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The effects of cocksfoot cover crop on soil water balance, evapotranspiration partitioning, and system production in an apple orchard on the Loess Plateau of China

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ABSTRACT

Cover cropping in orchards has been advocated on the Loess Plateau of China to prevent soil erosion and provide additional forage production; however, the effects of cover crops on water use processes in orchards have not been fully investigated and soil water sustainability in the system is still unclear. This study was conducted to investigate the effects of intercropping cocksfoot (*Dactylis glomerata*L.) and cocksfoot cutting management on soil water balance, evapotranspiration (ET) and its partitioning, and production in an apple orchard (*Malus pumila* M.). Field experiments were conducted at Qingyang experiment station in 2016-2018. The apple trees were at a spacing of 4 m × 4 m, and three soil management patterns were applied: clean tillage (CT), 2.4 m-wide cocksfoot strips set up between tree rows that were harvested with a high frequency (HF), and cocksfoot strips harvested with a low frequency (LF). The results showed that decline in soil water content in the dry season was promoted in the cover crop treatments. In tree interrow positions the soil water depletion was increased only in the 0–100 cm soil layer while in tree row positions the depletion in both the 0–100 and 100–200 cm soil layers was significantly increased ($P < 0.05$). Soil water replenishment in the 200–300 cm soil layer in the rainy season was reduced in the cover crop treatments. Increasing the harvesting frequency of cocksfoot could reduce its negative effects on soil water content in dry periods. The total system ET in LF was 477.7, 441.0 and 540.5 mm in 2016, 2017 and 2018, respectively, which was significantly greater than that in HF and CT in the dry year of 2016 and was comparable with two other treatments in 2017 and 2018. ET under the tree canopy was increased after sowing cocksfoot, but large amounts of water were saved by converting soil evaporation to cocksfoot transpiration. Sowing cocksfoot did not exert a significant negative effect on apple production in any of the three years ($P > 0.05$), and 2.07–6.32 t ha^{-1} additional forage biomass was produced. Cocksfoot with greater harvesting frequency is suggested to be applied to conserve soil and water in apple orchards in our study area.

1. Introduction

The Loess Plateau is one of the major apple production areas in China due to its preferable climate conditions such as abundant sunshine and large temperature ranges (Liu et al., 2013). Owing to the government policy support and benign market environment, the planting area of apple trees (*Malus pumila* M.) in this area increased rapidly during the last ten years (Zheng et al., 2017). According to a field questionnaire, tillage has been applied in the majority of apple orchards as a soil management method for decades (Wang et al., 2017a). Some studies showed that intensive soil tillage practices led to water and nutrient loss and decreased soil quality and productivity (Liu et al., 2013; Ling et al., 2017). Therefore, it is important to seek a proper soil management strategy to promote the sustainable development of apple orchards.

Cover crops are widely used in fruit orchard management worldwide and have been proven to be a potential way to increase biodiversity, control weeds and soil erosion, enhance soil organic matter and enzyme activities, and provide additional biomass production (Celette and Gary, 2013; Loewe et al., 2013; Uliarte et al., 2013; Meyer et al., 2015). The effects of cover crops on soil water content and the yield of the fruit depend on many factors such as cover crop species, weather conditions, orchard age, and canopy structure. Some studies indicated that vegetation in orchards could significantly increase infiltration and decrease soil and water loss. For example, Hernández et al. (2005) reported that the subterranean clover (*Trifolium repens* L.) cover in olive

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orchards was a beneficial way of conserving more available soil water, and did not compete or scarcely competed for soil water with the trees. Palese et al. (2014) also found that the spontaneous weeds vegetation covers in olive orchards located in southern Italy promoted infiltration of the precipitation and increased the water content of the deep soil layer, compared with the clean tillage. Bai et al. (2016) demonstrated the positive effect of sowing grain crops on soil water conditions in an apricot orchard in northeast China. However, Ramos et al. (2010) found that cover crops improved soil quality but extracted more water and reduced the orchard development and productivity. Licznar-Malanczuk (2015) also reported that blue fescue (*Festuca ovina* L.) competed for resources and resulted in the reduced growth and yield of apple trees. Water resources are limited and yearly precipitation is variable on the Loess Plateau of China (Wang et al., 2020), and farmers' apprehension over water competition and apple yield loss was the main reason that had limited the introduction of this soil management strategy (Wang et al., 2017a). Regarding research studies, Fang et al. (2016) showed that cover crops reduced soil moisture and fruit yield in a 5-year-old apple orchard, and Ling et al. (2017) showed that cover crops in a jujube orchard increased soil water content under the tree row, while it was decreased in the interrow. The studies addressing the effects of cover crops on soil water balance in fruit orchards are still lacking. As we know that the rooting depth of cover crops is usually much shallower than that of fruit trees, the main water uptake regions of the two species diverge in a vertical direction (Celette et al., 2010). Additionally, interspecific interaction in agroforestry could be alleviated by adjusting the distances between the cover crop and tree row (Zhang et al., 2014; Wang et al., 2017b; Delpuech and Metay, 2018). Therefore, interspecies water competition in the intercropped orchards could be alleviated and the system production could be increased by rational management of cover crops. Timely harvesting of cover crop is an efficient way to control growth and water use of cover crops, however, how the soil water balance and water use in the orchard are affected by cover crop harvesting management is still not clear.

The assessment of competition or complementarity in water use in the intercropped orchards could be facilitated by evapotranspiration (ET) quantification and partitioning (Padovan et al., 2018). The loss of water from the soil surface through evaporation is a major component in the soil water balance of the agricultural systems, and this is particularly the case for sparse canopies (Wang et al., 2015). Full ground cover was usually hardly achieved in young and just matured fruit orchards in a semiarid environment (Wang et al., 2019), which resulted in a large amount of water loss through soil evaporation. Cover crop between tree rows could reduce soil evaporation, but it may also increase water loss under the tree canopy through water consumption of cover crop (Ling et al., 2017). The reduction in evaporation rate in the shade was demonstrated in a subhumid climate in Kenya in which soil evaporation in agroforestry was reduced by 35% when compared to bare soil (Wallace et al., 1999). In a Mediterranean vineyard, compared to soil tillage, the two treatments with cover crop showed a higher water use, primarily during the spring (Monteiro and Lopes, 2007). Huang et al. (2014) reported that vegetation cover reduced soil evaporation and increased infiltration water, but the transpiration part might offset the evaporation reduction and infiltration increase. Terminating the cover crop at an appropriate time is an alternative for reducing water use and minimizing its negative effects on tree growth. For example, Centinari et al. (2013) compared soil evaporation versus tall fescue (*Festuca arundinacea*) ET within a vineyard ecosystem and confirmed that increasing the cutting frequency had a reducing effect on the cover crop ET, but the effect decreased over time after cutting. Quantification of water partitioning and its response to rainfall availability and cover crop management are essential for optimizing the design of fruit tree and cover crop agroforestry systems in semi-arid environments, but there are few studies on this issue.

Therefore, the objectives of this study were to (1) investigate the effect of cocksfoot cover crop on the soil water dynamics and water balance in different soil layers in the interrow and tree row in apple orchards; (2) determine the total system ET, ET under apple tree canopy, and transpiration of apple trees in the apple orchard with different soil management treatments; and (3) compare the apple production in the orchard with and without cocksfoot cover crop and quantify the biomass production of cocksfoot under different harvesting frequencies.

2. Materials and methods

2.1. Site description

The field experiments were carried out during the growing season in 2016-2018 in the apple orchard at the Qingyang Experimental Station of Lanzhou University (35°40´N, 107°51´E, with an altitude of 1297 m), which is located in the Gansu Province of China and at the central part of the Loess Plateau. The site is in a semiarid zone with a mean annual temperature of 9.2 °C, mean annual precipitation of 527.6 mm, and average annual sunshine duration of 2415 h. Soil at the site is silty loam. The particle size distribution, bulk density, field water capacity, and organic carbon content of soil in different soil layers measured at the beginning of the experiment are listed in Table 1.

2.2. Experimental design

The apple trees (*Malus pumila* M. cv Qingguan) were planted in North-South orientated rows in 2005, with both row and within row distances of 4.0 m. The tree crowns at full growth were between 3.0 and 3.6 m in height and between 3.2 and 4.1 m in width in 2016. Three plots with an area of 480 m^2 (including six 20 m-long tree rows) were built in the orchard to implement different soil management treatments. The soil management treatments were (1) no cover crop with clean tillage (CT), (2) cover crop of cocksfoot (*Dactylis glomerata* L.) that was harvested with a high frequency (HF, 4-6 times during the apple tree growth season), and (3) cover crop of cocksfoot with a low harvesting frequency (LF, 2-4 times during the apple tree growth season). Fig. 1 shows the plots with and without cocksfoot cover crop.

