REGULAR ARTICLE

Effect of the fodder species canola (*Brassica napus* L.) and daylily (*Hemerocallis fulva* L.) on soil physical properties and soil water content in a rainfed orchard on the semiarid Loess Plateau, China

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Abstract

Background and aims Understanding the variability in water availability in agroforestry systems in rain-fed orchards is vital for optimizing orchard management in semiarid areas. However, few studies have examined the soil capacity of water stock and supply in these systems over multiple years. We aim at (i) characterizing several soil physical properties related to water availability and inter-annual dynamics of soil water content and (ii) exploring their response to meteorological conditions and root distribution.

Methods Jujube (*Ziziphus jujuba* Mill.) intercropped with the fodder species canola (*Brassica napus* L.) (JFCS), jujube intercropped with daylily (*Hemerocallis fulva* L.) (JDLS), and a jujube orchard with clean tillage (JCS) were established on the Loess Plateau, China. Soil physical properties (including soil bulk density, soil

hydraulic conductivity, soil field capacity, and soil porosity), soil water content and fine root data were collected over the period 2014–2017.

Results Compared to JCS-Tree, the field capacity was significantly increased both in the JFCS-Tree and JDLS-Tree treatments, while soil capillary porosity increased significantly only in the JFCS-Tree. Compared to JCS-Inter-row, the JFCS-Inter-row and JDLS-Inter-row exhibited significantly decreased soil bulk density, and increased field capacity, saturated hydraulic conductivity, and improved soil porosity, but the non-capillary porosity in the JDLS-Inter-row treatment were not significantly modified. Compare to JCS-Tree treatment, the soil water at 0–60 cm significantly increased under JFCS-Tree and JDLS-Tree in four years. However, due to the deeper fine root distribution for both tree and crop under JDLS-Inter-row, the soil water content at 60–180 cm in JDLS-Inter-row significantly decreased more than JFCS-Inter-row and JCS-Inter-row.

Conclusions The introduced crop modified the soil physical properties and soil water content, indirectly under trees and directly between inter-rows through the role of fine roots, thereby changing the orchard environment in semi-arid areas. Agroforests can generally improve water condition at shallow soil layers compared to monocultural plantations, although such an effect may be accompanied with lower water stock at deeper soil layers in inter-rows, depending on crop species chosen.

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Introduction

Drylands account for around 40% of all terrestrial ecosystems, and nearly 38% of the world's population would be affected by climate change (Huang et al. 2016a). In particular, changes in precipitation and temperature have been identified as a concern for agricultural production in dryland agriculture (Slingo et al. 2005; Bradford et al. 2017; Huang et al. 2017). Typically, agricultural production in certain regions may be at risk in the future due to increased competition for water and more variability in extreme rainfall and drought (Altieri 2002; Altieri and Nicholls 2017). This issue not only threatens food production but could also jeopardize the many small farmers who depend on rain-fed agriculture for their livelihoods (Verdin et al. 2005; Zhang and He 2016). Agroforestry systems, as traditional intensive land use, are playing an important role in combating climate change and increasing system stability. Recently, many studies have demonstrated that agroforestry may be more climate-smart and resilient to climatic extremes than other agricultural methods and deliver more socioeconomic benefits (Altieri and Nicholls 2017; Sida et al. 2018). However, in environmentally fragile areas (e.g., arid and semiarid zones and hilly regions), establishing effective agroforestry is still a challenge because of the restrictions and limitations of economic conditions and water availability.

Soil physical properties are widely considered to be the key factors reflecting the effect of soil management (Merwin et al. 1994; Steele et al. 2012; Liu et al. 2013). It may be better to examine soil physical properties that indicate the capacity of a soil to function within an ecosystem or land-use area and to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Doran and Parkin 1994). Agroforestry is a successful and sustainable soil management approach, providing an alternative to conventional tillage in orchards (Ramos et al. 2010; King and Berry 2005; Tahir et al. 2016; Palese et al. 2014; Huang et al. 2016a, b; Li et al. 2007; Schwab et al. 2015; Abdulai et al. 2018). It could alter many aspects of soil physical properties, such as soil bulk density and soil porosity, which are essential soil structure favorable to crop root growth and soil water holding capacity (Xu and Zhang 2004; Liu et al. 2013). Meantime, the increase of soil saturated hydraulic conductivity and field capacity is essential to the faster downward movement of water (Klik et al. 1998; Siriri et al. 2005), improving

water retention and increasing plant available water content (Bilek 2007). These characteristics reflect the fundamental aspect of soil performances, which indeed are altered by the management practices (Steele et al. 2012; Schwab et al. 2015; Sun et al. 2018; Liu et al. 2013). Li et al. (2007) suggested that intercropped with herbage in an apple orchard, the soil bulk density reduced, the soil porosity increased, and the soil water-holding capacity enhanced greatly. Long-term use of winter rye cover crop significantly increased both the field capacity by 10–11% and plant available water by 21–22% (Basche et al. 2016). Nevertheless, these benefits are subject to the choice and management of relevant cover crops, to ensure that they promote beneficial ecosystem service while circumscribing above-ground and below the ground competition (Liu et al. 2013; Palese et al. 2014). Meanwhile, indicators of soil physical properties that respond on relatively long scales (e.g., several years) to change in management are critical for evaluating agroforestry system functioning (Schwab et al. 2015; Basche et al. 2016). However, these studies focus on the soil physical properties change in the entire ecosystem, little attention has been paid on the soil physical properties difference between understory and inter-row which were affected by crops in an agroforestry system.

In arid and semiarid areas, water availability in orchards will always be the main focus of attention. Inter-row vegetation consumes a substantial amount of water, which may not be supplemented by precipitation, causing a water shortage during tree growth (Li et al. 2007; Bai et al. 2018). Li et al. (2007) studied the grass in apple orchards and found that the impact of grass on soil water content depends on the type of rainfall. Moreover, their research suggested that grass increased soil water content under trees during normal years but decreased soil water content in drought years. Abdulai et al. (2018) suggested that cocoa agroforestry is less resilient than cocoa in full sun when subjected to sub-optimal or extreme climate because of the excessive consumption of soil water in agroforestry. Hence, understanding the effects of different rainfall years on agroforestry systems is necessary for developing sustainable plantations in dryland environments. However, most previous studies mainly focus on the soil physical properties in a permanent grass-vegetated orchard, while little is known about the effects of economic crops in orchards and the soil physical properties and soil water content dynamics in years with varying rainfall in semiarid areas.

The Loess Plateau is one of the main dryland regions of China, on which jujube orchards deliver key economic, social, and ecological functions (Zhao et al. 2009). Due to the complicated topography (i.e., hills and gullies) of the Loess Plateau and high irrigation costs, most jujube orchards are rain-fed and managed under clean tillage conditions (Gao et al. 2016). Unfortunately, rainfall is not synchronized with the critical stages of the jujube production cycle. Moreover, sites, where clean tillage is practiced are prone to soil erosion and land degradation, as this method is characterized by low rainfall infiltration and utilization during intensive precipitation and higher post-rain evaporation (Pan et al. 2017; Bai et al. 2018). Intercropping (grass) in orchards can modify the distribution of soil water content as it influences both soil physical properties (e.g., infiltration, water holding capacity) and the soil water loss rate (Shaxson and Barber 2003; Yang et al. 2016). This study seeks to investigate how an agroforestry system affects soil physical properties and soil water content in a rain-fed jujube orchard with two economic crops over four years and if they could be explained by meteorological and root data. An annual plant, the fodder species canola (*Brassica napus* L.), and a perennial plant, daylily (*Hemerocallis fulva* L.), were chosen to examine the role of crops in a jujube orchard. To assist farmers in northwest China, it is important to determine which crop and/or soil management approaches are the most suitable for jujube agroforestry in the context of scarce water resources in a semiarid environment. The results presented also contribute to a better understanding of changes in soil physical properties and water allocation within specific agroforestry systems in the semiarid area.

Materials and methods

Study site and experimental design

A jujube orchard in Qingjian County, Shaanxi Province, located in the north of the Loess Plateau, was chosen for this study. The site has typical loess hill and gully terrain (37°14′N, 110°21′E), and a temperate continental monsoon climate. The annual mean temperature is 8.6 °C, with the lowest mean monthly temperature (−6.5 °C) in January and the highest mean monthly temperature (28 °C) in July. Annual mean precipitation amounts to 505 mm, of which 70% generally occurs between July

and September. Field capacity at the site is about 25% (volumetric water content) while wilting occurs at about 7% (Table 1).

Jujube is the main economic crop grown in the area. A 6-year-old pear-jujube (*Ziziphus jujuba* Mill.) orchard was chosen for the experiment. This jujube orchard was mainly planted on the slopes of a hilly loess area (more details can be found in Ling et al. 2017). Each local small-scale farmer has their jujube orchard, with Daylily (*Hemerocallis fulva* L.) planted as a perennial species. The fodder species canola (*Brassica napus* L.) is an annual species, with farmers planting this crop in May and harvesting it at the end of October every year. More information is presented in Table 2.

