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# Canopy pruning as a strategy for saving water in a dry land jujube plantation in a loess hilly region of China

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ABSTRACT

*Aims:* Soil drying has occurred widely in artificial plantations in the semiarid loess region because the water consumption exceeds the rainfall. Jujube (*Ziziphus jujube* Mill. CV. Lizao) plantations have been planted to improve the economic income since 2000. In order to prevent soil drying and sustain artificial plantation development, we examined the relationships between the canopy size, water consumption, and water use efficiency in a dry land jujube plantation.

*Methods:* Seven treatments were tested comprising native jujube with no pruning and dwarfing jujube under different pruning levels ranging from 1 to 6. Jujube is a popular dwarfing canopy type in this region with a tree height of 2.2 m and this comprised level 1. Jujube received increased intensities of pruning as well as decreases in tree height and canopy size for levels 2–4. Jujube received severe pruning to a tree height of only 1.1 m at level 5, and the canopy was removed with only 30–40 cm of the trunk left for level 6. Soil water was detected using CNC100 neutron tubes. A thermal diffusion probe was used to monitor the sap flow in jujube trees throughout the whole growth period.

*Results:* During our study period, 2014 was a wet year with rainfall of 460.4 mm and 2015 was a dry year with rainfall of only 380.8 mm. Transpiration and water consumption by jujube decreased significantly whereas the soil water content increased as the pruning intensity increased in these two years. Compared with 15-year-old native jujube, the annual soil water consumption by 15-year-old dwarfing jujube (pruned at level 1) was 6.54 mm less and the soil water consumption depth moved upward by 2.2 m. The soil water recovered faster for jujube at level 6 and the soil water restoration depth reached 4.6 m after 3 years, with an annual restoration depth of 153.3 cm. Compared with level 1 jujube, at level 5, the height was halved, the transpiration was about 22.1%, and the water use efficiency was significantly improved by 1.1 times, thereby demonstrating that the water consumption could be regulated by the canopy size. Level 2 jujube had the highest water use efficiency with the optimal pruning level in the local region.

*Conclusions:* We found that pruning could effectively decrease water consumption, relieve deep soil drying, and improve the water use efficiency in jujube. The pruning level should be determined based on the water consumption rate and average rainfall to obtain high yields.

## 1. Introduction

Large scale afforestation was introduced in north China since 1978 in order to improve the ecological environment (Wang et al., 2012), but the ecological benefits have not yet been determined (Chen et al., 2007; Wang et al., 2002). Previous studies have shown that the plantations were sustained but with low survivability (Chinea, 2002; Du et al., 2005; Gao et al., 2011) and a dry soil layer was formed in the loess region according to Li (1983). The growth of the plantations was severely restricted by the low rainfall. In this region, the rainfall infiltration depth is less than 2 m (Zhao et al., 2009) and the groundwater table is very deep at below 50 m (Li, 1983), and thus natural protection and restoration are important for improving the ecological benefits. Previous studies have mainly evaluated the relationship between

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drought resistance and water consumption in different plantations, but little is known about how canopy pruning might regulate plantation growth and soil water consumption (Fan and Hao, 2004; Wang et al., 2011; Xue et al., 2011; Zhao et al., 2000).

Jujube (*Ziziphus jujube* Mill. CV. Lizao) trees are drought tolerant and jujube fruit has great economic value. Thus, jujube has become a major tree species in China due to its ecological and economical benefits under the policy of returning farmland to forestland since 1999. Native unpruned jujube grow widely in this region (2 m between trees and 3 m between tree rows, with 1667 trees $ha^{-1}$), and pruning was introduced in 2012 to improve the fruit yield (Ma et al., 2013).