Fertilizer was applied for apple trees, and all three treatments received the same amount of fertilizer. At the flowering stage of apple trees in each season, both sides of the tree row received 250 kg N ha^{-1} and 120 kg P ha^{-1}. In the clean tillage treatment, the soil was tilled in early April, and weeds were manually controlled approximately every two months during the growing season with a hoe, herbicides were not used. In the cover crop treatments, cocksfoot was sown on the interrows in July 2014 with a strip width of 240 cm. The distance from the strip border to the tree trunk was 80 cm. The sowing dose of cocksfoot was

Table 1
Particle size distribution, bulk density, field water capacity, and organic carbon content of the soil in different layers measured at the beginning of the experiment.

Soil layer (cm)	Particle size distribution (%)			Bulk density (g cm^{-3})	Field water capacity (%)	Organic carbon content(g kg^{-1})
	Sand	Silt	Clay			
0-10	15.4	77.0	7.6	1.39 ± 0.04	28.03 ± 0.34	6.08 ± 0.45
10-20	18.5	73.8	7.7	1.47 ± 0.08	27.82 ± 0.22	6.03 ± 0.44
20-40	15.7	75.6	8.7	1.38 ± 0.06	28.42 ± 0.31	5.04 ± 1.02
40-60	11.8	79.4	8.8	1.36 ± 0.04	30.04 ± 0.32	3.61 ± 0.65
60–80	12.9	78.6	8.5	1.35 ± 0.09	31.63 ± 0.45	4.72 ± 0.72
80–100	12.9	80.5	6.6	1.43 ± 0.12	28.82 ± 0.12	3.04 ± 0.22
100-150	13.8	78.0	8.2	1.39 ± 0.06	29. 78 ± 0.04	2.01 ± 0.35
150–200	15.8	77.0	7.2	1.43 ± 0.05	28.68 ± 0.41	1.48 ± 0.46
200-250	15.6	77.4	7.0	1.38 ± 0.03	29.43 ± 0.32	1.29 ± 0.55
250-300	15.2	76.8	8.0	1.39 ± 0.05	29.32 ± 0.31	0.78 ± 0.07

Note: Values are presented as the mean ± S.E. (n = 4).

Fig. 1. The two different soil management treatments in this study (a shows the cocksfoot cover crop treatment, and b shows the clean tillage that is widely adopted by local farmers).

Table 2
The harvesting dates of cocksfoot under two different harvesting frequencies in 2016-2018.

Year	2016		2017		2018	
Treatment	High Frequency	Low frequency	High Frequency	Low frequency	High Frequency	Low frequency
Harvesting date	May 1	June 3	May 12	June 30	April 28	May 15
	June 15	July 31	June 30	October 27	June 6	July 7
	July 9	October 29	August 10		July 7	August 29
	August 22		October 27		August 3	October 26
	October 29				September 28	
					October 26	

15 kg·ha^{-1}. The stubble height was approximately 3-5 cm after each harvesting. Table 2 summarizes the cocksfoot harvesting dates under the two treatments.

2.3. Measurements and calculations

2.3.1. Soil water content

Considering the uneven size of apple trees, we recorded the bottom trunk diameter distribution of the apple trees at the beginning of the experiment and found apple trees in our plots had a bottom trunk diameter of 19.8 ± 2.5 cm (mean ± standard deviation). Three representative apple trees (bottom trunk diameter around 20 cm) were selected in each plot for the soil water content measurements. The seasonal dynamics of soil water content in the 0–160 cm soil profile were measured with a Diviner 2000 monitoring system (Sentek Pty Ltd., Australia) at 3–5-day intervals. Under each selected tree, four sensor access tubes were settled, namely, at two positions of 100 cm and 200 cm from the tree trunk on the north (the tree row) and west (the interrow, located on the cocksfoot strips) directions, respectively, as shown in Fig. 2. The soil water content measuring positions in the CT plot were the same as those in the cocksfoot cover crop treatments.

At the beginning and the end of the apple tree growing season, the soil water content in the 0-300 cm soil profile was sampled with an auger (inner diameter of 40 mm) at depth intervals of 10 cm and was measured by the oven-drying method. Four samples were also taken under each tree, the sampling points corresponded with those measuring points of Diviner 2000. The gravimetric soil water content was converted to volumetric soil water content by multiplying by the bulk density.

2.3.2. System ET

System ET in both the cocksfoot cover crop treatments and the clean tillage treatment was estimated by calculating the water balance in the 0–300 cm soil layer:

$$ET = P + \Delta S - R + CR - DP \qquad (1)$$

where P is precipitation (mm); ΔS, the decrease in soil water stored in the 0–300 cm soil layer from the beginning to the end of each season (mm); R, the runoff (mm), which was neglected because the experimental site has a flat topography; CR, the capillary rise of water into the evaluated soil layer, which was also neglected since the underground water at the site was below 50 m and soil water content below 300 cm is usually lower than that in the root zone;and DP, soil water percolation through the bottom of the evaluated soil cores (this item was also neglected in our calculation since we observed in the previous study that rainfall water rarely infiltrated to the depth of 300 cm in our study area) (Shen et al., 2009).

2.3.3. ET under the tree canopy

The ET under the tree canopy includes soil evaporation under the tree row and the ET of cocksfoot strips in the interrows in the cocksfoot cover crop treatments, while that in the clean tillage treatment is only soil evaporation. Microlysimeters (MLs) were used to measure soil evaporation and cocksfoot ET (Centinari et al., 2013; Wang et al., 2015). A type I lysimeter for measuring soil evaporation was constructed using a polyvinyl chloride (PVC) tube with a depth of 15 cm and an inside diameter of 11 cm. A type II lysimeter for measuring cover crop ET was constructed using a steel tube with a depth of 30 cm and an inside diameter of 25 cm. The three representative apple trees selected for measuring soil water content and analyzing soil water balance were also used for installing lysimeters. In the cocksfoot cover crop treatments, two type I lysimeters were placed on the tree rows, and four type II lysimeters were placed on the cocksfoot strips, as shown in Fig. 2. Six type I lysimeters were set up in the clean tillage treatment at the same positions as in the cocksfoot cover crop treatments. Lysimeters were slowly hammered (a buffer is needed to prevent damage to the lysimeter) into the field to be filled with undisturbed soil and then put into a larger steel tube that was installed previously in the designed position. To keep the soil moisture within the microlysimeters similar to the surrounding soil, the soil in the microlysimeters was replaced every five days or immediately after rainfall (Zhao et al., 2015; Padovan et al., 2018). The daily soil evaporation was calculated from the weight loss of the lysimeters at approximately 8:00 local time every day by using an electronic scale with a precision of 0.1 g. The weighted means of soil evaporation on the tree row and cocksfoot ET on the cover crop strip

