropping soybean all increased continuously with the advancement of the growth period, and increased rapidly in the branching and pod stages, and then decreased. In 2020, compared with soybean monocropping, apple–soybean intercropping significantly increased the soybean plant height at the branching stage by 10.50%. In 2020, compared with soybean monocropping, intercropping significantly reduced the stem diameter of soybean at the flower and pod stage by 24.77%, and in 2021, intercropping significantly reduced the stem diameter by 21.88% at the soybean drum stage. Compared with soybean monocropping, intercropping significantly increased the leaf area of soybean at the pod and drum stages by 28.48% and 34.25%, respectively.

System yield and yield composition factors

As shown in Table 3, in two years, apple–soybean intercropping increased soybean pods per plant by 9.25%, and there was no significant difference compared with soybean monocropping. In contrast, intercropping significantly decreased the soybean 100-kernel weight by 10.67%. In 2020, intercropping significantly increased the number of soybean kernels per pod by 28.70% compared with soybean monocropping. Soybean yields dropped significantly by 69% in two years. Due to the different planting patterns, the seeding amount of the intercropping soybean was much lower than that of the monocropping soybean. In 2021, apple–soybean intercropping reduced the number of fruits per plant by 5.92%, the fruit weight by 4.38%, and the yield by 11.44%, but the differences were not significant. Calculating

the LER based on the production of soybeans and fruit trees in 2021 showed that $LER = 1.41 > 1$. This showed that apple and soybean intercropping had production advantages.

Table 3
Soybean and apple yield, and yield composition factors under different planting patterns in 2020 and 2021

Years	Treatment	Plant number·hm ⁻² Trees number·hm ⁻²	No. of pods·plant ⁻¹ No. of fruits·plant ⁻¹	No. of pods·Plant ⁻¹	100 grain weight(g) Single fruit weight(g)	Yield(kg·hm ⁻²)
2020	Monocropping soybeans	2.4*10 ⁵	40.63 ± 7.96 a	2.3 ± 0.80 a	29.74 ± 0.76 b	6636.51 ± 590.56 b
	Intercropping soybeans	1.1*10 ⁵	44.2 ± 12.38 a	2.96 ± 0.90 b	26.50 ± 0.68 a	3759.91 ± 338.53 a
2021	Monocropping soybeans	2.4*10 ⁵	40.74 ± 7.85 a	2.47 ± 0.80 a	30.04 ± 0.88 b	7243.20 ± 623.99 b
	Intercropping soybeans	1.1*10 ⁵	44.7 ± 10.44 a	2.88 ± 0.94 a	26.9 ± 0.87 a	3815.04 ± 349.07 a
	Monocropping apples	1100	8.44 ± 1.06 a		227.62 ± 14.43 a	2148.05 ± 254.75 a
	Intercropping apples	1100	7.94 ± 0.95 a		217.64 ± 10.95 a	1902.24 ± 189.59 a
Significant level: P < 0.05						

Discussion

Distribution of fine roots

Root distribution plays an important role in the interactions between species within intercropping fields. In such fields, the root distributions of different species differ in time and space, and there is interspecies competition for resources, such as soil water and nutrients, which is very different from monoculture fields (Li et al., 2017). In the present study, the fine roots of single-cropping and intercropping apples were mainly distributed in the 20–40-cm soil layer and the fine roots of intercropping soybean were mainly distributed in the 0–20 cm, showing that fine roots were more widely distributed throughout the intercropping system. This root distribution pattern reduces the underground competition among species and improves the utilization rate of deep soil resources (Forey et al., 2021). Although intercropping promoted the growth of apple fine roots in the 40–60-cm soil layer, the growth of apple fine roots in the

0–40-cm soil layer was inhibited where apple and soybean roots overlapped. This is direct evidence of changes in the fine root distribution in apple–soybean intercropping systems, in which plants promote root development in deeper soils to absorb more water and nutrients when competition is unavoidable (Malézieux et al., 2009). In addition, the rapid growth period of the fine roots of apples is from autumn to the spring of the next year, while the rapid growth period of the fine roots of soybeans is from spring to summer. Intercropping also inhibited the distribution of fine roots 50 cm away from the tree. This probably occurred because irrigation and fertilization in the intercropping system made the fine root distribution of the intercropped apples more uniform, thereby improving the distribution of fine roots 100 cm away from the tree. In the apple monoculture treatment, only one drip irrigation tape was laid on both sides of the tree in the tree row, and the irrigation range was limited, so that the fine roots mainly gathered at 50 cm away from the tree.