There were three treatments in this study: the jujube/canola system (JFCS, Rotary tilling before planting canola and then clean tillage after), the jujube/daylily system (JDLS, Clean tillage) and the jujube conventional system (JCS, clean tillage) as the control. In a single original orchard, we randomly selected three plots as experimental areas, and each plot was divided into three treatments using random splits. The plot used had an

Table 1 List of symbols and abbreviations

Symbols	Definition
JFCS	Jujube intercropped with the fodder species canola
JFCS-Tree	Under tree of JFCS treatment
JFCS-Inter-row	Inter-row of JFCS treatment
JDLS	Jujube intercropped with daylily
JDLS-Tree	Under tree of JDLS treatment
JDLS-Inter-row	Inter-row of JDLS treatment
JCS	Jujube orchard with clean tillage
JCS-Tree	Under tree of JCS treatment
JCS-Inter-row	Inter-row of JCS treatment
GP	Growth period
DP	Dormant period
LMM	Linear mixed model
HC	Hydraulic conductivity (cm d^{-1})
FRLD	Fine root length density (cm cm^{-3})
BD	Bulk density (g cm^{-3})
FC	Field capacity (%)
PD	Particle density (g cm^{-3})
TP	Total porosity (%)
CP	Capillary porosity (%)
NCP	Non-capillary porosity (%)

Table 2 Main characteristics of jujube trees under every treatment (JFCS, JDLS, JCS), as well as the two tested economic crops. The standard error of the mean is shown in brackets. JFCS-jujube intercropped with the fodder species canola, JDLS-jujube intercropped with daylily, JCS-clean cultivation jujube orchard (control)

	Jujube in JFCS	Jujube in JDLS	Jujube in JCS	Fodder species canola	Daylily
Density	640 (trees ha^{-1})	640 (trees ha^{-1})	640 (trees ha^{-1})	150 thousand (plants ha^{-1})	40 thousand (plants ha^{-1})
Type	Economic forest	Economic forest	Economic forest	fodder economic crop	Traditional economic crop
Phenology	Deciduous tree	Deciduous tree	Deciduous tree	Annual Cruciferae	Perennial Liliaceae
Diameter at breast height (mm)	70.13 (10.3)	69.43 (11.4)	70.56 (13.52)	–	–
Height (m)	2.14 (0.5)	2.23 (0.46)	2.22 (0.45)	0.95 (0.25)	1.24 (0.14)
Crown area (m^2)	2.00 (0.2)	2.25 (0.31)	2.11 (0.15)	0.26 (0.13)	0.38 (0.1)
Root distribution	Randomly distributed in the soil profile	Randomly distributed in the soil profile	Randomly distributed in the soil profile	More concentrated in 0–20 cm	More concentrated in 0–50 cm
Slope aspects	326–349°	326–349°	326–349°	326–349°	326–349°
Slope gradient	15–18°	15–18°	15–18°	15–18°	15–18°
Altitude (m)	995	996	995	996	996
Soil type	Silt loam soil	Silt loam soil	Silt loam soil	Silt loam soil	Silt loam soil
Growth period	May–October	May–October	May–October	Mid May–October	April–October
Pruning of tree branches	Mid-June (summer pruning), November (winter pruning)	Mid-June (summer pruning), November (winter pruning)	Mid-June (summer pruning), November (winter pruning)		
Dormant period	November–April	November–April	November–April	November- Mid May	November–March
Harvest	Harvest fruit	Harvest fruit	Harvest fruit	Green fodders	Harvest flowers
Average dry matter (g per plant)	–	–	–	24.9 (3.9)	158.5 (17.8)

area of 45 m² (5 m × 9 m), and each treatment included three replicate plots, resulting in a total of nine study plots. More details can be found in Table 2. In the JFCS treatment, the rotary tilling was carried out before planting (annually in May) the canola and clean tillage repeated every year (since 2008). In the JDLS treatment, as the daylily is a perennial crop, clean tillage was maintained as for the JCS treatment after 2008 when the daylily was planted in the orchard. In the JCS treatment, clean tillage was employed because this is the most popular tillage system for weed removal practiced by the small farmers in the region.

Fine root collection

Fine root (≤2 mm) samples were collected at 20 cm increments to a depth of 180 cm under jujube tree (50 cm from the tree trunk) and between crop row (9 Oct. 2014, 6 Oct. 2015, 29 Sep. 2016, and 24 Sep. 2017). In every plot, three sample sites were selected under the tree and between rows, respectively. Roots of jujube trees and crops are easily distinguishable by color as the tree roots are brown, the daylily's is light yellow, and the canola's is white. The soil samples were collected with root auger, which internal diameter of 6 cm. Soil samples of root and soil were sealed in sample bags. The samples were gently washed in a 1 mm sieve, and the roots retained on the sieve were removed with tweezers. Dead roots were identified based on color (dead roots are dark) and mechanics (dead roots are little elastic) and discarded, despite subjectivity. Finally, using a Vernier caliper with a precision of 1×10^{-2} mm, the coarse roots (>2 mm) were separated from the fine roots (≤2 mm). The fine roots were scanned with a scanner at 300 dpi, and the files were saved in the TIFF format. The fine root lengths were calculated using DElLTA-T SCAN® image analysis software (Delta-T scan, Delta-T Devices Company, UK) based on the images of the fine roots. After the measurements were collected, the fine root samples in each layer were oven-dried at 70 °C and weighed to determine the root dry weight.

The root was described by the FRLD in vertical distribution (at 0–60 cm and 60–180 cm soil depths) and expressed the steepness of the root density decreased with soil depth by the β value of the regression equation:

$$y = 1 - \beta^d \qquad (1)$$

Where y is the cumulative root biomass fraction in g cm^{-3} and d is the soil depth in cm (Gale and Grigal

1987). High β values indicate a large proportion of root biomass concentrates in deeper soil depths, whereas low values stand for a large proportion of root mass concentrates near the soil surface.

Soil sampling

On four dates covering the experimental period (7 Oct. 2014, 4 Oct. 2015, 27 Sep. 2016, and 26 Sep. 2017) soil was sampled at four depths: (0–5 cm, 5–10 cm, 10–20 cm, and 20–40 cm). The sampling position was beneath jujube trees and in the middle of the row, near the soil water content monitoring site. In every plot, four replicates under trees and two replicates between the rows were collected, totaling 54 soil samples in nine plots. A stack of the ring was pushed vertically into the soil, and when the top ring was nearly full, an empty ring was placed on top stack slightly below the soil surface. The stack was then carefully dug out, excess soil removed, and a metal cover with filter paper affixed to top and bottom to protect the soil during transit and storage.

Measurements of soil physical properties

Several soil parameters were evaluated to determine the impact of the different treatments on soil physical properties. Soil bulk density (BD) and soil saturated hydraulic conductivity of the 0–5 cm, 5–10 cm, 10–20 cm, and 20–40 cm soil layers were determined using the core method (length 5 cm, diameter 5 cm). The core samples were immediately weighed, and then dried at 105 °C for 24 h to a constant weight and reweighed to calculate the soil bulk density. The soil samples were kept saturated under a constant head (5 cm) and recorded the water flow per unit time to calculate the saturated hydraulic conductivity. Field capacity (FC) was determined using a core of undisturbed soil (Wilcox method, Duan et al. 2010). A piece of filter paper was placed on the bottom of the core, fixed it with a mesh bag and rubber band, and filter paper was also placed on the top. The core was submerged for 12 h. After this, another core of dry soil was placed on top of the original soil core. After a further 8 h to allow water absorption, about 20 g of wet soil was taken from the middle of the original core and dried to calculate the field capacity. It is noteworthy that field- and lab- determined soil hydraulic properties (e.g., field capacity and soil hydraulic conductivity) could be noticeably different (Ferrer et al. 2008; Duan

et al. 2010). For instances, Ferrer et al. (2008) found the field capacity measured by pressure plates (-33 kPa) was higher than by field method. Duan et al. (2010) suggested that if the soil structure was destroyed in the laboratory, the measured field capacity could be significantly higher. Also, soil hydraulic conductivity obtained from by laboratory-produced larger than in field, which affected by the size of the soil core (Bagarello and Provenzano 1996). In this study, all the soil physical properties in the different treatments were sampled and measured using the same method and at the same time, so the results could directly comparable between treatments (Bao 2007).

Total soil porosity (TP) was calculated using Eq. 2, based on the relationship between the soil bulk density and soil particle density. Soil Particle density (PD) is approximately 2.65 g cm^{-3} for minerals soils, as widely used in studies of the Loess Plateau (Wang et al. 2016; Zhang et al. 2019). Since the study area soil had relatively low organic matter, we used the 2.65 g cm^{-3} value. Capillary porosity (CP) was calculated on the basis of the relationship between field capacity and soil bulk density (Eq. 3 and S1). Non-capillary porosity (NCP) was calculated as the difference between total porosity and capillary porosity (Eq. 4). The equations used were as follows:

$$TP = \left(1 - \frac{BD}{PD}\right) \times 100\% \tag{2}$$

$$CP = FC \times BD \times 100\% \tag{3}$$

$$NCP = TP - CP \tag{4}$$

Soil water content dynamics

A portable Time Domain Reflectometry (TDR) system (TIME-PICO IPH / T3; IMKO, Ettlingen, Germany) was used to take volumetric measurements. The tubes for measurements were installed under the trees (30 cm away from the tree trunk) and crops (in the middle between the tree rows). Four replicates under trees and two under crops were collected in every plot. A total of 54 soil water content monitoring tubes were installed across all nine plots. Each TDR tube reached a depth of 180 cm, with 20 cm increments. Soil water content was

measured every two weeks between mid-May to Mid-October, with additional monitoring after rainfall. In 2016, soil water content could only be measured until September because of bad weather conditions. The winter months, influenced by the arctic air from Siberia, are cold and dry, and precipitation is rare. This period lasts from November to March. Soil water content was, therefore, measured from March to April, to represent the jujube dormant period (2014–2015, 2015–2016, 2016–2017). A total of 67 measurements were taken, with each sampling session completed in 2 h. The TRIME-TDR system was calibrated against volumetric water content under field conditions. Based on jujube growth characteristics (Jin et al. 2018), there are two periods every year: a dormant period (DP, March to April) and a growth period (GP, May–October, DOY). The jujube growth period can be further classified into four stages: leaf emergence (Early-May–Mid-June); blossoming and young fruit (Mid-June-Mid-July); fruit swelling (Mid-July–Mid-September); and fruit maturation (Mid-September–Mid-October).