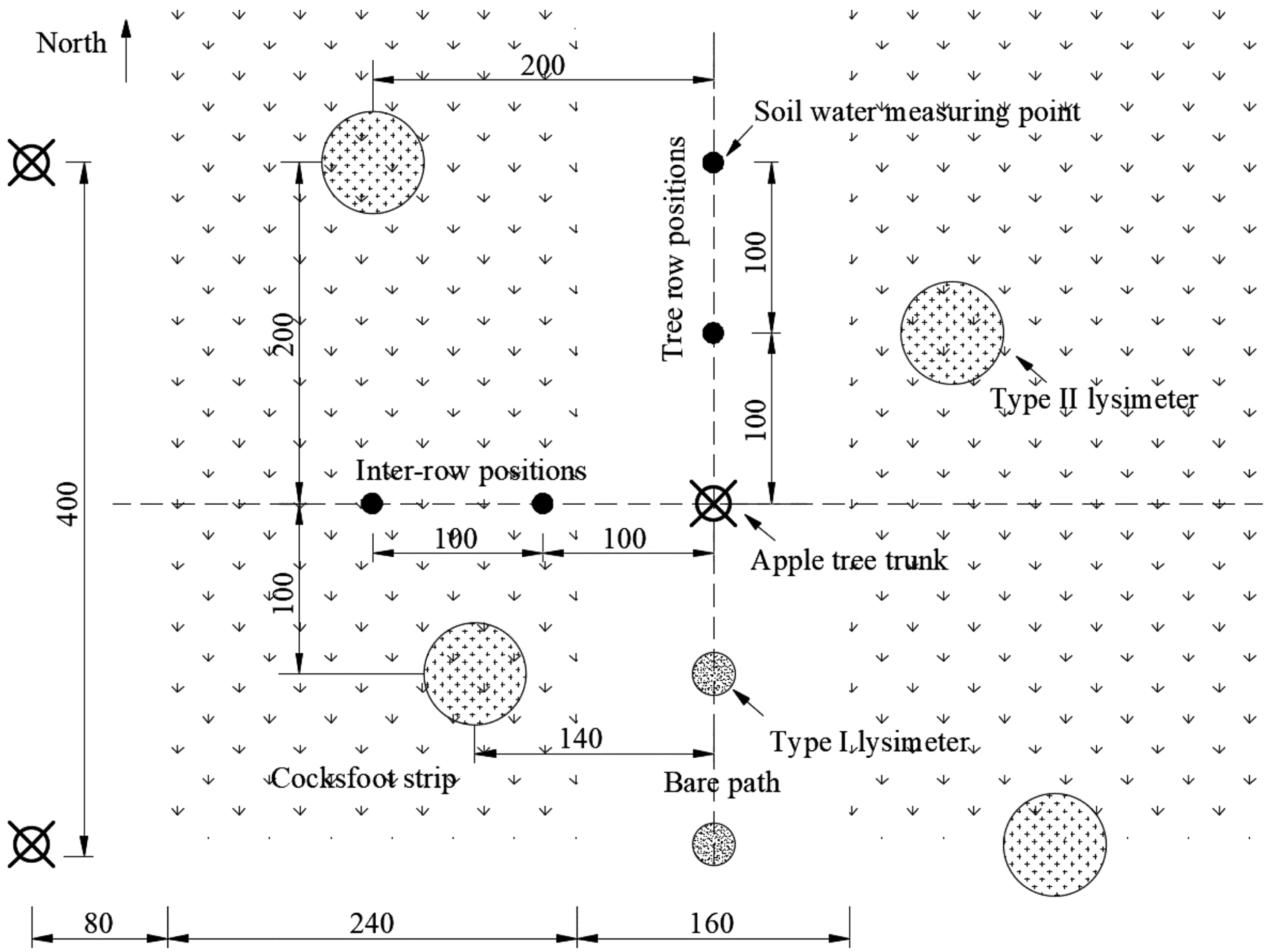

Fig. 2. Distribution of the points for soil water measurements and the positions of the microlysimeters (type I and II lysimeters are used to measure soil evaporation and cocksfoot ET, respectively) under the cocksfoot cover crop and clean tillage treatments (unit of length is cm).

were used to represent the ET under the tree canopy in the cover crop treatments, and the weighted average soil evaporation in tree row and interrow was used to represent the ET under the tree canopy in the clean tillage treatment.

Some lysimeter measurements on rainfall days or days right after heavy rainfall events were missed. The missed data accounted for 29.9%, 40.7%, and 39.3% of the total dataset, they were estimated with the Penman-Monteith method (Monteith, 1965). The understory vapor pressure deficit and the wind function were assumed to be negligibly small (Ritchie, 1972), so the simplified Penman-Monteith equation was used:

$$\lambda ET_{under} = R_{ns}\frac{\Delta}{\Delta + \gamma} \tag{2}$$

where ET_{under} is the ET under the tree canopy (mm day^{-1}); R_{ns}, the net radiation transmitted through the tree canopy (MJ m^{-2} day^{-1}); Δ, the slope of the saturation water vapor pressure vs the temperature curve (kPa °C^{-1}); and γ, the psychrometric constant (kPa °C^{-1}). The transmitted radiation was estimated with the model developed by Wang et al. (2019).

The transpiration of apple trees was obtained by subtracting ET under the tree canopy from the total system ET calculated with the soil water balance method.

2.3.4. Apple and cocksfoot production

Cocksfoot was sampled before each harvesting with a quadrat of 1.0 × 1.0 m^2. Five randomized samples were taken in every cocksfoot cover crop treatment, and plant samples were dried to constant weight at 75 °C to give the aboveground dry matter production. All of the apples on six trees in the different treatments were collected and weighed, and the yield of trees was averaged to obtain the final yield of each treatment.

2.3.5. Weather parameter

Meteorological data (air temperature, relative humidity, wind speed at 2 m height, solar irradiance and precipitation) were recorded half-hourly at the onsite agriculture meteorological station (Vantage Pro2, Davis Instruments, Hayward, CA, USA).

2.4. Statistical analysis

Experimental data were analyzed using SPSS 20.0. One-way analysis of variance (ANOVA) was performed to determine the difference between the measured parameters for different treatments. The least significant difference (LSD) at $P = 0.05$ was used to elucidate any significant differences.

3. Results

3.1. Weather conditions

Fig. 3 presents the monthly air temperature and precipitation during the apple tree growing seasons in the three years compared with the long-term values (1961–2015). The monthly air temperature basically changed with a single-peak curve. The values during the growing seasons from April to October in the three years were apparently greater

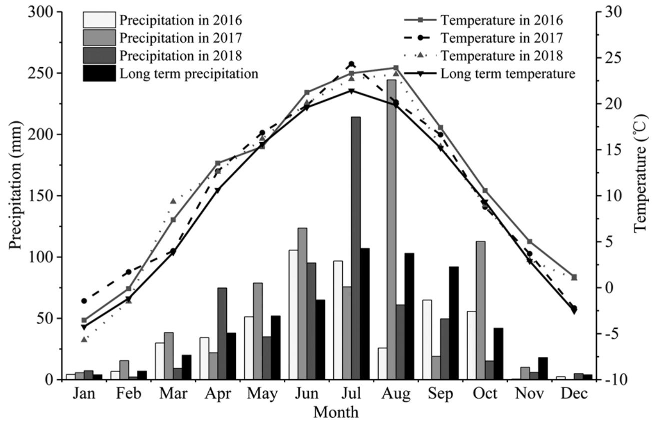

Fig. 3. Monthly air temperature and precipitation in 2016, 2017 and 2018 compared with the long-term values at the experimental site (1961–2015).

than the long-term values. The annual precipitation in 2016, 2017, and 2018 was 478, 746, and 574 mm, respectively, with 400, 617 and 526 mm distributed over the growing season. The rainfall distribution in 2016 was consistent with the long-term average, but the amount of rainfall in the rainy season was far less than the long-term average, so 2016 was deemed as a dry year. The total amount of rainfall in 2017 was very abundant due to rainfall in August and October, which was as much as two-fold higher than the long-term value. So 2017 was deemed as a wet year. Rainfall in July 2018 was extremely high, but in the next three months, it was less than the long-term values. The total amount of rainfall was close to the long-term value, so 2018 was deemed as a normal year.

3.2. Apple and cocksfoot yield

Fresh fruit yields of apples and the aboveground dry matter yield of cocksfoot in the three experimental years are shown in Table 3. Apple yield in 2018 was largely reduced by freeze damage in the flowering stage of apple trees. Averaging over different soil management treatments, the final fresh fruit yield of apples ranged between 57.3-59.3, 45.0-45.5 and 18.8-22.0 t ha^{-1} in 2016, 2017 and 2018, respectively, and no significant difference was found among different treatments in all three years. Five and three harvestings of cocksfoot were applied under HF and LF in 2016 and the total dry matter yield were 6.32 and 5.67 t ha^{-1}, respectively. Four and two harvestings were applied in 2017 with the total yield of 3.02 and 2.07 t ha^{-1} and five and three harvestings were applied in 2018 with the total yield of 4.34 and 4.47 t ha^{-1}. The dry matter yield of cocksfoot under HF was significantly greater than that under LF in 2016 and 2017, but no significant difference was found in 2018.

3.3. Soil water storage dynamics in the 0–160 cm soil layer

Soil water content measured with the Diviner 2000 sensor was used to show the effects of cover crop and its harvesting frequency on temporal soil water storage dynamics in the 0–160 cm soil layer in the orchard during apple tree growing seasons under different rainfall patterns. The average soil water storage in the tree row and interrow was analyzed (Fig. 4). We can see that there were two apparent drying periods in 2016. Soil water storage in the cocksfoot cover crop treatments was depleted more than in the CT treatment. Soil water storage in the 0–80 cm soil layer decreased by 22.0% and 18.3% from the beginning to the end of the season under LF and HF, respectively, whereas the decrease was only 8.0% under CT. In the 80–160 cm soil layer, the soil water storage decreased by 9.4%, 10.8% and 8.9% under LF, HF and CT, respectively. The average soil water storage over the whole season for the 0–80 cm soil layer under LF and HF was 11.9% and 6.5% lower than that under CT, respectively, and it was 5.5% and 1.1% lower than under CT in the 80–160 cm soil layer. Soil water storage dynamics in 2018 showed a similar trend as that in 2016 except that much more rainfall occurred in the mid-season and the soil water storage was well recharged. However, a sharp decrease in soil water storage occurred in the late season due to limited rainfall. Soil water storage in the 0–80 cm layer decreased by 31.2%, 25.2% and 19.6% from the beginning to the end of the growing season under LF, HF and CT, respectively, and decreased by only 1.8%, 7.8% and 3.0% in the 80–160 cm layer. The average soil water storage under LF and HF was 10.8% and 3.7% lower, respectively, than that under CT in the 0–80 cm soil layer, and was 5.9% and 1.3% lower than that under CT in the 80–160 cm layer.