Studies have shown that artificial plantations grow poorly in the loess region because the rate of evapotranspiration exceeds the rainfall (Cao et al., 2012; Chen, 2005), thereby leading to continuous drying of the deep soil. Studies in ecology, soil hydrology, and forestry have investigated how to restore the soil moisture (Cao et al., 2010; Chen et al., 2008b). Ma et al. (2012) found that the soil dry layer extended to 5.6 m in a 12-year-old jujube plantation. Wang et al. (2009) showed that the soil dry layer was deeper than 20 m in an artificial plantation and it would take more than 150 years to restore the soil water under normal rainfall after the death of an artificial plantation. It appears that the plantations started well but then degraded the soil water ecology and it will be difficult to reconstruct the plantations (Chen et al., 2008a; Li, 1983; Liu and Diamond, 2005).

Understanding the relationships between the tree canopy, tree height, and water consumption are important for predicting how a plantation might adapt to a drought environment, as well as being essential for assessing water regimes. However, little is known about how the canopy pruning level is related to soil water consumption, particularly under field conditions. Li et al. (2003) found that summer pruning might reduce the water consumption by apple trees and improve the water status. Forrester et al. (2013) also showed that pruning could increase the water use efficiency in eucalyptus plantations in south-eastern Australia by removing the least efficient lower canopy foliage and increasing the efficiency of the remaining foliage, thereby potentially reducing the susceptibility to drought and improving the water use efficiency.

Deep soil drying in forestland is caused by excessive transpiration (Chen et al., 2008b). Previous studies have focused mainly on preventing deep soil drying by increasing the soil moisture (i.e., by utilizing rainwater harvesting) and decreasing soil evaporation (i.e., mulching to conserve the soil moisture). In order to reduce deep soil drying and maintain the soil ecology for sustainable development, we proposed the concept of water-saving pruning (Wang et al., 2017) by regulating the canopy size in terms of the amount of branches and biomass, thereby decreasing transpiration. Our objective was to examine jujube water consumption and the soil water content under different pruning levels and find ways to reduce deep soil drying. We examined the effects of the tree height, canopy size, branch length related to jujube water consumption, and soil water with native jujube (no pruning) and dwarfing jujube at different pruning levels. We tested the following hypotheses: (1) compared with native jujube, dwarfing jujube might decrease the water consumption and move the water consumption depth upward; (2) the soil water may be restored faster due to the reduced water consumption after decreasing the canopy size in jujube; and (3) pruning might be beneficial for jujube growth and prevent deep soil drying.

## 2. Materials and methods

### 2.1. Site description

The study site was located in Mizhi county, Shaanxi province, China (37°5′N, 119°49′E), which is in an area classified as a temperate, semiarid climate zone (Fig. 1). The study site is in a typical loess hilly region with a sloping gradient ranging from 23°to 45°. Further details of the site description, topography, and soil properties were provided previously by Ma et al. (2013). The soil in the area is a sandy loam with an average soil bulk density of 1.29 g $cm^{-3}$ in the 0–1 m depth, an average field capacity of 23.4%, and wilting water content of 5.06%. The mean annual precipitation was 451.6 mm in the last 30 years (Fig. 2), where > 50% of the total annual rainfall occurred in July, August, and September. Of the two years when the study was conducted, 2014 was a wet year with annual rainfall of 460.4 mm and 2015 was a dry year with annual rainfall of 334.8 mm. The annual average temperature was 8.4 °C, the annual average sunshine was 2761 h, and the annual total radiation was 580.5 kJ $cm^{-2}$. The average monthly temperature, rainfall and evapotranpiration ($ET_0$) are shown in Table 1, where $ET_0$ is the reference crop evapotranspiration rate determined using the Penman-Monteith equation (Allen et al., 1998) according to meteorological data.