An automatic weather station (Rainroot Scientific Limited, Beijing, China) was installed 50 m from the study area. Sensors were installed at a height of 2.0 m and CR100 (Campbell Scientific Inc.; Edmonton, Canada) dataloggers collected data every 30 min from May–October during 2014–2017. The system recorded rainfall, air temperature, relative humidity, solar radiation, and wind speed. Reference evapotranspiration (ET_0, mm d^{-1}) was calculated based on the FAO Penman-Monteith equation (Allen et al. 1998) using data from the weather station in every year, as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\dfrac{900}{T + 273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{5}$$

Where R_n is net radiation (MJ m^{-2} d^{-1}); G is the soil heat flux (MJ m^{-2} d^{-1}); Δ is the vapor pressure curve slope (kPa °C^{-1}); γ is a psychrometric constant (kPa °C^{-1}); T is the mean air temperature (°C); u_2 is wind speed at 2 m height (m s^{-1}); and $e_s - e_a$ is saturation vapor pressure deficit (kPa). The equation uses standard climatological records of solar radiation, air temperature, humidity and wind speed. The calculation process is shown in the supplementary (Eq. S2).

Statistical analysis

The temporal and spatial variations in soil water content under trees and between rows during the dormant and growth periods were plotted on a contour map derived by applying kriging interpolation.

A linear mixed model (LMM) was used to analyze the soil water content and soil physical properties data because the data were hierarchical and clustered among plots within the study site. Observations were collected repeatedly over the course of four years from the same plots. The data sets were analyzed in R, with the data file split into observations representing the four distinct years. In order to examine the soil water content change with soil depth in each month, we considered soil water content in the 0–60 cm and 60–180 cm layers. The LMM was fitted to soil water content in the four years (normal year 2014, drought year 2015, normal year 2016, normal year 2017). The LMMs include fixed effects associated with the treatments as well as random effects that are associated with the plants sampled for each treatment, thus capturing within-plant correlations. We considered treatment × month as fixed effects, to evaluate the change in soil water content in different treatments in different months during the four years. When analyzing changes in soil physical properties using the LMM, we considered the treatments and soil depths to be the fixed effects. The changes in soil physical properties with time were not analyzed. Random sampling position was treated as a random effect. The proportion of variance in the measurements can be attributed to random plant (position) effects and was estimated using random intercepts in the LMM (Gueorguieva and Krystal 2004).

To describe the variation in soil characteristics between treatments, we used R (R Core Team 2016) and *ImerTEST* (Kuznetsova et al. 2016) to perform a linear mixed-effects analysis. The Chi-square (Chisq) test was used to examine treatment differences, a p value of 0.05 was the threshold for statistical significance. Pairwise comparisons were performed using the HSD-Tukey test at the 95% probability level ($p < 0.05$). Principle Components Analysis (PCA) and Pearson analysis were conducted in R to analyze interrelations between soil physical properties (0–40 cm), fine root length density (0–60 cm and 60–180 cm), and soil water content under tree and inter-row (0–60 cm and 60–180 cm). Data analysis was carried out using Microsoft Excel

2013 (Microsoft, Redmond, CA), IBM SPSS Statistics 23 (IBM, Stanford, USA), Origin 2016 Pro software (Origin Lab, Northampton, MA), and Surfer 12.0 (Golden Software, Golden, USA).

Results

Meteorological variability

The annual rainfall during the study years amounted to 383.4 mm, 254.6 mm, 319.4 mm, and 398.6 mm, respectively (Fig. 1). Based on the Qingjian County precipitation records from the years 1956–2006, years 2014, 2016 and 2017 could be considered normal, while 2015 could be considered a drought year. Effective rainfall and frequency are crucial factors in determining any increase in soil water content. A single rainfall event delivering less than 5 mm is considered ineffective. Rainfall occurred 60 times in 2014, with 31.6% effective; 55 times in 2015, with 25.5% effective; 60 times in 2016, with 23% effective; and 68 times in 2017, with 39% effective. The average temperature during each month in the period 2015–2017 was slightly higher than that recorded in 2014 (Fig. 1). The ET_0 changes from month to month reveal that the study site dries quickly during early jujube growth stages (May–July) (Fig. 1), corresponding to the time of seasonal drought in the region.

Vertical change of tree and crop fine root

The jujube FRLD was significantly higher in JFCS-Tree and JDLS-Tree than in JCS-Tree at 0–60 cm (Fig. 2a). At the inter-row, the FRLD of tree in JFCS-Inter-row and JDLS-Inter-row were significantly higher and significantly lower than in the JCS-Inter-row at 0–60 cm, respectively (Fig. 2c). Furthermore, The FRLD of tree in JDLS-Inter-row was significantly higher than the JCS-Inter-row at 60–180 cm (Fig. 2d). The β value indicated that both the JFCS-Tree and JDLS-Tree tended to allocate more fine root biomass at shallower depths than the JCS-Tree (Table 3). At the inter-row, the β value of the tree in JFCS-Inter-row was lower than in JCS-Inter-row showed a concentration of fine root biomass at upper soil layers. Conversely, the β value of the tree in JDLS-Inter-row tended to allocate more fine root biomass at deeper soil layers compared to JCS-Inter-row (Table 3).

Fig. 1 Monthly rainfall, average temperature, and reference evapotranspiration over the experimental period
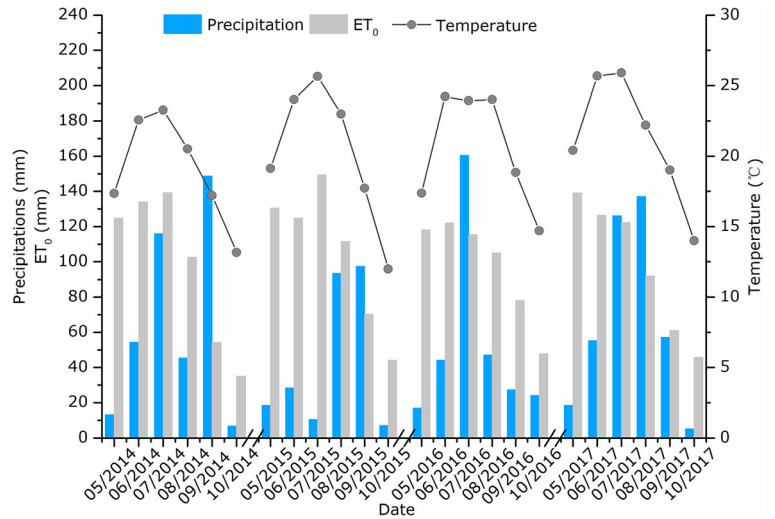
The canola FRLD was significantly higher than daylily at 0–60 cm but significantly lower than daylily at 60–180 cm (Fig. 2e–f). Also, the daylily

FRLD β value suggested a higher proportion of fine root biomass concentrated at deeper soil layers than the canola (Table 3).
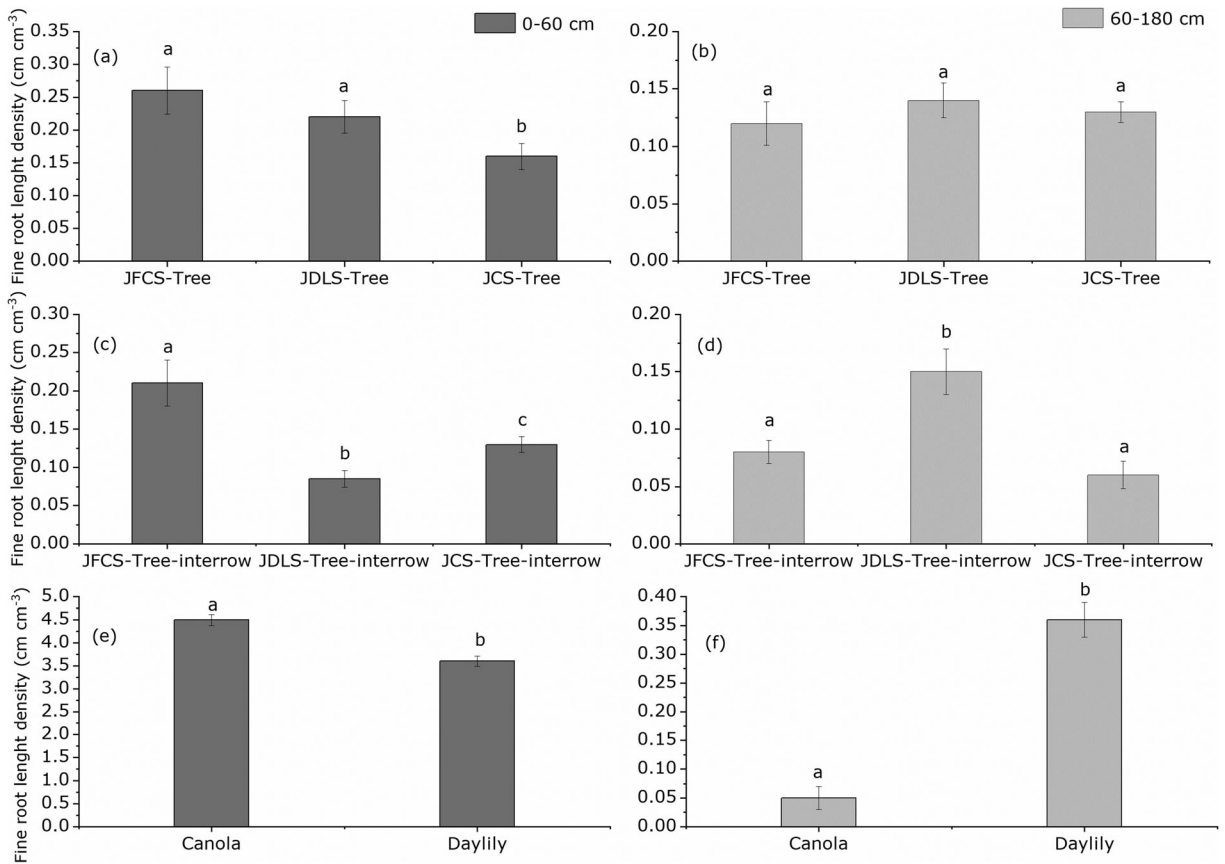