At the beginning of 2017, the soil water storage in the LF treatment was lower than the other two treatments. Limited rainfall occurred from April through mid-August, and the soil water storage maintained low values in this period, especially under LF. Soil water storage was substantially recharged by several heavy rainfalls during the late season. Soil water storage in the 0–80 cm soil layer increased by 33.0%, 21.0% and 21.9% from the beginning to the end of the season under LF, HF and CT, respectively, and it increased by 27.3%, 25.7% and 16.0% in the 80–160 cm soil layer. The seasonal average soil water storage in the 0–80 cm soil layer under LF and HF was 12.0% and 6.2% lower than that under CT, respectively, while it was 9.8% and 3.0% lower than that in CT in the 80–160 cm soil layer.

Table 3
Fresh fruit yield of apples and aboveground dry matter yield of cocksfoot. The yield of cocksfoot was calculated based on the land area occupied by both the cocksfoot strip and the bare path.

Year	Treatment	Apple yield (t ha^{-1})	Cocksfoot yield (t ha^{-1})						
			1st cutting	2nd cutting	3rd cutting	4th cutting	5th cutting	6th cutting	Total
2016	LF	57.3 a	2.36	2.09	1.23				5.67 b
	HF	57.7 a	1.33	1.62	0.90	1.31	1.17		6.32 a
	CT	59.3 a							
2017	LF	45.5 a	0.57	1.50					2.07 b
	HF	45.1 a	0.95	0.82	0.59	0.66			3.02 a
	CT	45.0 a							
2018	LF	22.0 a	1.46	0.74	1.32	0.95			4.47 a
	HF	18.8 a	0.50	1.00	0.63	0.95	1.02	0.25	4.34 a
	CT	20.9 a							
Year (Y)		< 0.001							< 0.001
Treatment (T)		0.980							0.809
Y × T		0.994							0.889

Note. LF: cocksfoot was harvested with a low frequency; HF: cocksfoot was harvested with a high frequency; CT: clean tillage. Means with the same letter are not significantly different at the 0.05 significance level in the growing season of each year.

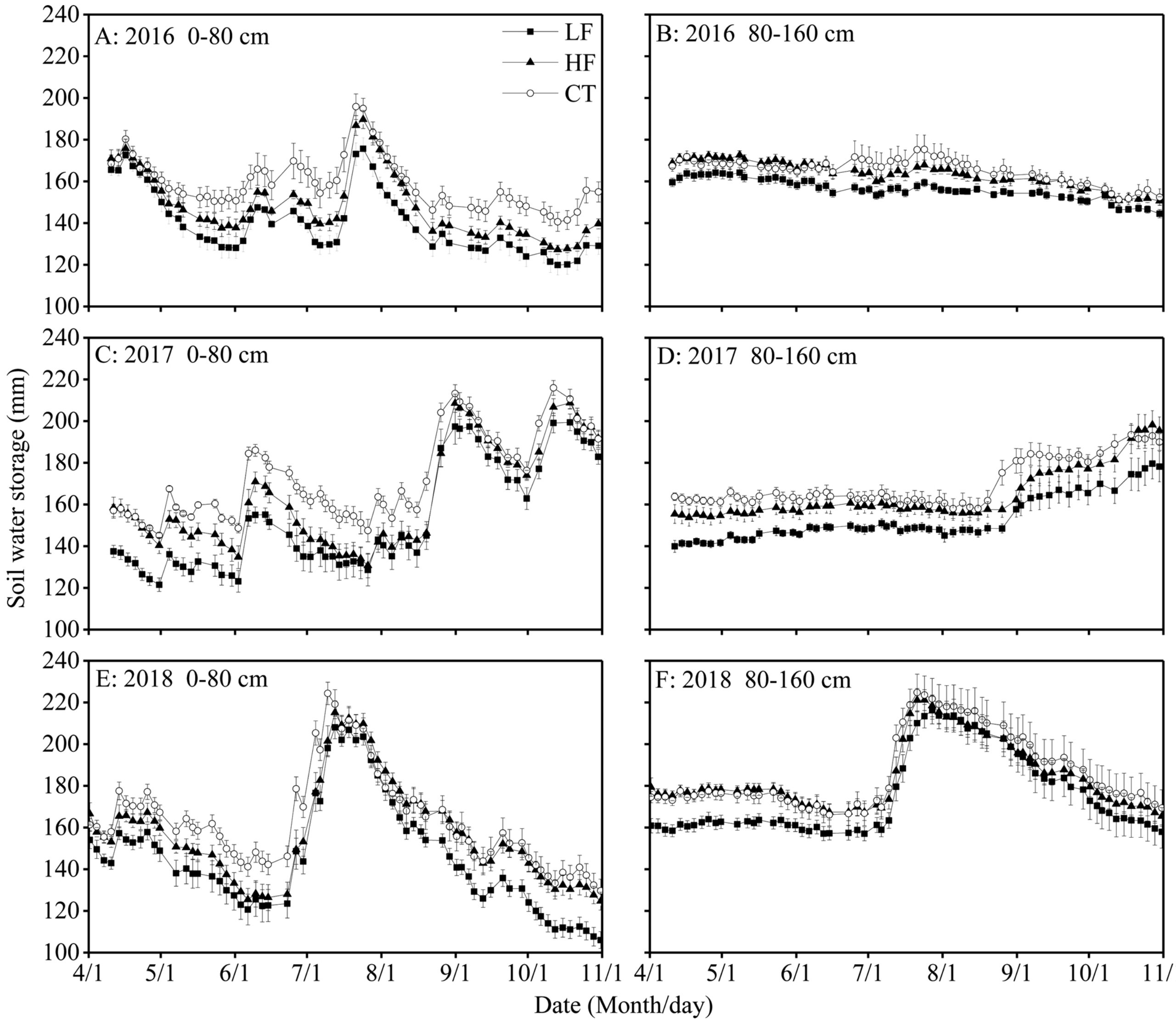

Fig. 4. Temporal dynamics of the average soil water storage in the 0-160 cm soil layers under the cocksfoot cover crop and clean tillage treatments in 2016-2018. LF: cocksfoot cover crop harvested with a low frequency; HF: cocksfoot cover crop harvested with a high frequency; CT: clean tillage. Error bars represent the standard error of the mean.

3.4. Soil water balance in the 0-300 cm soil layer

The soil water depletion in the 0–100, 100–200 and 200–300 cm soil layers from the beginning to the end of the apple tree growing seasons are shown in Fig. 5. In 2016, soil water storage in all layers was depleted, and the amount of depletion decreased as the depth of soil layer increased. In the 0–100 cm soil layer at the tree interrow, soil water depletion under LF was significantly greater than that under HF, and that under HF was significantly greater than that under CT; however, the differences in soil water depletion in the 100–200 and 200–300 cm soil layers were not significant among the three treatments. In the 0–100 cm soil layer at the tree row, soil water depletion was also the greatest under LF, but that under HF was comparable to that under CT. Different with that in the interrow, in the tree row, the water depletion in the 100–200 cm soil layer significantly increased under the cover crop treatments. The depletion in the 200–300 cm soil layer in the three treatments was at a similar level; however, we should note that the soil water depletion was higher in the tree row than in the interrow.

Soil water storage in the 0–200 cm soil layer was largely replenished in all of the treatments in 2017. Soil water replenishment in the 0–100 cm layer was not significantly different among the three treatments in both the tree row and the interrow. In the 100–200 cm layer, soil water replenishment was also not significantly different in the interrow, but it was significantly lower in LF in the tree rows. In the 200–300 cm soil layer at the interrow, soil water replenishment under CT was the greatest, but it was not significantly greater than that in other two treatments ($P > 0.05$). In the tree row, soil water storage of 10.1 mm was replenished under CT, but a depletion of 6.6 and 7.8 mm occurred under LF and HF, respectively.

Soil water in the 0–100 cm soil layer was depleted but that in the layers below was replenished for the three treatments in 2018. In the interrow, soil water depletion in the 0–100 cm soil layer under LF was significantly higher than that under HF and CT. A small amount of soil water replenishment occurred in the 100–300 cm soil layer, and no significant difference was found among the three treatments. In the tree row, soil water depletion in the 0–100 cm soil layer was at the same level in the three treatments. Additionally, soil water replenishment in the 100–300 cm soil layer of the three treatments showed no significant difference.