Distribution of soil moisture content

It is essential to maintain sustainable soil water for vegetation, especially in arid regions where water scarcity is the greatest restrictive factor for vegetation growth and sustainable development (Huang et al., 2021). Soil moisture plays a central role in driving the growth patterns in semi-arid environments (Bosi et al., 2019). In many studies, researchers have found that the trees in an agroforestry system can improve soil moisture conditions (Thierfelder et al., 2017). At the soybean branching stage, the overall differences in the water content of each soil layer of the single-cropping apple and soybean–apple intercropping systems were not significant. The shading ability of soybean at the branching stage was weak, and the growth was vigorous. The root system had a strong ability to consume soil water within the overlapping range of the soybean root system and the apple root system. In the soybean flowering stage and seed drum stage, apple–soybean intercropping increased the soil water content within the range of 100–200 cm from the tree. There were three possible reasons for this phenomenon: 1) irrigation between tree rows; 2) the higher water content adjacent to the crop was probably related to reduced evaporation due to the canopy shade and reduced crop transpiration because of reduced wind speed and increased humidity (Campi et al., 2009; Lin, 2010; Teodoro et al., 2010); and 3) the improved soil quality due to the presence of inter-row crops could enhance infiltration during even limited rainfall events and reduce water loss during inter-rainfall periods (Schwab et al., 2015). For single-cropping apples, a drip irrigation belt was laid 30 cm away from the tree. The ground between the tree rows was bare, the soil moisture had a strong evaporation capacity, and there was only a small amount of rainfall to supplement soil moisture. Therefore, with the advancement of the growth period and increasing distance from the tree, the soil water content in the range of 100–200 cm decreased continuously.

Soil NO_3^- -N content

In organic farming, the input of nitrogen into the system by leguminous crops or the enhanced use of soil space by a deep-rooting crop in combination with a shallow-rooting crop are examples of how the resource use efficiency of a cropping system can be increased (Ramachandran Nair et al., 2009). Rhizobia attached to soybean roots perform nitrogen fixation. However, the nodule biomass was lower at

the tree-crop interface, Therefore, the effect of rhizobia on the soil nitrate nitrogen content was not discussed in the present study. In this experiment, the soil nitrate nitrogen content was higher under the single-cropping apple and soybean–apple intercropping treatments at the soybean branching stage. This was because the basal fertilizer was applied in the field before soybean planting. During this period, the soybean grew vigorously, resulting in intercropping. The soil nitrate nitrogen content in the soybean planting area under this treatment is lower than that of the apple monocropping treatment. Because the soybean root system was mainly distributed in the 0–20-cm soil layer during this period, the fine roots of the intercropped apple could obtain nutrients from the deeper soil (Lopez-Diaz et al., 2011). The soil nitrate nitrogen content at a distance of 50 cm from the tree was higher than that under the apple monoculture. In the soybean pod stage, a topdressing was carried out in each system. In the soybean planting area, due to the vigorous growth of soybeans, the competition for resources between apples and soybeans was fierce. As a result, the soil nitrate nitrogen content of the intercropping treatment was lower than that of the apple monoculture. For the apple monoculture, the soil nitrogen content at a distance of 50 cm from the tree was lower than that of other locations. Although a drip irrigation belt was laid at a distance of 50 cm from the tree, topdressing could be carried out in the later stage. However, due to the concentrated distribution of apple fine roots, a large amount of nitrogen was absorbed, resulting in a low nitrate nitrogen content in the soil. Due to low rainfall in this area, the nutrients in the soil are not easily leached out, and the consumed nutrients are mainly absorbed by plants. In agroforestry systems, the alternate distribution of roots can effectively reduce the leaching of soil nutrients (Borden et al., 2016). When soil resources are abundant and evenly distributed, plants mainly absorb resources in shallow soil (Yang et al., 2020), resulting in a large change in water and nutrient content in the shallow soil layer and small changes in the deep layer in irrigated agroforestry systems

Relationship between fine root distribution and soil water and nitrogen distribution

Whether agroforestry has an overall positive or negative effect on soil moisture remains a focus of studies investigating water dynamics in arid and semiarid regions (Yun et al., 2012). In this experiment, analyzing the correlation between the distribution of fine roots and the soil water content and soil nitrate nitrogen distribution in single-cropping apple and soybean–apple intercropping treatments demonstrated that compared with apple monocropping, soybean and apple intercropping reduced the correlation coefficient between the root system and the soil moisture and nitrate nitrogen content. This indicated that the influence of soil water content and nitrate nitrogen on the distribution of soil fine roots decreased in the intercropping system, which may have been due to the sufficient irrigation and fertilization provided by drip irrigation in the intercropping system. This also indicated that the irrigated agroforestry system could reduce the competition between crops and trees for soil nutrients and water. In irrigated agriculture, it was found that the binary linear regression equation better described the relationship between the distribution of soil fine roots and the soil water content and nitrate nitrogen content in apple monocropping and soybean–apple intercropping systems, and the combined effect of nitrate and water on fine roots was greater than their individual effects.