### 2.2. Jujube stands

Jujube were planted in 2000. Our population comprised native unpruned jujube covering 40 ha, 140 ha of dwarfing jujube that followed the contour line of the slope, and 6 ha of farmland planted with potato (*Solanum tuberosum*). Potato was grown as an annual crop and it has been cultivated in this region for several years. It could not form a permanent drying soil layer because its short roots only absorb soil moisture from the upper layer. The native jujube trees are large in size, so dwarfing jujube (pruned at level 1) has become popular recently in order to improve productivity and it was the typical pruning level in this region. The size of jujube trees is determined by the height and canopy, which depend mainly on the trunk and lateral branches. Leaves and shedding shoots are mostly present on the lateral branches. Thus, pruning was conducted according to the height, canopy, main branch number and length, and the secondary branch number and length. To maintain the pruning level, we marked each pruned branch and they were pruned every five days during the overall growth period (germination to leaf sprouting, flowering to fruit setting, fruit development, and fruit ripening) from May to October in 2014 and 2015. We measured the tree height from the ground to the top and the total branch length using a standard tape measure. We also measured the maximum canopy size from aspects parallel to the tree (length) and perpendicular to the tree (width).

Our study comprised seven treatments according to the size of the trees, i.e., native jujube with no pruning and dwarfing jujube with different pruning levels ranging from 1 to 6 (Table 2). All of the jujube stands were on the upper part of the east slope with a gradient of 25° and the observation plots were located in the middle covering an area greater than 0.3 ha. Baffle plates were set at the top and bottom of the observation plots at 0.2 m above the ground to prevent runoff. Six trees at similar growth stages were treated with six replicates for each stand.

We excavated a rectangular trench in the ground at 1 m from the tree trunk and 1.5 m from the tree rows down to a depth of 3 m, and embedded a thick plastic sheet as a moisture barrier to prevent root and water interactions in the level 1, 2, 3, and 4 stands (Fig. 3). Liu et al. (2013) showed that more than 50% of the fine roots of 12-year-old jujube trees are distributed at a depth of 0–0.8 m. Thus, a depth of 3 m was considered sufficient. The level 5 jujube plot was prepared in 2009. We planted one jujube tree in the middle of each observation area with a length of 2 m, width of 1 m, and depth of 1 m, where they were separated from each other by cement walls with thick plastic sheet at the bottom to prevent penetration (Fig. 4). The jujube trees were severely pruned to only half of the usual dwarfing jujube height (level 1). For the level 6 jujube, the canopy was removed using a saw and only 30–40 cm of the trunk height remained in March 2012 in order to regenerate jujube, which was the smallest tree size (Fig. 5). New branches grew and three branches were retained in 2013.