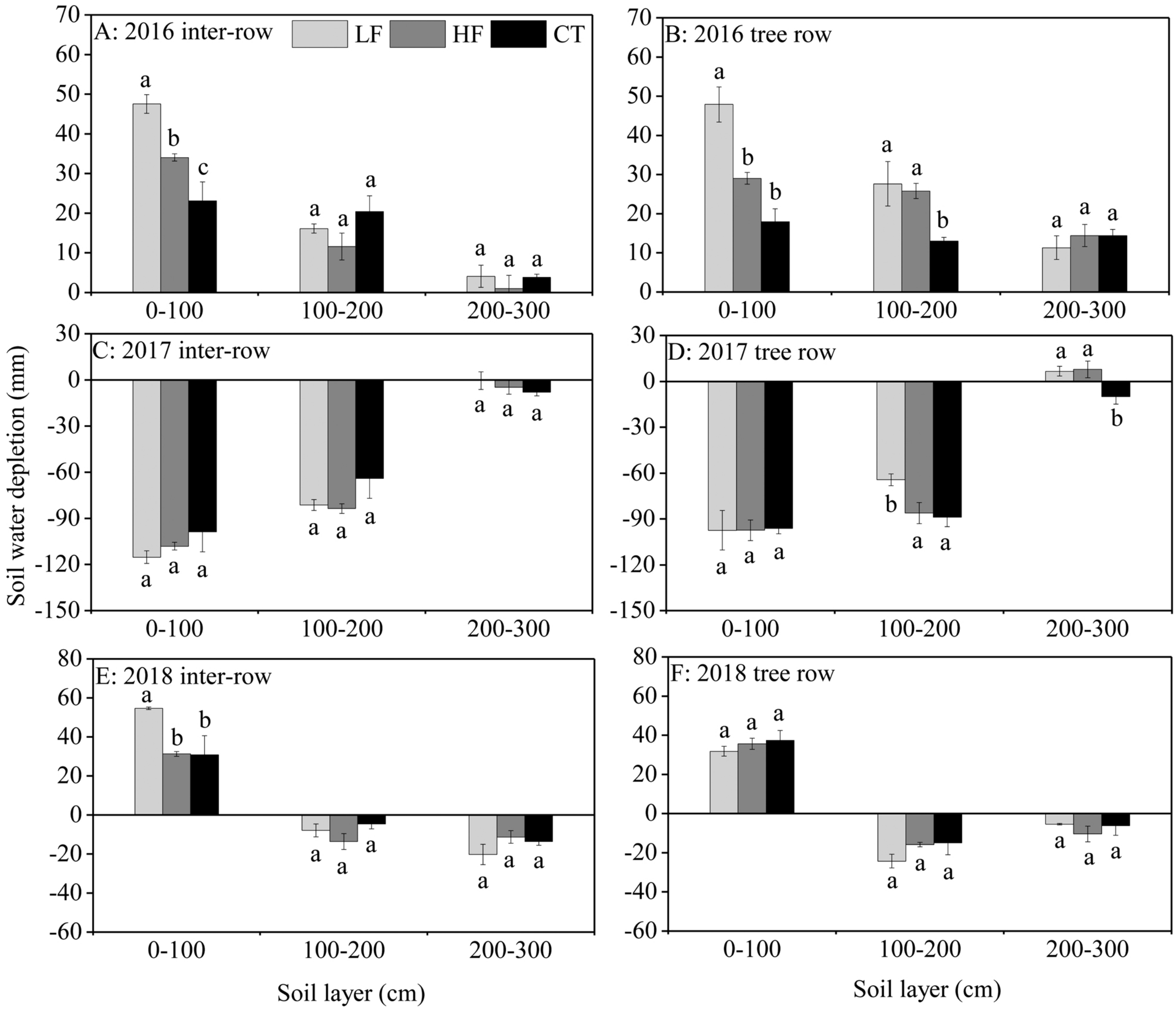

Fig. 5. Soil water depletion in the 0–100, 100–200 and 200–300 cm soil layers in the interrows (A, C and E) and tree rows (B, D and F) under different soil management treatments from the beginning to the end of the growing seasons in 2016-2018. LF: cocksfoot cover crop harvested with a low frequency; HF: cocksfoot cover crop harvested with a high frequency; CT: clean tillage. Error bars represent the standard error of the mean. Means with the same letter are not significantly different at the 0.05 significance level.

3.5. ET under tree canopy

Fig. 6 shows the daily dynamics of the ET under tree canopy (ET_{under}) in different treatments in three representative periods with different canopy characteristics in 2016. The ET_{under} in LF and HF was the weighted average of the cocksfoot ET and soil evaporation on the tree row, and that in the CT was the weighted average soil evaporation in tree row and interrow. In mid-April, LAI_{tree} is very low, so the ET_{under} was the main source of the system ET in the orchard. During the period after a rainfall of 21.2 mm, ET_{under} in the CT decreased quickly to a steady value of approximately 1.0 mm day^{-1}, while that under LF and HF decreased more slowly and was significantly greater than that in CT on most of the days after rainfall (Fig. 6A). Cocksfoot in the HF was firstly harvested in early May, while that under LF still maintained a high LAI. After harvesting, the ET_{under} under HF was reduced compared with that under LF. Although the difference between HF and LF was significant only on two days, the total difference was as high as 25.2% in the 15 days (Fig. 6B). In mid-July, the soil was wet and the evaporation power was relatively high, although LF and HF had very distinct LAI, their ET_{under} values were not significantly different (Fig. 6C). The apple tree reached its maximum LAI at this time, potential evaporation decreased, and the surface soil layer maintained a high water content for a longer time, so the ET_{under} under CT was also maintained at a relatively great value, which was only 8.1% less than that under LF during this period.

3.6. System ET and ET partitioning

Total system ET, ET under the apple tree canopy (ET_{under}) and the transpiration of apple trees in different soil management treatments are presented in Table 4. The total system ET under LF was 477.7, 441.0 and 540.5 mm in 2016, 2017 and 2018, respectively. In the dry season of 2016, ET in LF was significantly greater than that in HF and CT ($P < 0.05$), while in 2017 and 2018, the ET values from the three treatments were comparable with each other. ET_{under} in the CT treatment was 241.3, 246.8, and 279.6 mm in 2016, 2017 and 2018, respectively, which accounted for 54.0%, 56.9% and 51.7% of the total system ET, while in the cocksfoot cover crop treatments, ET_{under} in the tree rows only accounted for 16.9%-21.5% of the total system ET. ET_{under} in the orchard was increased after sowing cocksfoot; under LF, it was 19.1%, 6.4% and 11.4% greater than that under CT in 2016, 2017 and 2018, respectively, and under HF, it was 11.8%, 2.3% and 9.0%