Crop growth and yield

Comparing single-cropping soybeans and intercropping soybeans showed that intercropping increased the plant height and leaf area of soybeans and decreased the stem diameter of soybeans before and during the growth period so that the biomass was concentrated in the stems. Studies have shown that reduced solar radiation availability leads to heightened understory plants and increased leaf ratio and size. These strategies are used by plants to intercept and absorb more solar radiation (Sgarbossa et al., 2020; Wu et al., 2017)

A previous study showed that high shading conditions reduced the transpiration flow of soybean plants, limiting the redistribution of nutrients and inhibiting photosynthesis, thereby resulting in an increase in flower abortion and, consequently, fewer pods per plant and a lower number of grains per plant (Caron et al., 2018). The results of the present study were in direct contrast with these findings. The apple trees in this study were 2–3 years old and at the young stage. The fruit trees had no actual yield in the first year of the experiment, and in the second year of the experiment, there was no significant difference in yield and yield composition between single-cropping and intercropping apples. This showed that intercropping in the irrigated agroforestry system had little effect on the yield of fruit trees. In this study, the LER of the soybean and apple intercropping was $1.41 > 1$, indicating that soybean and apple intercropping had planting advantages. The results indicate that the implementation of agroforestry in irrigated agriculture is conducive to maintaining soil moisture, and that soil resources are evenly distributed in the overlapping areas of crops and trees, while under rainfed agroforestry conditions, the overlapping areas of crops and trees will cause the excessive consumption of resources, such as soil water content (Ling et al., 2019). Therefore, it can be concluded that irrigated agroforestry has more advantages than rainfed agroforestry.

Conclusions

The distribution of fine roots, soil moisture, and soil nitrogen in two cropping modes (apple monocropping and soybean–apple intercropping) during different growth periods of two years were studied. Crop growth and yield were investigated, including in soybean monoculture treatments. This study showed that compared with apple monocropping, apple–soybean intercropping increased the richness of fine roots in the field, and the fine roots of apple decreased in the shallow layer and increased in the deep layer in the overlapping area of the two species. Intercropping cropping also increased the soil water content between the rows of apple trees and decreased the nitrate nitrogen content in the soil in the overlapping root system. The irrigated agroforestry system reduced the influence of soil water and nutrients on the distribution of fine roots and eased the competition between species for soil nutrients and water. Intercropping soybean increased the soybean plant height and leaf area, and decreased the stem diameter in the middle and late growth stages. There was no significant difference between monocropping and intercropping apples in terms of yield and yield components, while intercropping soybean increased its pods per plant and kernels per pod and decreased its 100-grain weight. In terms of the LER (1.41), soybean–apple intercropping has great planting advantages. Further research should be conducted to determine the impact of irrigation on soil resource utilization in irrigated agroforestry systems to determine whether the system offers potential for extension.

Abbreviations

PAR, photosynthetically active radiation; BU, the bud stage of cotton; FL, the flowering stage of cotton; BO, the boll stage of cotton; LER, land equivalent ratio; MAI, monetary advantage index; LY, lint yield of cotton; TEMP, air temperature; WSPD, wind speed; HP, harvest plant; BNP, boll numbers per plant; BW, boll weight; LP, lint percentage.

Declarations

Conflicts of interest

The authors declare no conflicts of interest.

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Figures

Figure 1

The location of the study site

Figure 2

Diagram of a soybean-apple intercropping system

Figure 3

Two-dimensional fine root length density distribution in different growth stages in monocropping apple and soybean–apple intercropping systems.

(left: A, D) soybeans branching stage; (B, E) soybean flower and pod stage; (right: C, F) seed filling stage; in the 2020(top) and 2021(bottom) seasons. Significant level: $P < 0.05$

Figure 4

Two-dimensional soil moisture content distribution in different growth stages of monocropping apple and soybean–apple intercropping system.

(left: a, d, g, j) soybeans branching stage; (b, e, h, k) soybean flower and pod stage; (right: c, f, i, l) seed filling stage; in the 2020(top two rows) and 2021(bottom two rows) seasons. Significant level: $P < 0.05$

Figure 5

Two-dimensional soil NO₃⁻-N content distribution in different growth stages of monocropping apple and soybean apple intercropping systems.

The (left: a, d, g, j) soybean branching stage; (b, e, h, k) soybean flower and pod stage; and (right: c, f, i, l) seed-filling stage in the 2020 (top two rows) and 2021 (bottom two rows) seasons. Significance level: P < 0.05

Figure 6

Dynamic changes in the plant height, stem thickness, and leaf area of soybean under different planting patterns in 2020 and 2021

Significant level: P < 0.05