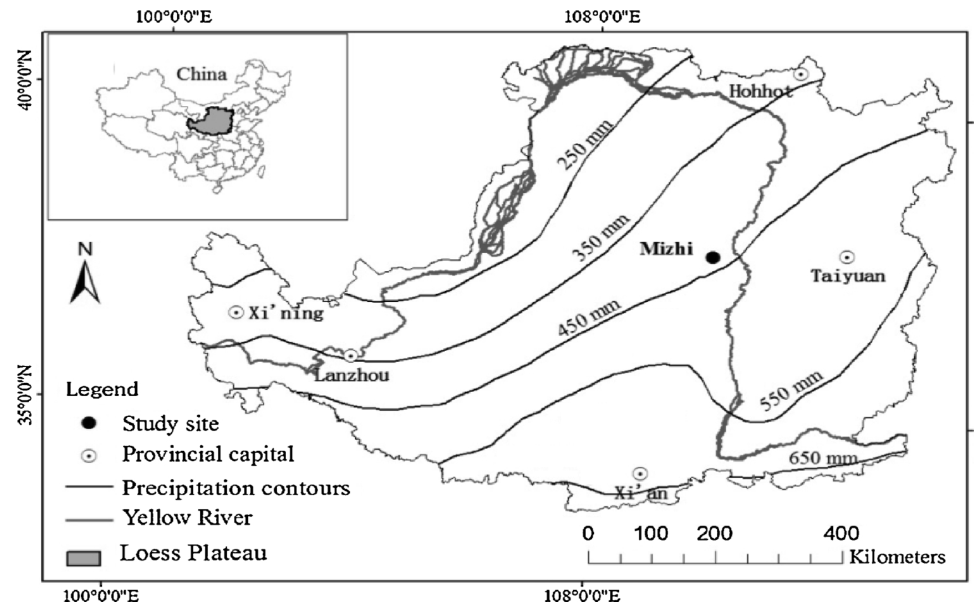


**Fig. 1.** Location of the study site.

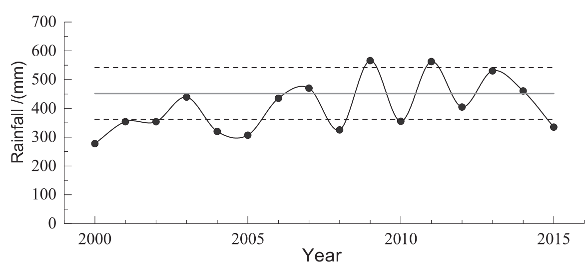


**Fig. 2.** Annual rainfall (mm) during the 15-year study period. The solid line is the recent 30-year average, the dashed lines represent 20% above and below the average rainfall amounts.

### 2.3. Soil moisture

The volumetric soil water content was monitored using neutron moisture gauges (CNC100). The neutron tubes were installed 80 cm away from the trunk. Soil water was monitored every 10 days at 0.2 m depth interval down to depths of 10 m for the native unpruned jujube, dwarfing jujube (pruned at level 1), farmland, and jujube with the canopy removed (level 6), but to depths of 3 m for level 1, 2, 3, and 4 jujube, and 1 m for level 5 jujube. The soil water storage capacity was calculated as:

$$W = 10 \times H \times \theta, \tag{1}$$

where W (mm) is the soil water storage capacity, H (cm) is the soil depth, and θ ($cm^3\ cm^{-3}$) is the soil volumetric water content.

### 2.4. Transpiration monitoring

Thermal diffusion probes (TDP-20, Dynamax Co., USA) were used to monitor the sap flow in jujube trees for 24 h during the overall growth period. Thermal diffusion probes (length = 20 mm, diameter = 2 mm) were installed on the east aspects of the jujube trunks at 0.4 m above the ground to eliminate detection errors (Lu et al., 2004), and they were wrapped with silver paper to avoid interference from the external environment. Sap flow data were collected every 10 min with a CR1000 data logger (Campbell, Co., USA) and the sap flow density was calculated as follows (Granier, 1987)

$$Js = 119 \times \left(\frac{\Delta T_m - \Delta T}{\Delta T}\right)^{1.231} \tag{2}$$

where Js ($g\ m^{-2}\ s^{-1}$) is the sap flow density, and $\Delta T_m$ and $\Delta T$ (°C) are the

**Table 1**
Average monthly temperature, rainfall and evapotranspiration ($ET_0$).

| Month | 2014 Temperature (°C) | 2014 Rainfall (mm) | 2014 Evapotranspiration (mm) | 2015 Temperature (°C) | 2015 Rainfall (mm) | 2015 Evapotranspiration (mm) |
|---|---|---|---|---|---|---|
| Jan. | −4.7 | 0.0 | 0.40 | −4.8 | 2.8 | 0.44 |
| Feb. | −2.3 | 17.8 | 1.17 | −1.2 | 10.6 | 1.11 |
| Mar. | 7.3 | 10.4 | 1.91 | 6.7 | 0.6 | 1.91 |
| Apr. | 14.2 | 69.8 | 2.76 | 13.3 | 28.0 | 2.81 |
| May. | 18.4 | 41.0 | 2.50 | 19.4 | 39.4 | 2.46 |
| Jun. | 23.2 | 56.0 | 2.62 | 22.8 | 42.6 | 2.57 |
| Jul. | 24.3 | 115.8 | 4.43 | 26.3 | 40.0 | 8.03 |
| Aug. | 21.7 | 38.6 | 2.50 | 23.5 | 50.4 | 4.11 |
| Sept. | 18.2 | 86.8 | 0.98 | 18.4 | 89.2 | 0.96 |
| Oct. | 12.3 | 13.0 | 1.30 | 11.0 | 26.2 | 1.28 |
| Nov. | 3.0 | 11.0 | 1.74 | 5.0 | 1.6 | 1.75 |
| Dec. | −6.7 | 0.2 | 2.15 | −3.1 | 3.4 | 2.17 |
| Average | 10.8 | 38.4 | 2.0 | 11.5 | 27.9 | 2.5 |