Fig. 2 Fine root length density of trees and crops in three treatments under tree and inter-row at 0–60 cm and 60–180 cm. Lower case Latin letters indicate statistically significant differences

between the different treatments. The root sampling point under the tree is 50 cm away from the trunk. Inter-row root sampling points in the middle of rows

Table 3 Vertical decrease in the biomass of fine roots down to 180 cm soil depth of tree and crops in the three treatments under tree and inter-row expressed by the β value of the regression equation $y = 1 - \beta^d$ (Gale and Grigal 1987), with y being the cumulative root biomass fraction in g cm^{-3} and d being the soil depth in cm

Positions	Under tree			Inter-row		
	β	R^2	p	β	R^2	p
JFCS-Tree	0.95	0.98	<0.01	0.95	0.95	<0.01
JDLS-Tree	0.96	0.95	< 0.01	0.99	0.94	<0.01
JCS-Tree	0.98	0.99	<0.01	0.97	0.97	<0.01
Canola	–	–	–	0.91	0.95	<0.01
Daylily	–	–	–	0.94	0.98	<0.01

High β values indicate a large proportion of root biomass in deeper soil depths, whereas low values stand for a large proportion of root mass near the soil surface. Given are the R^2 and p values of the respective regression models. The root sampling points under the tree are 50 cm away from the trunk. Inter-row root sampling points are between inter-row

Soil physical properties

The JFCS-Tree and JDLS-Tree soil bulk density, soil saturated hydraulic conductivity, total porosity, and non-capillary porosity were not significantly different from the equivalent values under the JCS-Tree treatment, but did decrease significantly with soil depths (0–5 cm > 5–10 cm > 10–20 cm > 20–40 cm) (Tables 4, 5 and S1). The field capacity under JFCS-Tree and JDLS-Tree were 1.6%–5.2% and 0.6%–2.9% higher than JCS-Tree (Table 4 and S1), respectively. However, there were no significant differences with soil depths. The soil capillary porosity was significantly higher under JFCS-Tree was 0.15%–5.1% higher than JCS-Tree (Table 5 and S1) but not significantly different with soil depths. In contrast, soil capillary porosity was not significantly different between JDLS-Tree and JCS-Tree, but there were significantly decreased with soil depths (0–5 cm > 5–10 cm > 10–20 cm > 20–40 cm).

Compared to the JCS-Inter-row, the JFCS-Inter-row and JDLS-Inter-row both significantly decreased the soil bulk density and increased the soil field capacity (Table 6 and S2). In addition, the soil saturated hydraulic conductivity decreased significantly with soil depths (0–5 cm > 5–10 cm > 10–20 cm > 20–40 cm). The soil bulk density decreased in the JFCS-Inter-row and JDLS-Inter-row, varying by 4.69%–6.28% and 1.9%–3.9%; the field capacity increased, by 10.7%–13.1% and 8.4%–10.4%; the

soil saturated hydraulic conductivity increased, by 21.88%–36.24% and 23.89%–30.57%, respectively, over the four years.

Table 7 and S2 showed that, compared with JCS-Inter-row, the JFCS-Inter-row treatment exhibited significantly increased soil total porosity (5.1%–6.9%), capillary porosity (4.6%–6.8%), and non-capillary porosity (1.7%–11%) over the four years with significant decreased between soil depths (0–5 cm > 5–10 cm > 10–20 cm > 20–40 cm). Compared to the JCS-Inter-row, the JDLS-Inter-row treatment exhibited significantly increased total soil porosity (2.1%–4.4%) and capillary porosity (5.1%–6.8%) with significant decreased between soil depths (0–5 cm > 5–10 cm > 10–20 cm > 20–40 cm), but there was no significant effect on the non-capillary porosity during the four years.

Soil water content variations under jujube trees

Compared to the jujube JCS-Tree, the values for JFCS-Tree and JDLS-Tree average soil water content (0–180 cm) were significantly higher during the GP and DP period (Fig. 3a–c and Fig. S1). The interannual variations in soil water content in 2014 (Fig. S1, i) was quite different from 2015 to 2017 for JCS-Tree (Fig. S1: j-l), but such difference was not strong, if one compared in 2014 (Fig. S1: a, e) and 2015–2017 (Fig. S1: b-d, f-h) of JFCS-Tree and JDLS-Tree. Compared to JCS-Tree, JFCS-Tree and JDLS-Tree significantly increased in terms of soil water content at a depth of 0–60 cm over the four study years (Fig. 4a–d, Table S3). In contrast, the soil water content measurements at a depth of 60–180 cm did not differ significantly over the four years (Fig. 4e–h). When analyzed on a monthly basis, soil water content at a depth of 0–60 cm in the JFCS-Tree and JDLS-Tree treatments also significantly higher than the JCS-Tree over the four years (Figure 4a1–d1). For the depth of 60–180 cm, the analysis only revealed significant month-to-month soil water content differences in 2015, which was a drought year (Figure 4e1–h1). In 2015, the soil water content significantly decreased between April and October in all three treatments. This change occurred at the same time during the drought and implied that this event influenced soil water content in the 60–180 cm layer.

Table 4 Effect of soil management on jujube orchard soil physical properties under trees

Soil layer (cm)	Treatments	Bulk density (g cm^{-3})				Field capacity (%)				Saturated hydraulic conductivity (cm d^{-1})			
		2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017
0–5 cm	JFCS-Tree	1.35a	1.34a	1.36a	1.35a	24.32a	25.37a	24.05a	25.25a	53.30a	58.48a	53.18a	51.38a
	JDLS-Tree	1.36a	1.36a	1.34a	1.38a	23.48a	24.14a	24.17a	25.82a	46.32a	52.03b	55.09a	46.37a
	JCS-Tree	1.35a	1.34a	1.36a	1.38a	23.40b	23.18a	23.33b	23.11b	52.30a	54.51b	53.54a	49.44a
5–10 cm	JFCS-Tree	1.33a	1.34a	1.41a	1.37a	25.55a	24.36a	25.83a	24.39a	43.52a	45.88a	45.83a	46.26a
	JDLS-Tree	1.35a	1.35a	1.37a	1.35a	24.54a	25.09a	24.63a	24.80a	46.31a	48.03a	44.65a	49.78a
	JCS-Tree	1.35a	1.37b	1.41a	1.41a	23.54b	23.65b	24.38a	24.73a	44.41a	45.01a	46.96a	44.44b
10–20 cm	JFCS-Tree	1.37a	1.41a	1.39a	1.38a	24.34a	24.48a	25.06a	24.02a	42.30a	47.07a	41.90a	45.17a
	JDLS-Tree	1.36a	1.39a	1.38a	1.39a	23.71a	23.75a	24.22a	24.44a	39.40a	46.03a	43.84a	53.18a
	JCS-Tree	1.36a	1.42a	1.42a	1.38a	23.65a	24.48a	23.30a	24.29a	41.72a	47.12a	43.05a	44.94a
20–40 cm	JFCS-Tree	1.37a	1.36a	1.41a	1.38a	23.45a	24.50a	24.97a	24.32a	35.10a	33.32a	36.53a	35.51a
	JDLS-Tree	1.40b	1.40b	1.42a	1.42a	24.12a	23.86a	24.37a	24.15a	33.45a	35.32a	43.02b	36.51a
	JCS-Tree	1.36a	1.41b	1.38a	1.39a	24.62a	24.23a	23.95a	24.26a	33.64a	34.68a	41.03a	35.48a
Average	JFCS-Tree	1.36	1.36	1.39	1.37	24.42	24.68	24.98	24.50	43.56	46.19	44.36	44.02
	JDLS-Tree	1.37	1.37	1.38	1.38	23.96	24.21	24.35	24.80	41.37	45.35	46.65	46.43
	JCS-Tree	1.36	1.38	1.39	1.39	23.80	23.89	23.74	24.10	43.02	45.33	46.15	43.57

Values within a column for the same soil layer followed by different letters are significantly different at $p = 0.05$

Soil water content variations under inter-row crops

Compared to the jujube GP, the average soil water content in all treatments between rows was significantly higher in the DP in 2015 (Fig. and Fig.). The average soil water content in the JDLS-Inter-row treatment was significantly lower than in the JCS-Inter-row in the four years. In addition, significantly lower values were recorded in JFCS-Inter-row compared to JCS-Inter-row in 2015 and 2016 in the GP and DP