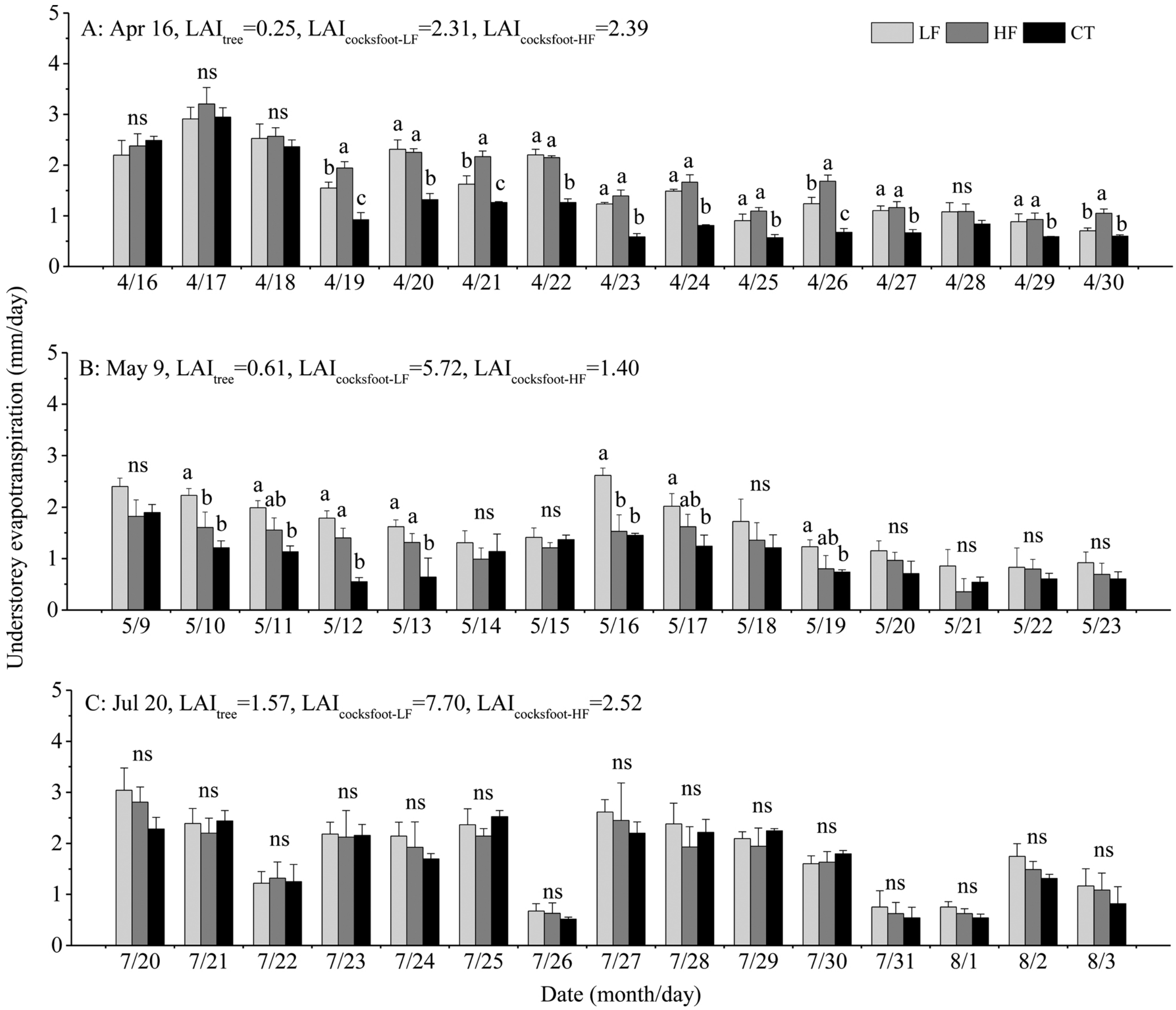

Fig. 6. Comparison of ET under tree canopy among three soil management treatments during three typical periods. The ET under tree canopy in CT was the weighted average soil evaporation in tree row and interrow, and that in LF and HF was the weighted average of the cocksfoot ET and bare path soil evaporation. LF: cocksfoot cover crop harvested with a low frequency; HF: cocksfoot cover crop harvested with a high frequency; CT: clean tillage. Error bars represent the standard error of the mean. Different letters indicate significant difference between treatments at 0.05 levels. The ns represents no significant difference.

Table 4
Comparison of the total system ET, ET under the tree canopy (ET_{under}), and transpiration of apple trees among different soil management treatments in 2016-2018.

Year	Treatment	Total system ET (mm)	ET_{under} in interrows (mm)	ET_{under} in tree rows (mm)	Transpiration of apple trees (mm)
2016	LF	477.7 a	206.7 a	80.8 b	190.2 a
	HF	458.3 b	185.0 b	84.7 b	188.6 a
	CT	446.8 b	144.5 c	96.8 a	205.4 a
2017	LF	441.0 a	170.2 a	92.4 b	178.3 a
	HF	430.9 a	159.8 b	92.6 b	178.5 a
	CT	434.0 a	150.6 b	96.2 a	187.2 a
2018	LF	540.5 a	205.4 a	106.2 a	228.9 b
	HF	534.1 a	195.4 a	109.3 a	229.3 b
	CT	540.6 a	168.5 b	111.2 a	261.0 a

Note: means with the same letter are not significantly different at the 0.05 significance level. LF: cocksfoot cover crop harvested with a low frequency; HF: cocksfoot cover crop harvested with a high frequency; CT: clean tillage.

greater than under CT. The transpiration of apple trees was significantly decreased in the cover crop treatments in 2018, but it was not significantly affected in 2016 and 2017.

4. Discussion

4.1. System production

Cocksfoot strips on the apple tree interrow did not show any adverse effect on apple production compared with traditional CT treatment. This result was in accordance with the study by Bai et al. (2016), who also found that cover crop did not adversely affect fruit production in an apricot-based agroforestry under a semiarid environment. Interspecific interaction in the intercropped orchards was greatly affected by system design and management (Klodd et al., 2016; Garcia et al., 2018). Competition for resources in a jujube (*Zizyphus jujuba* Mill.) and cotton (*Gossypium hirsutum* L.) agroforestry system was strongly influenced by cotton density (Zhang et al., 2014) and the distance between the tree row and cotton strip (Wang et al., 2017b). Cocksfoot was planted in strips, and a 160-cm-wide path was left under the tree crown in our experiments, which alleviated the interspecific competition for resources.

The production of apples was greatly affected by seasonal water availability on the semiarid Loess Plateau of China. Although rainfall in 2016 was limited, the soil water condition was good at the beginning of the growing season, so a relatively high production was obtained in this year. However, the limited rainfall promoted the depletion of soil water storage, which largely affected the early development of apple trees in the next season. Rainfall in the early season of 2017 was very limited and the apple tree developed slowly, the maximum LAI of apple trees in 2017 was 18.9% lower than that in 2016 (Wang et al., 2019), which corresponded well with the production performance as we found that the apple production in 2017 was 22.2% lower than that in 2016. Freezing damage during the flowering stage of apple trees largely reduced apple production in 2018.

The apple orchard in our experiments maintained low canopy coverage throughout the season, and more than 20% of incoming light could be captured by sowing cocksfoot in the interrow (Wang et al., 2019), so as much as 5.67-6.32 and 4.34-4.47 t ha^{-1} additional forage dry matter was harvested in the cover crop systems in 2016 and 2018, respectively. The production of cocksfoot in 2017 was limited by soil water availability. The effect of harvesting frequency on the production of forage crop is uncertain, as repeatedly cutting would stimulate the recovery growth and provide positive effects in biomass production (Van Heerden, 1986); however, heavy cutting frequency might reduce the growth potential and the final total production (Walter, 1991). Although light interception under HF was reduced by harvesting frequently, light use efficiency was greatly promoted at the same time (Collins and Balasko, 1981; Trytsman et al., 1997), so the cocksfoot under the HF plots produced more forage dry matter with less light interception in 2016 and 2017. The effect of harvesting frequency had little effect on cocksfoot production in 2018, which might be because harvesting frequency in the LF was too high (4 times), although the LF maintained a greater coverage, the biomass accumulation was not significantly affected.

4.2. Soil water balance

Soil water content in 0–160 cm was continuously measured and well indicated the effects of cocksfoot cover crop on soil water dynamic under different rainfall conditions, although no statistical test was performed for each measurement. In the 0–80 cm soil layer, obvious increase of water depletion was found in the drying periods under LF and HF treatments, while in the wetting periods, the difference in soil water storage between cover and non-cover treatments was narrowed. In comparison, soil water in the 80–160 cm layer was less affected by rainfall variability, soil water storage in LF maintained lower values throughout the three seasons and the water depletion was more difficult to be recharged compared with the surface layer. The soil water dynamics clearly indicated the advantage of HF over LF in maintaining high soil water content, especially in the 80–160 cm layer.

Mature apple trees on the Loess Plateau have deep root systems (Song et al., 2018). So soil water balance in the 0–300 cm was analyzed. Cocksfoot cover crop mainly increased the soil water depletion in the 0–100 cm soil layer at both the interrow and tree row in the dry year of 2016 and normal year of 2018 (Fig. 5A, E). At the tree row positions, the water depletion in the 100–200 cm soil layer were also promoted by cocksfoot in the dry year of 2016 (Fig. 5B), which might be because the apple tree was forced to absorb more water in the tree row when soil water in the interrow was excessively used by cocksfoot, the complementary use of water is common in intercropping systems (Bedoussac et al., 2015; Wang et al., 2020). Soil water infiltration to the deep soil layer was relatively slow in the rainy season, so the great amount of rainfall in 2017 mainly replenished the soil water in the 0–100 and 100–200 cm soil layers, while very little or no replenishment occurred in the 200–300 cm layer until the end of the growing season (Fig. 5C, D). Cocksfoot cover could improve soil structure and improve rainfall infiltration efficiency (Abbas et al., 2017), so the soil water replenishment in the 200–300 cm soil layer was more significant in the interrow compared with the tree row in the cocksfoot cover crop treatments in 2017 and 2018. The root density under tree row may be greater than that in the interrow in the 200–300 cm soil layer (Cardinael et al., 2015), so apple trees absorbed more water from the tree row and water depletion in the tree row was greater than that in the interrow in all the three seasons. Soil water in the deep soil layer was difficult to be recharged in arid and semiarid environments, and over-use of soil water in the deep layer could contribute to soil desiccation (Wang et al., 2011), which is a potential threat to the ecosystem sustainability. After three years of the agroforestry system in our experiments, soil water in the 200–300 cm soil layer under the cocksfoot strip was balanced while that under the tree row position was not fully recharged. Thus, caution should be given to the long-term effects of sowing cover crop in apple orchards in this study area.