$ET_0$ is the reference crop evapotranspiration rate determined by Penman-Monteith equation.

**Table 2**
Jujube trees stand characteristics.

| Jujube stands | | Tree height/m | Canopy (length × width)/ m | Main branch number | Secondary branch number | Secondary branch overall length/m |
|---|---|---|---|---|---|---|
| Native | (no pruning) | 4.6 ± 0.2a | 4.3 × 4.3 | 1 ~ 2 | 32 ~ 42 | 16.0 ± 1a |
| Dwarfing | Level 1 | 2.2. ± 0.2b | 2.2 × 2.2 | 3 | 27 | 8.0 ± 0.2b |
| | Level 2 | 2.0 ± 0.18bc | 2.2 × 2.0 | 3 | 24 | 6.0 ± 0.15c |
| | Level 3 | 1.8. ± 0.18c | 1.8 × 1.8 | 2 | 14 | 4.0 ± 0.12d |
| | Level 4 | 1.6. ± 0.14c | 1.6 × 1.6 | 1 | 6 | 3.0 ± 0.10e |
| | Level 5 | 1.1. ± 0.03d | 1.0 × 1.0 | 1 | 4 | 1.6 ± 0.12f |
| | Level 6 | 0.4 ± 0.1e | 1.1 × 1.1 | 3 | 4 | 0.75 ± 0.08 g |

Figures are mean ± SD.
[a,b,c,d,e,f,g] different letters indicate significant differences between means for different treatments ($P < 0.05$, Duncan's test, n = 6).

temperature differences between the probe and atmosphere under no sap flow and upward sap flow conditions, respectively. Therefore, the daily transpiration was calculated as:

$$AT = \sum_{i=1}^{144} (J_{si} \times A_s \times 10^{-5}) \quad (3)$$

where AT (mm $d^{-1}$) is the daily transpiration, $A_s$ ($cm^{-2}$) is the area of sap flow, and $J_{si}$ is the sap flow density at 10 × i min. $A_S$ was calculated as:

$$A_S = 0.8249 \times DBH + 1.5634, \quad (4)$$

where DBH (cm) is the jujube tree diameter at breast height. Regression was performed between $A_S$ and DBH, where the regression coefficient ($R^2$) was 0.8901, and the correlation coefficient (r) was 0.943 ($P$ = 0.01).

### 2.5. Jujube water consumption

We calculate the water consumption by the jujube plants with the water balance method. There was no effective runoff because we set baffle plates at the top and bottom of the observation plot. The ground water table is more than 50 m deep (Li, 1983) in the loess region. Thus, the runoff and ground water could be neglected. The water consumption was calculated as:

$$ET = P - \Delta S \quad (5)$$

where ET is the water consumption by the jujube plantation, P is the rainfall, and $\Delta S$ is the variation in the soil water storage capacity.

$$\Delta S = S_{present} - S_{initial} \quad (6)$$

We did not determine the soil water in this region before the jujube planted so the local farmland soil water capacity was regarded as $S_{initial}$, and $S_{present}$ is the current jujube plantation soil water capacity.