Table 5 Effect of soil management on jujube orchard soil physical properties under trees

Soil layer (cm)	Treatments	Total porosity (%)				Capillary porosity (%)				Non-capillary porosity (%)			
		2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017
0–5 cm	JFCS-Tree	0.49a	0.50a	0.49a	0.49a	0.33a	0.34a	0.33a	0.34a	0.16a	0.16a	0.16a	0.15a
	JDLS-Tree	0.49a	0.49a	0.49a	0.48a	0.32a	0.33a	0.32a	0.36a	0.17a	0.16a	0.17a	0.12a
	JCS-Tree	0.49a	0.49a	0.49a	0.48a	0.32a	0.31b	0.32a	0.32b	0.17a	0.18a	0.17a	0.16a
5–10 cm	JFCS-Tree	0.50a	0.49a	0.47a	0.48a	0.34a	0.33a	0.36a	0.33a	0.16a	0.17a	0.11a	0.15a
	JDLS-Tree	0.49a	0.49a	0.48a	0.49a	0.33a	0.34a	0.34a	0.33a	0.16a	0.15a	0.14b	0.16a
	JCS-Tree	0.49a	0.48a	0.47a	0.47a	0.32b	0.32b	0.34a	0.35b	0.17a	0.16a	0.13b	0.12b
10–20 cm	JFCS-Tree	0.48a	0.47a	0.47a	0.48a	0.33a	0.34a	0.35a	0.33a	0.15a	0.12a	0.13a	0.15a
	JDLS-Tree	0.49a	0.48a	0.48a	0.48a	0.32a	0.33a	0.33a	0.34a	0.16a	0.15a	0.15a	0.14a
	JCS-Tree	0.49a	0.46a	0.47a	0.48a	0.32a	0.35a	0.33a	0.34a	0.17a	0.12a	0.14a	0.14a
20–40 cm	JFCS-Tree	0.48a	0.49a	0.47a	0.48a	0.32a	0.33a	0.35a	0.34a	0.16a	0.16a	0.12a	0.14a
	JDLS-Tree	0.47a	0.47a	0.46a	0.47a	0.34a	0.33a	0.35a	0.34a	0.13b	0.14a	0.12a	0.12a
	JCS-Tree	0.49a	0.47a	0.48a	0.48a	0.33a	0.34a	0.33b	0.34a	0.15a	0.13b	0.15a	0.14a
Average	JFCS-Tree	0.49	0.49	0.48	0.48	0.33	0.34	0.35	0.34	0.16	0.15	0.13	0.15
	JDLS-Tree	0.48	0.48	0.48	0.48	0.33	0.33	0.34	0.34	0.16	0.15	0.14	0.13
	JCS-Tree	0.49	0.48	0.47	0.47	0.32	0.33	0.33	0.34	0.17	0.15	0.14	0.14

Values within a column for the same soil layer followed by different letters are significantly different at $p = 0.05$

Table 6 Effect of soil management on the jujube orchard soil physical properties between rows

Soil layer (cm)	Treatments	Bulk density (g cm^{-3})				Field capacity (%)				Saturated hydraulic conductivity (cm d^{-1})			
		2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017
0–5 cm	JFCS-Inter-row	1.28a	1.30a	1.31a	1.27a	25.75a	25.50a	26.12a	25.41a	76.74a	77.24a	69.52a	78.72a
	JDLS-Inter-row	1.34a	1.34a	1.33a	1.30b	25.32a	26.20a	26.32a	26.02a	75.61a	67.48a	75.28a	73.92a
	JCS-Inter-row	1.38b	1.37b	1.39b	1.36b	23.40b	23.31b	22.54b	23.19b	58.49b	57.62b	55.63b	55.22b
5–10 cm	JFCS-Inter-row	1.29a	1.32a	1.31a	1.30a	26.55a	26.35a	25.83a	26.35a	58.78a	61.30a	65.24a	62.41a
	JDLS-Inter-row	1.34a	1.33a	1.35a	1.33a	24.45a	25.15a	24.65a	24.85a	55.71a	66.77a	59.92a	57.43b
	JCS-Inter-row	1.40b	1.37b	1.42b	1.41b	23.40b	22.64b	22.34b	22.74b	42.83b	45.15b	51.78c	42.97b
10–20 cm	JFCS-Inter-row	1.33a	1.32a	1.33a	1.32a	24.35a	25.50a	25.15a	25.08a	57.02a	54.63a	52.03a	57.90a
	JDLS-Inter-row	1.34a	1.36a	1.35a	1.36b	24.50a	23.75a	24.25a	24.46a	53.15a	56.21a	53.36a	53.11a
	JCS-Inter-row	1.40b	1.40b	1.41b	1.39b	22.40b	22.54b	22.34b	22.36b	43.12b	42.94b	46.10b	40.00b
20–40 cm	JFCS-Inter-row	1.34a	1.35a	1.35a	1.33a	24.35a	24.50a	25.01a	24.38a	49.52a	46.02a	48.11a	47.02a
	JDLS-Inter-row	1.38b	1.41b	1.37a	1.39a	24.62a	23.93a	24.42a	24.19a	54.08a	49.60a	50.20a	51.31a
	JCS-Inter-row	1.39b	1.41b	1.40b	1.41b	22.01b	22.32b	23.01b	22.31b	44.03b	38.14b	39.22b	41.53b
Average	JFCS-Inter-row	1.31	1.32	1.33	1.31	25.25	25.46	25.53	25.31	60.51	59.80	58.7	61.21
	JDLS-Inter-row	1.35	1.36	1.35	1.35	24.72	24.76	24.91	24.88	59.64	60.01	59.69	56.07
	JCS-Inter-row	1.39	1.39	1.41	1.39	22.80	22.70	22.56	22.65	47.12	45.9	48.18	44.93

Values within a column for the same soil layer followed by different letters are significantly different at $p = 0.05$

(Fig. 3d–f). There was a quite difference in 2015 (Fig. S2, b) from 2014, 2016, 2017 (Fig. S2: a, c, d) in JFCS-Inter-row, and in 2014 (Fig. S2: e) from 2015 to 2017 (Fig. S2: f-h) in JDLS-Inter-row, but not strong, when compared in JCS-Inter-row (Fig. S2: i-l). Compared to JCS-Inter-row, JFCS-Inter-

Table 7 Effect of soil management on the jujube orchard soil porosities between rows

Soil layer (cm)	Treatments	Total porosity (%)				Capillary porosity (%)				Non-capillary porosity (%)			
		2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017
0–5 cm	JFCS-Inter-row	0.52a	0.51a	0.51a	0.52a	0.33a	0.33a	0.34a	0.32a	0.19a	0.18a	0.16a	0.20a
	JDLS-Inter-row	0.49a	0.49a	0.50a	0.51a	0.34a	0.35a	0.35a	0.34a	0.16a	0.14a	0.15a	0.17b
	JCS-Inter-row	0.48b	0.48b	0.48b	0.49b	0.32b	0.32b	0.31b	0.32a	0.16b	0.16b	0.16b	0.17b
5–10 cm	JFCS-Inter-row	0.51a	0.50a	0.51a	0.51a	0.34a	0.35a	0.34a	0.34a	0.17a	0.15a	0.17a	0.17a
	JDLS-Inter-row	0.49a	0.50a	0.49a	0.50a	0.33a	0.33a	0.33a	0.33a	0.17a	0.16a	0.16a	0.17a
	JCS-Inter-row	0.47b	0.48b	0.46b	0.47b	0.33a	0.31b	0.32b	0.32b	0.14b	0.17a	0.15b	0.15b
10–20 cm	JFCS-Inter-row	0.50a	0.50a	0.50a	0.50a	0.32a	0.34a	0.33a	0.33a	0.17a	0.17a	0.16a	0.17a
	JDLS-Inter-row	0.49a	0.49a	0.49a	0.49a	0.33a	0.32a	0.33a	0.33a	0.17a	0.16a	0.16a	0.15a
	JCS-Inter-row	0.47b	0.47b	0.47b	0.48b	0.31b	0.32a	0.31b	0.31b	0.16b	0.16b	0.15b	0.16b
20–40 cm	JFCS-Inter-row	0.49a	0.49a	0.49a	0.50a	0.33a	0.33a	0.34a	0.32a	0.17a	0.16a	0.15a	0.17a
	JDLS-Inter-row	0.48a	0.47a	0.48a	0.48a	0.34a	0.34a	0.33a	0.34a	0.14a	0.13a	0.15a	0.14a
	JCS-Inter-row	0.48b	0.47b	0.47b	0.47b	0.31b	0.31b	0.32b	0.31b	0.17b	0.15b	0.15b	0.15b
Average	JFCS-Inter-row	0.51	0.50	0.50	0.51	0.33	0.34	0.34	0.33	0.18	0.16	0.16	0.18
	JDLS-Inter-row	0.49	0.49	0.49	0.49	0.33	0.34	0.34	0.33	0.16	0.15	0.15	0.16
	JCS-Inter-row	0.47	0.48	0.47	0.47	0.32	0.31	0.32	0.32	0.16	0.16	0.15	0.16