4.3. ET partitioning

For rain-fed orchards in semiarid environments, soil moisture in shallow layers is depleted by both root water uptake and soil evaporation. Soil evaporation could take a great proportion of water use in young fruit plantations if the canopy coverage is low (Tournebize et al., 1996; Gong et al., 2005). Apple trees were planted at a low density in our experiments, and the maximum leaf area index was < 2.0 in the three seasons. So as much as 51.7–56.9% of the total ET was consumed through evaporation in the CT treatment. Soil evaporation mainly occurred in a shallow layer of less than 20 cm, but the root development and water extraction of cocksfoot extended to a larger area. So the system with cocksfoot cover crop showed higher ET under the tree canopy than the clean tillage orchard. Because the leaf density and ground coverage of cocksfoot were very large most of the time (Wang et al., 2019), very little evaporation occurred on the cocksfoot strip and most of the water was consumed by cocksfoot. The proportion of soil evaporation on bare path in the agroforestry plots accounted for only 16.9–21.5% of the total ET; thus, a large amount of water was converted from soil evaporation to plant transpiration by covering cocksfoot in the apple orchard.

Harvesting cover crop at an appropriate time is essential for minimizing its negative effects, such as competition for water (Alcántara et al., 2011). We found that reducing the coverage of cocksfoot could reduce its water use, but the effect was only outstanding in the dry period, and the effect diminished gradually as the cocksfoot grew up quickly. Centinari et al. (2013) also reported that the ET of cover crop was largely reduced by increasing the cutting frequency and the reduction decreased over time with the cover crop regrowth. In the rainy season, soil evaporation was also very prominent, and the advantage of HF in saving water became negligible. The effect of increased harvesting frequency on controlling water use was not remarkable in 2017 and 2018, which might be because the designed harvesting frequency for the HF was not high enough to keep the ground cover at a low level, so a greater mowing frequency is recommended. In addition, the reduction in cocksfoot transpiration might be offset by the increase in apple tree transpiration in HF.

The system ET in the orchard was increased after sowing cocksfoot, especially under LF, which was mainly due to the increase in ET under the tree canopy. Transpiration of apple trees was reduced by the cocksfoot cover crop only in 2018, but it was mainly affected by yearly rainfall pattern; thus, it can be concluded that water competition between apple tree and cocksfoot is weak. The rooting depth of cocksfoot in our experiments was approximately 90 cm (data not shown), so it directly affected soil water in the 0–100 cm soil layer. The rooting depth of a mature apple tree could be as great as 400 cm or greater (Song et al., 2018). At the same time, the cocksfoot was planted in strips that were 80 cm away from the tree trunk. So the main water uptake region of the two species diverged in both the vertical and horizontal directions in the soil profile. Wang et al. (2017b) found that interspecific competition for resources in a jujube and cotton intercropping could be significantly reduced by adjusting the distance between the tree row and cotton strip. Delpuech and Metay (2018) also indicated that grapevine yields increased as the cover crop soil coverage decreased. Therefore, adverse effects of cocksfoot cover crop on apple tree water use could be well controlled by adjusting the cocksfoot spatial structure.

Therefore, advantages in system production were found in the apple tree and cocksfoot agroforestry in the three-year experiments, but the long-term effect on soil water content in the deep layer is uncertain. The magnitude of water consumption, plant density, and the distance from trees must be considered for orchard managers when sowing cover crop together with apple trees in semiarid regions. The balance between economic return and depletion of orchard resources will guide such management practices, and many agronomic measures such as regular canopy pruning, additional irrigation, and fertilization should also be investigated and applied in the agroforestry system in the future.

5. Conclusions

Investigation of the soil water distribution and ET partitioning is essential for understanding water use processes in agroforestry and for improving agroforestry design. In this study, we found that sowing cocksfoot between apple tree rows had no adverse effects on apple production, and additional forage dry matter was obtained. A substantial proportion of ET was wasted through soil evaporation in the traditional plot applying clean tillage, but this was largely reduced by sowing cocksfoot on the orchard floor. The total ET in the orchard was increased after sowing cocksfoot in the dry season of 2016, which was mainly attributed to the increase in ET under the tree canopy. The transpiration of apple trees was not significantly affected in the first two years. Cocksfoot cover crop had no significant adverse effects on the soil water content in the 200–300 cm soil layer in the short term. Increasing the harvesting frequency of cocksfoot could reduce understory water consumption, so cocksfoot with a high harvesting frequency in the apple orchard could be used to produce additional biomass on the semiarid Loess Plateau of China. The long-term effects of agroforestry on soil water balance and apple production in our study area need to be ascertained by long-term experiments and simulation studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abbas, F., Hammad, H.M., Fahad, S., Cerda, A., Rizwan, M., Farhad, W., Ehsan, S., Bakhat, H.F., 2017. Agroforestry: a sustainable environmental practice for carbon sequestration under the climate change scenarios-a review. Environ. Sci. Pollut. Res. 24, 11177–11191. https://doi.org/10.1007/s11356-017-8687-0.

Alcántara, C., Pujadas, A., Saavedra, M., 2011. Management of cruciferous cover crops by mowing for soil and water conservation in southern Spain. Agric. Water Manage. 98, 1071–1080. https://doi.org/10.1016/j.agwat.2011.01.016.

Bai, W., Sun, Z.X., Zheng, J.M., Du, G.J., Feng, L.S., Cai, Q., Yang, N., Feng, C., Zhang, Z., Evers, J.B., van der Werf, W., Zhang, L.Z., 2016. Mixing trees and crops increases land and water use efficiencies in a semi-arid area. Agric. Water Manage. 178, 281–290. https://doi.org/10.1016/j.agwat.2016.10.007.

Bedoussac, L., Journet, E., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E.S., Prieur, L., Justes, E., 2015. Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. Agron. Sustain. Dev. 35, 911–935. https://doi.org/10.1007/s13593-014-0277-7.

Cardinael, R., Mao, Z., Prieto, I., Stokes, A., Dupraz, C., Kim, J.H., Jourdan, C., 2015. Competition with winter crops induces deeper rooting of walnut trees in a Mediterranean alley cropping agroforestry system. Plant Soil. 391, 219–235. https://doi.org/10.1007/s11104-015-2422-8.

Celette, F., Gary, C., 2013. Dynamics of water and nitrogen stress along the grapevine cycle as affected by cover cropping. Eur. J. Agron. 45, 142–152. https://doi.org/10.1016/j.eja.2012.10.001.

Celette, F., Ripoche, A., Gary, C., 2010. WaLIS—A simple model to simulate water partitioning in a crop association: The example of an intercropped vineyard. Agric. Water Manage. 97, 1749–1759. https://doi.org/10.1016/j.agwat.2010.06.008.

Centinari, M., Filippetti, I., Bauerle, T., Allegro, G., Valentini, G., Poni, S., 2013. Cover crop water use in relation to vineyard floor management practices. Am. J. Enol. Vitic. 64, 522–526. https://doi.org/10.5344/ajev.2013.13025.

Collins, M., Balasko, J.A., 1981. Effects of N fertilization and cutting schedules on stockpiled tall fescue. I. Forage yield[1]. Agron. J. 73, 803–807.

Delpuech, X., Metay, A., 2018. Adapting cover crop soil coverage to soil depth to limit competition for water in a Mediterranean vineyard. Eur. J. Agron. 97, 60–69. https://doi.org/10.1016/j.eja.2018.04.013.

Fang, K.K., Li, H.K., Wang, Z.K., Du, Y.F., Wang, J., 2016. Comparative analysis on spatial variability of soil moisture under different land use types in orchard. Sci. Hortic. 207, 65–72. https://doi.org/10.1016/j.scienta.2016.05.017.

Garcia, L., Celette, F., Gary, C., Ripoche, A., Valdés-Gómez, H., Metay, A., 2018. Management of service crops for the provision of ecosystem services in vineyards: A review. Agric. Ecosyst. Environ. 251, 158–170. https://doi.org/10.1016/j.agee.2017.09.030.

Gong, D.Z., Kang, S.Z., Zhang, J.H., 2005. Responses of canopy transpiration and canopy conductance of peach (*Prunus persica*) trees to alternate partial root zone drip irrigation. Hydrol. Processes. 19, 2575–2590. https://doi.org/10.1002/hyp.5732.

Hernández, A.J., Lacasta, C., Pastor, J., 2005. Effects of different management practices on soil conservation and soil water in a rainfed olive orchard. Agric. Water Manage. 77, 232–248. https://doi.org/10.1016/j.agwat.2004.09.030.

Huang, J., Wang, J., Zhao, X.N., Wu, P.T., Qi, Z.M., Li, H.B., 2014. Effects of permanent ground cover on soil moisture in jujube orchards under sloping ground: A simulation study. Agric. Water Manage. 138, 68–77. https://doi.org/10.1016/j.agwat.2014.03.002.