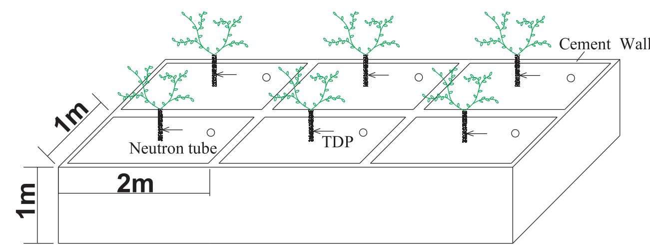


**Fig. 4.** Experimental layout for the severely pruned dwarfing jujube trees (level 5). Arrows represent TDP probes, and circles represent neutron tubes.

**Fig. 5.** Experiment jujube of canopy removal area (level 6).

### 2.6. Water use efficiency

The water use efficiency was expressed as the fruit yield per jujube water consumption:

$$WUE = \frac{Y}{ET} \quad (7)$$

Where *WUE* is the water use efficiency (kg $m^{-3}$), *Y* is the fruit yield (kg

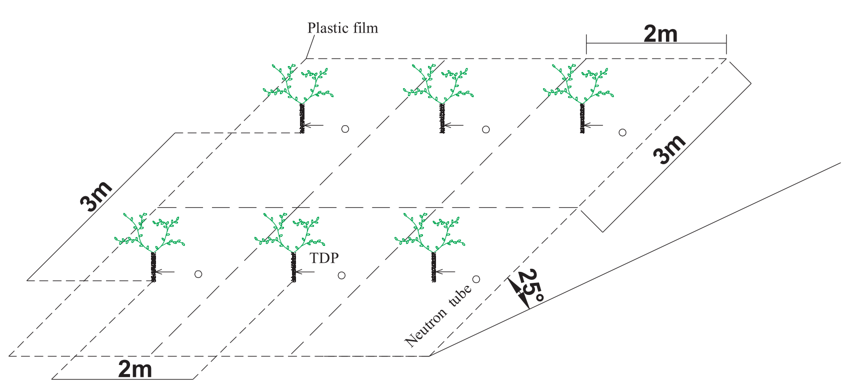


**Fig. 3.** Experimental layout for the dwarfing jujube trees (levels 1–4). Dashed lines represent plastic film down to a depth of 3 m. Arrows represent TDP probes, and circles represent neutron tubes.

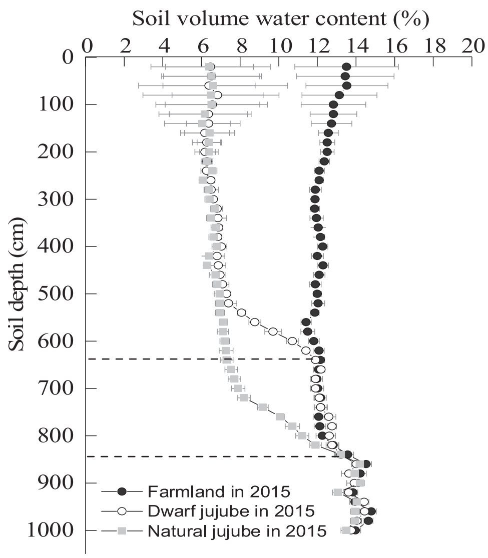


**Fig. 6.** Soil water volumetric content in the 0–10 m depth during 2015. Solid circles represent farmland, blank circles represent dwarfing jujube (pruned as level 1) and solid rectangles represent native jujube. Error bars are standard errors (n = 6).

$ha^{-1}$), and *ET* is the water consumption by the jujube plantation ($m^3\ ha^{-1}$).

Statistical calculations were performed using Excel (2012) and SPSS Statistics (18.0). ANOVA tests were used to determine differences in the tree height, secondary branch length, fruit yield, jujube water consumption, transpiration, and water use efficiency. Significant differences were accepted at the $P < 0.05$ level (Duncan's test). Figures were prepared with Sigmaplot (12.5) and AutoCAD (2010).