Values within a column for the same soil layer followed by different letters are significantly different at $p = 0.05$
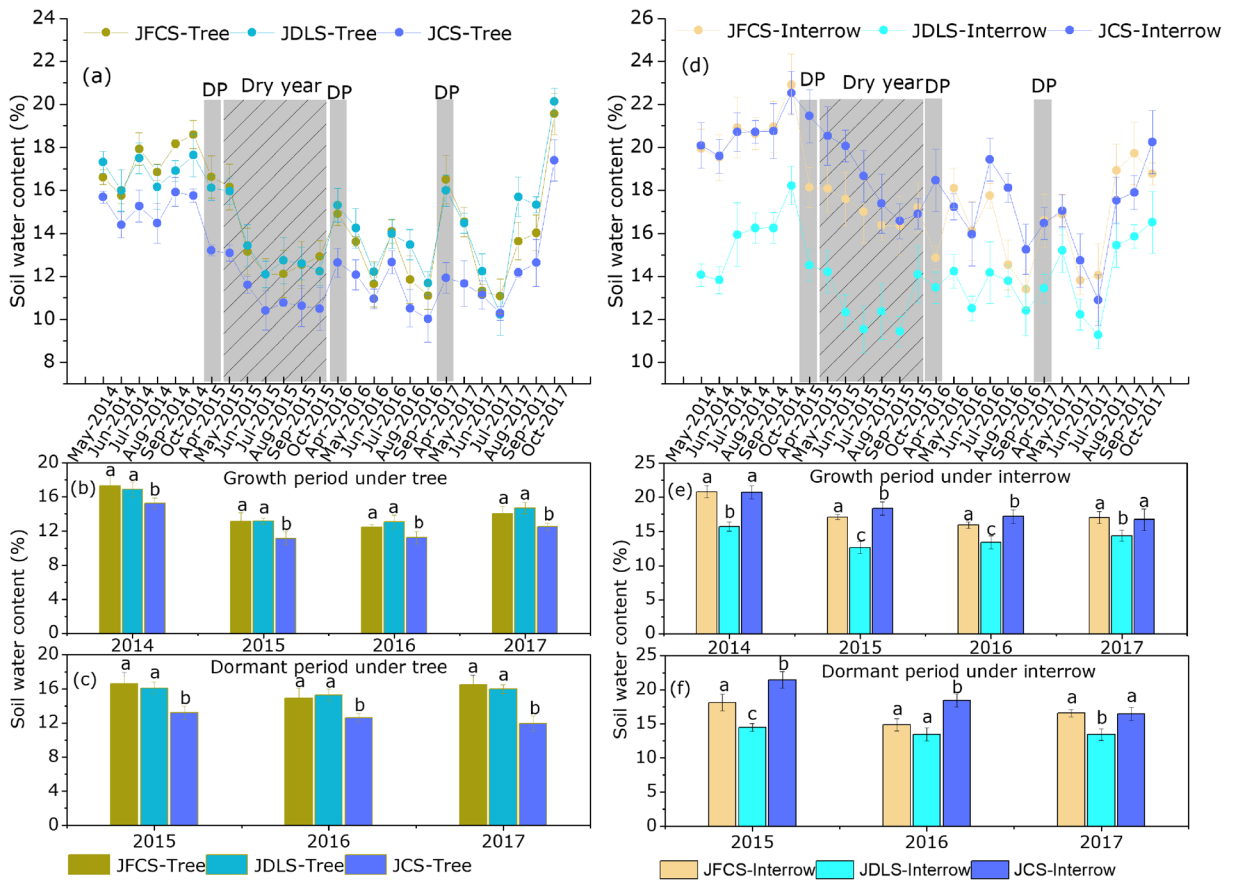
Fig. 3 The soil water content (0–180 cm) change with dormant period (DP) and growth period (GP) in four years. Different letters represent significantly different values ($p = 0.05$)

row and JDLS-Inter-row soil water content from a depth of 0–60 cm exhibited significant differences among the three treatments in 2015–2017, but no significant between-treatment differences in 2014 (Fig. 5a–d, Table S4). In the 60–180 cm layer, the soil water content measurements revealed that JDLS-Inter-row significantly decreased compared to the clean cultivation plots during each of the four study years (Fig. 5e–f). At the same depth, the soil water content measured for plots intercropped with JFCS-Inter-row significantly decreased compared to the clean cultivation plots in 2015–2017, but not in 2014 (Fig. 5e–f). When analyzed month-by-month, there were significant between-treatment soil water content differences at the 0–60 cm depth over the four study years (Figure 5a1–d1), but no significant differences between intercropping and clean cultivation could be discerned in the 60–180 cm layer during the study period (Figure 5e1–h1).

Interrelations between soil physical properties, soil water content and fine root under tree

The under-tree FC and CP showed a close relationship with the FRLD of tree at 0–60 cm along the PC1 axis. Also, the soil physical properties (except the FC) showed a close association with soil water content at 0–60 cm and 60–180 cm along the PC2 axis (Fig. 6a; Table S5). From the Pearson analysis (Table 8), the FC, TP, CP, and soil water content under tree at 0–60 cm were positively correlated to the FRLD of tree at 0–60 cm. The BD showed a negative correlation with soil water content at both 0–60 cm and 60–180 cm, while the TP and NCP showed a positive correlation with soil water content at 60–180 cm. Moreover, HC and CP showed a positive correlation with soil water content at 0–60 cm and a negative correlation with soil water content at 60–180 cm.
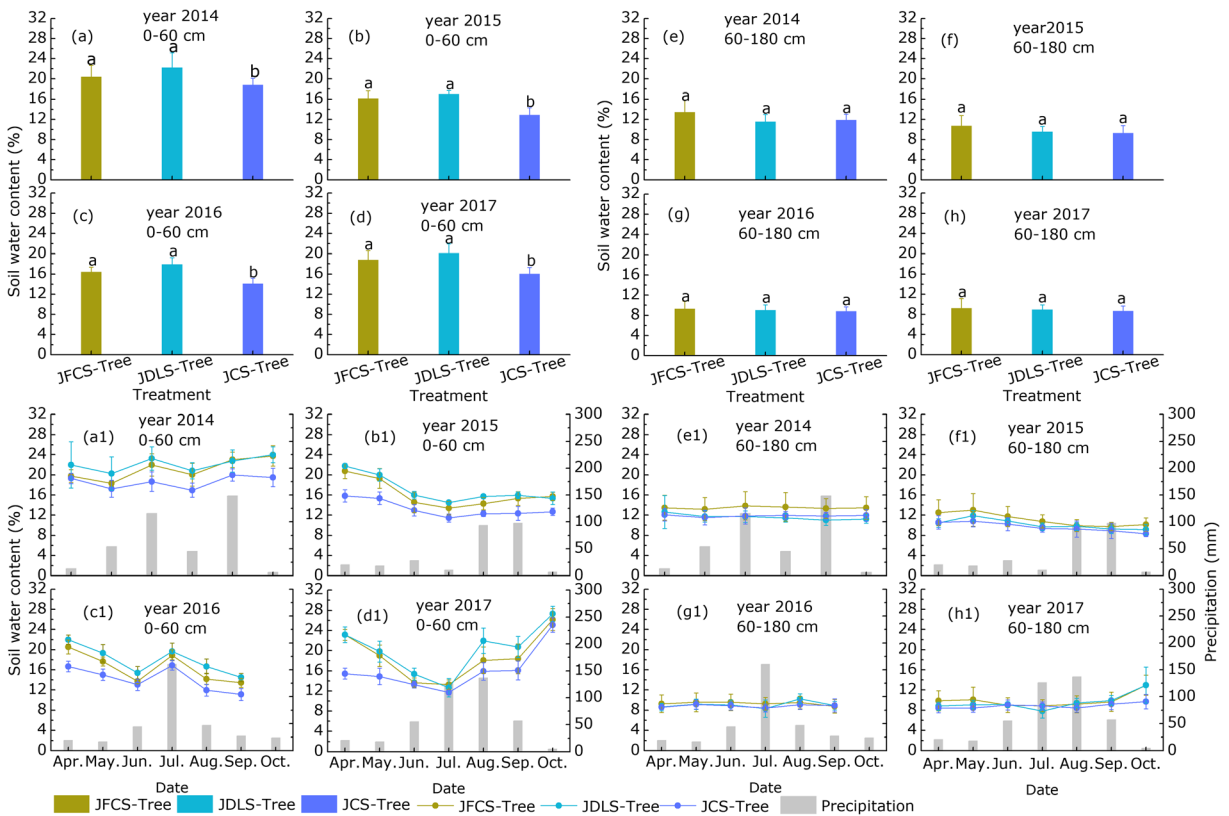
Fig. 4 Average and monthly soil water content changes under jujube trees for every treatment throughout the study period (2014–2017). Different letters represent significantly different values ($p = 0.05$)

Interrelations between soil physical properties, soil water content and fine root at inter-row

At the inter-row, The HC and CP showed a close relationship related to the FRLD of daylily and soil water content at 60–180 cm along the PC1 axis. All the soil physical properties and soil water content at 0–60 cm showed a close correlation with FRLD of tree at 0–60 cm and FRLD of canola along the PC2 axis (Fig. 6b; Table S6). According to the Pearson results (Table 9), the FRLD of trees at 0–60 cm showed a positive correlation with TP and NCP, and a negative correlation with BD. While FRLD of trees at 60–180 cm showed a positive correlation with HC and CP, and a negative correlation with soil water content at 60–180 cm. All the soil physical properties were positively related to the FRLD of canola at 0–60 cm and 60–180 cm, except for that BD was negatively associated with FRLD of canola. The FRLD of daylily at 0–60 cm and 60–180 cm showed a positive correlation with CP and a negative correlation with NCP and soil water content at 60–180 cm. Moreover, the HC and FC were only positively correlated to FRLD of daylily at 0–60 cm. A negative correlation was found between BD and soil water content at 0–60 cm, meantime, FC and CP were negatively correlated to soil water content at 60–180 cm. Besides, HC, FC, and NCP were positively correlated to soil water content at 0–60 cm.