Klodd, A.E., Eissenstat, D.M., Wolf, T.K., Centinari, M., 2016. Coping with cover crop competition in mature grapevines. Plant Soil. 400, 391–402. https://doi.org/10.1007/s11104-015-2748-2.

Licznar-Malanczuk, M., 2015. Suitability of blue fescue (*Festuca ovina* L.) as living mulch in an apple orchard-preliminagy evaluation. Acta Sci. Pol. Hortorum Cultus. 14 (6), 163–174.

Ling, Q., Gao, X.D., Zhao, X.N., Huang, J., Li, H.C., Li, L.S., Sun, W.H., Wu, P.T., 2017. Soil water effects of agroforestry in rainfed jujube (*Ziziphus jujube* Mill.) orchards on loess hillslopes in Northwest China. Agric. Ecosyst. Environ. 247, 343–351. https://doi.org/10.1016/j.agee.2017.06.031.

Liu, Y., Gao, M.S., Wu, W., Tanveer, S.K., Wen, X.X., Liao, Y.C., 2013. The effects of conservation tillage practices on the soil water-holding capacity of a non-irrigated apple orchard in the Loess Plateau, China. Soil Tillage. Res. 130, 7–12. https://doi.org/10.1016/j.still.2013.01.012.

Loewe, M.V., González, O.M., Balzarini, M., 2013. Wild cherry tree (*Prunus avium* L.) growth in pure and mixed plantations in South America. For. Ecol. Manag. 306, 31–41. https://doi.org/10.1016/j.foreco.2013.06.015.

Meyer, A.H., Wooldridge, J., Dames, J.F., 2015. Effect of conventional and organic orchard floor management practices on arbuscular mycorrhizal fungi in a 'Cripp's Pink'/M7 apple orchard soil. Agric. Ecosyst. Environ. 213, 114–120. https://doi.org/10.1016/j.agee.2015.07.026.

Monteiro, A., Lopes, C.M., 2007. Influence of cover crop on water use and performance of vineyard in Mediterranean Portugal. Agric. Ecosyst. Environ. 121, 336–342. https://doi.org/10.1016/j.agee.2006.11.016.

Monteith, J.L., 1965. Evaporation and Environment. Sym. Soc. Exp. Biol. 19, 205–234.

Padovan, M.P., Brook, R.M., Barrios, M., Cruz-Castillo, J.B., Vilchez-Mendoza, S.J., Costa, A.N., Rapidel, B., 2018. Water loss by transpiration and soil evaporation in coffee shaded by *Tabebuia rosea Bertol* and *Simarouba glauca dc*. compared to unshaded coffee in sub-optimal environmental conditions. Agric. Forest Meteorol. 248, 1–14. https://doi.org/10.1016/j.agrformet.2017.08.036.

Palese, A.M., Vignozzi, N., Celano, G., Agnelli, A.E., Pagliai, M., Xiloyannis, C., 2014. Influence of soil management on soil physical characteristics and water storage in a mature rainfed olive orchard. Soil Tillage Res. 144, 96–109. https://doi.org/10.1016/j.still.2014.07.010.

Ramos, M.E., Benítez, E., García, P.A., Robles, A.B., 2010. Cover crops under different managements vs. frequent tillage in almond orchards in semiarid conditions: Effects on soil quality. Appl. Soil Ecol. 44, 6–14. https://doi.org/10.1016/j.apsoil.2009.08.005.

Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resource Res. 8, 1204–1213.

Shen, Y.Y., Li, L.L., Chen, W., Robertson, M., Unkovich, M., Bellotti, W., Probert, M., 2009. Soil water, soil nitrogen and productivity of lucerne–wheat sequences on deep

silt loams in a summer dominant rainfall environment. Field Crop Res. 111, 97–108. https://doi.org/10.1016/j.fcr.2008.11.005.
Song, X.L., Gao, X.D., Dyck, M., Zhang, W., Wu, P.T., Yao, J., Zhao, X.N., 2018. Soil water and root distribution of apple tree (*Malus pumila* Mill) stands in relation to stand age and rainwater collection and infiltration system (RWCI) in a hilly region of the Loess Plateau, China. Catena. 170, 324–334. https://doi.org/10.1016/j.catena.2018.06.026.
Tournebize, R., Sinoquet, H., Bussière, F., 1996. Modelling evapotranspiration partitioning in a shrub/grass alley crop. Agric. Forest Meteorol. 81, 255–272.
Trytsman, M., Kruger, A.J., Wassermann, V.D., Stoltz, M.A., 1997. Production of irrigated *Trifolium repens* L. under a cutting regime in the subtropical region of Gauteng, South Africa. Afr. J. Range For. Sci. 14 (3), 81–86. https://doi.org/10.1080/10220119.1997.9647926.
Uliarte, E.M., Schultz, H.R., Frings, C., Pfister, M., Parera, C.A., Del Monte, R.F., 2013. Seasonal dynamics of CO_2 balance and water consumption of C_3 and C_4-type cover crops compared to bare soil in a suitability study for their use in vineyards in Germany and Argentina. Agric. Forest Meteorol. 181, 1–16. https://doi.org/10.1016/j.agrformet.2013.06.019.
Van Heerden, J.M., 1986. Effect of cutting frequency on the yield and quality of legumes and grasses under irrigation. J. Grassl. Soc. Sth. Afr. 3 (2), 43–46. https://doi.org/10.1080/02566702.1986.9648031.
Wallace, J.S., Jackson, N.A., Ong, C.K., 1999. Modelling soil evaporation in an agroforestry system in Kenya. Agric. Forest Meteorol. 94, 189–202.
Walter, D.W., 1991. Cutting frequency and cutting height effects on rough fescue and Parry oat grass yields. J. Range. Manag. 44, 82–86.
Wang, L.G., Jiang, C.F., Liu, X.Y., Zhang, W.E., Wang, Z.K., Li, J.C., Shen, Y.Y., 2017a. An investigation of willingness and factors determining orchardists behavior of growing forage within the apple orchard in Qingyang. Gansu. Pratacultural Sci. 34, 2584–2590 (in Chinese).
Wang, Q., Zhang, D.S., Zhang, L.Z., Han, S., van der Werf, W., Evers, J.B., Su, Z.C., Anten, N.P.R., 2017b. Spatial configuration drives complementary capture of light of the understory cotton in young jujube plantations. Field Crop Res. 213, 21–28. https://doi.org/10.1016/j.fcr.2017.07.016.
Wang, Y.Q., Shao, M.A., Zhu, Y.J., Liu, Z.P., 2011. Impacts of land use and plant characteristics on dried soil layers in different climatic regions on the Loess Plateau of China. Agric. Forest Meteorol. 151, 437–448. https://doi.org/10.1016/j.agrformet.2010.11.016.
Wang, Z.K., Cao, Q., Shen, Y.Y., 2019. Modeling light availability for crop strips planted within apple orchard. Agric. Syst. 170, 28–38. https://doi.org/10.1016/j.agsy.2018.12.010.
Wang, Z.K., Wu, P.T., Zhao, X.N., Gao, Y., Chen, X.L., 2015. Water use and crop coefficient of the wheat–maize strip intercropping system for an arid region in northwestern China. Agric. Water Manage 161, 77–85. https://doi.org/10.1016/j.agwat.2015.07.012.
Wang, Z.K., Jiang, H.L., Shen, Y.Y., 2020. Forage production and soil water balance in oat and common vetch sole crops and intercrops cultivated in the summer-autumn fallow season on the Chinese Loess Plateau. Eur. J. Agron. 115, 126042. https://doi.org/10.1016/j.eja.2020.126042.
Zhang, D.S., Zhang, L.Z., Liu, J.G., Han, S., Wang, Q., Evers, J., Liu, J., van der Werf, W., Li, L., 2014. Plant density affects light interception and yield in cotton grown as companion crop in young jujube plantations. Field Crop Res. 169, 132–139. https://doi.org/10.1016/j.fcr.2014.09.001.
Zhao, P., Li, S., Li, F.S., Du, T.S., Tong, L., Kang, S.Z., 2015. Comparison of dual crop coefficient method and Shuttleworth–Wallace model in evapotranspiration partitioning in a vineyard of northwest China. Agric. Water Manage. 160, 41–56. https://doi.org/10.1016/j.agwat.2015.06.026.
Zheng, W., Wen, M.J., Zhao, Z.Y., Liu, J., Wang, Z.H., Zhai, B.N., Li, Z.Y., 2017. Black plastic mulch combined with summer cover crop increases the yield and water use efficiency of apple tree on the rainfed Loess Plateau. PloS One. 12, e185705. https://doi.org/10.1371/journal.pone.0185705.