## 3. Results

### 3.1. Effects of pruning on the soil water storage and consumption in the 0–10 m depth

The average soil volume water contents in the 10 m soil profiles in the native unpruned jujube, dwarfing jujube (pruned at level 1), and farmland plots during 2015 are shown in Fig. 6. The average soil volume water contents in the 10 m depth were in the following order: farmland (12.62%) > dwarfing jujube (9.40%, pruned at level 1) > native jujube (8.42%), and they differed significantly. In general, only the rainfall was consumed on farmland without drying the deep soil layer (Wang et al., 2007). Thus, the water consumed by jujube comprised the cumulative rainfall plus the soil volume water reduction compared with that on farmland. The soil water storage was 1261.61 mm in farmland, 939.83 mm in dwarfing jujube plots, and 841.66 mm in native jujube plots in the 0–10 m depth. Thus, compared with farmland, the soil water storage was 321.78 mm lower in the dwarfing jujube plots and 419.95 mm lower in the native jujube plots. The total rainfall was 6215.9 mm from 2000 to 2015 and the annual average rainfall was 414.39 mm. Thus, the water consumption rates in the 15-year-old dwarfing jujube and native jujube plots were 6537.68 mm (6215.9 plus 321.78) and 6635.85 mm (6215.9 plus 419.95), respectively, and the annual water consumption rates were 435.85 mm and 442.39 mm, where they exceeded the annual rainfall by 21.46 mm and 28 mm. The annual water consumption in the dwarfing jujube plots was 6.54 mm less than that in the native jujube plots. The soil water contents in the 15-year-old dwarfing jujube plots and native jujube plots were lower in the 6.4 m and 8.6 m depths, respectively, compared with that in farmland, and thus the soil water consumption