Discussion

Soil physical properties change under tree and inter-row

A favorable soil physical property is essential for a better orchard environment and high-quality production (Palese et al. 2014; Xu and Zhang 2004). At the inter-row, both agroforestry systems considered herein modified the inter-row bulk density, field capacity, saturated hydraulic conductivity, and soil porosity. This conclusion is consistent with Steele et al. (2012) and Schwab et al. (2015), who found that the long-term use
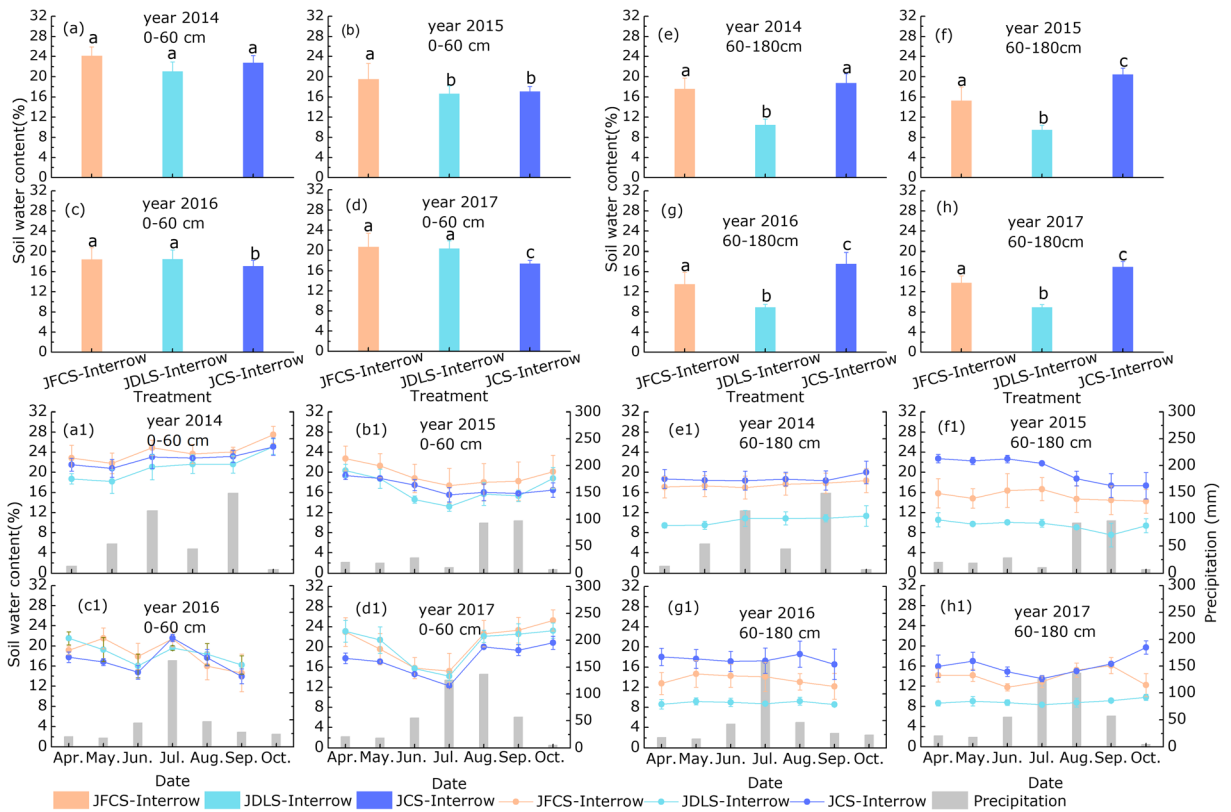
Fig. 5 Average and monthly soil water content changes under inter-rows for every treatment throughout the study period (2014–2017). Different letters represent significantly different values (*p* = 0.05)

of cover crops could change the orchard micro-surface environment, leading to benefits such as reduced soil

bulk density and increased hydraulic conductivity (Sun et al. 2018). Higher soil porosity and field capacity
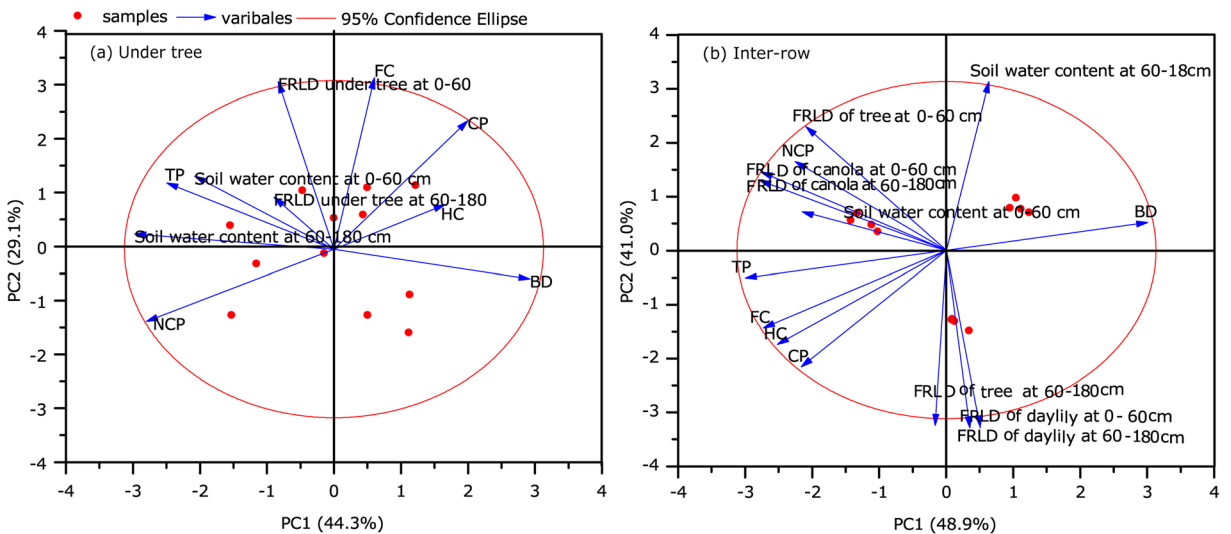

Fig. 6 Results of a principal components analysis based on plot-level data of soil physical properties (0–40 cm), fine root length density and soil water content at 0–60 cm and 60–180 cm under tree (**a**) and between inter-row (**b**) for the three treatments

Table 8 Pearson correlation of linear regressions between the parameter soil physical properties (0–40 cm soil depth), FRLD of tree root at 0–60 cm and 60–180 cm, and soil water content at 0– 60 cm and 60–180 cm under tree in all treatments (The significant values are printed bold)

Variables	FRLD under tree at 0–60 cm	FRLD under tree at 60–180 cm	Soil water content under tree at 0–60 cm	Soil water content under tree at 60–180 cm
Bulk density	−0.23	−0.42	**−0.51**	**−0.85**
Saturated hydraulic conductivity	0.32	0.42	**0.51**	**−0.53**
Field capacity	**0.80**	0.04	0.37	−0.04
Total porosity	**0.55**	0.15	0.3	**0.84**
Capillary porosity	**0.52**	−0.09	**0.53**	**−0.53**
Non-capillary porosity	0.1	0.15	0.35	**0.85**
Soil water content under tree at 0–60 cm	**0.66**	**0.60**	–	**0.73**
Soil water content under tree at 60–180 cm	−0.29	0.38	**0.73**	–

would increase water infiltration, facilitate the faster downward movement of water, and enhance water-holding capacity (Liu et al. 2013; Huang et al. 2016b). Popova et al. (2016) suggested that root systems are able to grow in a heterogeneous soil environment to modify soil properties. In this study, the results suggested that the FRLD of canola at 0–60 cm and 60–180 cm and daylily at 0–60 cm are significant related to soil physical properties (Fig. 6b, Table 9), indicated the role of crop root to modify the soil physical properties (DuPont et al. 2014). The root can be targeted as a natural management tool for soil structural porosity to enhance water holding capacity as well as saturated hydraulic conductivity

(Bodner et al. 2014). Dexter et al. (2001) and Jiang et al. (2018) suggested that roots were directly involved in the improvement of hydraulic behavior and bulk density in field. Compared to JCS-Inter-row, the non-capillary porosity was significantly higher in JFCS-Inter-row, but not in JDLS-Inter-row (Table 7). The modification degree of soil properties may depend on the root traits and quantity, lager and longer root and more concentrated root distribution would get better performance on soil properties (DuPont et al. 2014; Jiang et al. 2018). The FRLD of daylily and tree at inter-row was lower than the FRLD of canola and tree at 0–60 cm. Meantime, the average β value in the JFCS-Inter-row

Table 9 Pearson correlation of linear regressions between the parameter soil physical properties (0–40 cm soil depth), FRLD of tree and crop root at 0–60 cm and 60–180 cm, and soil water content at 0–60 cm and 60–180 cm in the inter-row in all treatments (The significant values are printed bold)

Variables	FRLD under tree at 0–60 cm	FRLD under tree at 60–180 cm	FRLD of canola at 0–60 cm	FRLD of canola at 60–180 cm	FRLD of daylily at 0–60 cm	FRLD of daylily at 60–180 cm	Soil water content under inter-row at 0–60 cm	Soil water content under inter-row at 60–180 cm
Bulk density	**−0.63**	−0.21	**−0.94**	**−0.81**	−0.05	−0.47	**−0.66**	0.34
Saturated hydraulic conductivity	0.21	**0.55**	**0.92**	**0.55**	**0.88**	0.05	**0.77**	−0.49
Field capacity	0.33	−0.17	**0.98**	**0.66**	**0.54**	−0.1	**0.57**	**−0.59**
Total porosity	**0.63**	0.31	**0.91**	**0.81**	−0.25	−0.47	0.16	−0.23
Capillary porosity	0.35	**0.76**	**0.94**	0.43	**0.54**	**0.54**	−0.34	**−0.76**
Non-capillary porosity	**0.7**	0.44	**0.82**	**0.78**	**−0.52**	**−0.53**	**0.72**	0.32
Soil water content under inter-row at 0–60 cm	0.23	0.46	0.43	0.43	−0.15	−0.15	–	0.17
Soil water content under inter-row at 60–180 cm	0.47	**−0.89**	−0.34	−0.39	**−0.88**	**−0.88**	0.17	–

was smaller than in JDLS-Inter-row, suggesting more fine root biomass concentrated in topsoil in the JFCS-Inter-row, which facilitates the formation of more soil porosity (Scanlan 2009; Whalley et al. 2005). This was supported by the Bodner et al. (2014), who indicated species with dense of fine root systems induced heterogenization of the pore space and higher micropore volume. However, Cardinael et al. (2015) found that because of competition with crops, the tree roots tended to concentrate relatively more in deeper soil layers. This phenomenon was also found in JDLS-Inter-row of tree fine root distribution (Fig. 2), which may not favor the formation of more soil porosity at topsoil than JFCS-Inter-row.

In this study, the two agroforestry systems have limited effect on soil bulk density, hydraulic conductivity, total porosity, and non-capillary porosity under tree row, compared to inter-row. This is a difference from Cardinael et al. (2015), who worked on soil organic carbon and found agroforestry only has a noticeable effect on the tree row. This may highlight the importance of characterizing and taking into account spatial heterogeneity of the indicators in the assessment of ecosystem functioning and service provisioning for agroforestry systems. In our experiment, the field capacity under tree were both increased in each agroforestry system compare to JCS (Table 4). This may be because of greater amount of fine root aggregated in soil, which increased the soil porosity and field capacity (Bodner et al. 2014). In our study, The PCA and Pearson analysis suggested that the FRLD of tree at 0–60 cm was correlated with the field capacity and soil capillary porosity, which agree with Bodner et al. (2014)'s result (Fig. 6a, Table 8). However, we found that the soil capillary porosity was only increased in JFCS, not in the JDLS, compared with JCS. This may due to the denser FRLD of tree in JFCS-Tree than JDLS-Tree (Table 3), which induced higher soil porosity (Scanlan 2009; Whalley et al. 2005). Scanlan (2009) suggested that the pore radius reduced via root ingrowth. Dense fine root systems provided intense root-soil contact space, which could enhance soil micropores formation in soil. The increase of soil porosity is conducive to the increase of water holding capacity in the field (Li et al. 2013). This reflected in our conclusion that the field capacity increased higher in JFCS-Tree, compared to JDLS-Tree (Table 4 and S1).

Soil water content response during jujube growth and dormant periods in the four years

The periods of blossoming and young fruit development (Mid-June–Mid-July) and fruit swelling (Mid-July–Mid-September) are the stages of the jujube production cycle that require the most water (Cui et al. 2008; Li et al. 2011; Feng et al. 2017; Han et al. 2012a, b). Favorable soil bulk density and saturated hydraulic conductivity can enhance the rainfall into the soil layers (Steele et al. 2012; Schwab et al. 2015); Subsequently, the higher field capacity and soil porosity could keep more soil water in soil layers (Li et al. 2013; Bilek 2007; Pan et al. 2017). Hence, the tested intercropping systems could be pivotal to alleviating tree water stress during the growth period in semiarid areas (Basche et al. 2016). In this study, most of the rainfall in the Loess Hilly region was concentrated in July to September (About 70% of annual rainfall), with less rainfall from March to June (Fig. 1). There is great potential, during this stage, to store soil water content in the orchard (Palese et al. 2014). The benefit to soil physical properties was found better in the agroforestry systems than the control (Palese et al. 2014; Schwab et al. 2015), and more soil water could be stored in soil (Li et al. 2013; Li et al. 2007). In our study, soil water content in the JDLS-Tree and JFCS-Tree plots during the jujube dormant period was noticeably higher than that in JCS-Tree (Fig. 3a–c). This indicates that significant carryover effects in two agroforestry than control, from the previous year, had a role in determining the soil water content at the start of the growing season (Fig. 3 and S1). This is an important water source for jujube trees, particularly during the early growth period when precipitation is scarce (May-to-June, Fig. 1). Other studies have also shown how the soil water content left over from the previous dormant period is pivotal in determining the growth conditions for the next year's crop (Enloe et al. 2004; Yimam et al. 2014; Palese et al. 2014; Jin et al. 2018). Moreover, soil water content remaining from a normal year could be used in a drought year (Fig. S1-S2).

Testing intercropping species for effective agroforestry systems

In this study, jujube intercropped with two plants, canola and daylily, resulted in significantly more soil water content in the 0–60 cm layer compared to the JCS-Inter-row control in four years, but not in 2014 both in two

agroforestry inter-row and 2015 in JDLS-Inter-row (Fig. 5 and Table S4). This result may be because, in 2014, effective rainfall distribution was more uniform and the average temperature was the lowest among four years, resulting in lower soil evaporation in all treatments (Bai et al. 2018). During the 2015–2017 period, effective rainfall was less, and temperatures were higher. The soil water content from JCS-Inter-row declined more quickly than JFCS-Inter-row and JDLS-Inter-row due to lower infiltration and higher soil evaporation. Since both of these mechanisms were affected by soil physical properties and vegetation cover (de Almeida et al. 2018; Bai et al. 2018), significant differences in soil water content were observed in 2015–2017 between the two agroforestry systems and the control. Islam et al. (2006) suggested that vegetation cover may consume more soil water by crop root water uptake. Perennial and semi-perennial crops are characterized by proportionally more water capture in deep layers than annual crops (Ferchaud et al. 2015), contributed by its deeper rooting in soil depths (Fig. 2 and Table 3). The Pearson analysis also suggested that the FRLD of daylily at 0–60 cm and 60–180 cm and FRLD of tree at 60–180 cm have a negative relationship with soil water content at 0–60 cm and 60–180 cm (Table 9). This result implies that an agroforestry system that includes intercropping with the perennial daylily consumes more water than a system including intercropping with the annual canola (Ferchaud et al. 2015).

In any successful agroforestry system, complementarity in the use of above- and below-ground resources between the tree and the crop must outweigh between-species competition (Cannell et al. 1996). In semiarid regions, soil water content becomes a more crucial factor than light and nutrients, as limited water resources severely affecting crop growth. Planting crops between rows of trees increases surface vegetation cover and creates a new "soil-vegetation-atmosphere" environment that differs from the "soil-atmosphere" environment from a clean cultivation orchard. Moreover, Li et al. (2007) revealed that the ecological suitability of orchard grass is a problem worthy of attention in the context of orchards in northern China. They found that grass should be used cautiously when managing orchards in the Loess Plateau, where annual precipitation can be less than 550 mm. Due to the imbalance between precipitation and the growth and development of vegetation, soil water content variations in orchards depend on grass type and rainfall patterns. Padovan et al. (2018) found the evergreen shadow tree

Simarouba glauca to be more suitable than deciduous *Tabebuia rosea* for intercropping in a coffee plantation due to lower water consumption. The selection of appropriate crop species is essential for the success of an agroforestry system. As mentioned before, grass has a positive effect on soil water content under tree during normal year and drought year (Fig. 3a–c; Fig. S1). While, there is lower soil water content under intercropping area than monoculture, especially in JDLS-Inter-row (Fig. 3d–f; Fig. S2). It is worth reminding that there is a clear trade-off between tree and inter-row species: while jujube gains more soil water content, inter-row species may induce water deficit. This implies agroforestry could be "a sword with two blades" in terms of water use (Li et al. 2007; Padovan et al. 2018).

Conclusions

Soil physical properties, soil water content, and fine root data were analyzed at two agroforestry systems (JFCS and JDLS) and control (JCS) over four rainfall years. This study demonstrated the two agroforestry systems examined influence most of the inter-row soil physical properties (e.g., the soil bulk density, saturated hydraulic conductivity, field capacity, total porosity, capillary porosity and non-capillary porosity (only significant in JFCS-Inter-row)), which attributed to the role of crops fine root. Meantime, the under-tree field capacity and capillary porosity (only significant in JFCS-Tree) were modified. Furthermore, they led to increased soil water content at 0–60 cm under tree, which ultimately reduced the risk of tree damage due to water stress. The JFCS-Inter-row showed a different water absorption strategy compared to JDLS-Inter-row, characterized by the soil water content and fine root distribution between inter-rows. These revealed that the JFCS treatment was more beneficial for improving soil water content than JDLS treatment. Agroforestry is an easy and effective risk avoidance strategy for farmers who may suffer from increased climatic stress and food insecurity. Although agroforestry systems are potentially favorable to reform soil physical properties and water conditions in the semiarid orchard, it needs to pay attention to the excessive consumption of resources (e.g., soil water content) at the crop-tree overlapping area. This implies the importance of selecting relevant cover crops with particular traits when designing the semiarid agroforestry system.

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