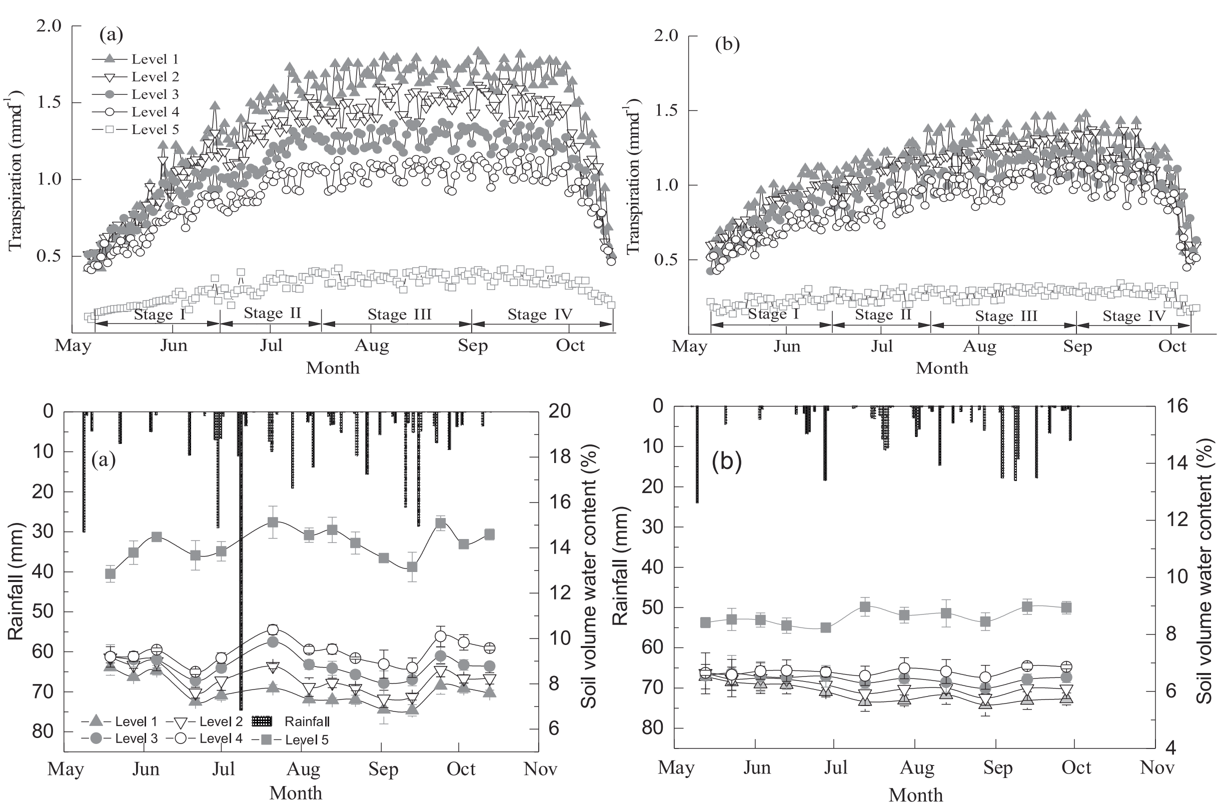


**Fig. 7.** Daily actual transpiration and soil water volumetric content for jujube under different pruning level in 2014 (a) and 2015 (b). Stage I–IV denote jujube growth periods from germination to leaf sprouting, flowering to fruit-setting, fruit development and fruit ripening, respectively. Solid triangles represent jujube pruned at level 1, empty triangles represent jujube pruned at level 2, solid circles represent jujube pruned at level 3, empty circles represent jujube pruned at level 4 and solid rectangles represent jujube pruned at level 5. Error bars are standard errors (n = 6).

depths extended to 6.4 m and 8.6 m, while the annual soil water consumption depths were 42.6 cm and 57.3 cm. The results showed that dwarfing jujube could decrease the water consumption and pruning can play an important role in regulating the water consumption in plantations, as shown by Ma et al. (2012)

### *3.2. Effects of pruning on daily transpiration, water consumption, and soil water characteristics (levels 1–5)*

Fig. 7 shows the daily transpiration and soil water during the whole growth period for jujube at levels 1 to 5. Transpiration decreased significantly as the pruning intensity increased. The daily transpiration varied throughout the whole growth period from May to October, but the trends were similar in all of the plots. Thus, transpiration increased gradually after May (dormancy breaking), before a stable higher transpiration rate was maintained from July to October, and it decreased drastically until dormancy when the leaves fell after October. The maximum daily transpiration amounts were 1.83 mm, 1.64 mm, 1.37 mm, 1.18 mm, and 0.42 mm for jujube at levels 1 to 5, respectively. There were no obvious differences between dwarfing jujube at levels 1 and 2 after August because jujube at level 2 could not effectively regulate the water consumption related to the canopy during the rainy season.

The jujube water consumption also decreased significantly as the pruning intensity increased, and the effect was more obvious with more rainfall. The soil water content throughout the whole jujube growth period was higher in 2014 than 2015 because there was more rainfall in 2014, and the soil water content increased as the pruning intensity increased. The differences in the soil water contents among different pruning levels were also larger in 2014 than 2015, where the maximum differences were 7.51% in 2014 and 3.33% in 2015.

We found that there was an opposite and reciprocal relationship between soil water and growth, where more soil water could support growth but rapid growth could consume more soil water. The interaction between soil water and growth was stronger in the wet year (2014) than the dry year (2015). Wei et al. (2015) indicated that a soil water content of 6% is a threshold that can affect transpiration in jujube. Thus, transpiration is restricted due to stomata closure when the soil water content is lower than 6%. We also found that the soil water content tended to be stable below 6% due to limited transpiration by jujube.

In our study, each jujube tree only occupied 2 $m^2$ at level 5, which was only one-third of the area for the dwarfing jujube plants. Thus, each tree only received one-third of the rainfall compared with the dwarfing jujube in this region. The jujube trees could survive in the case of severe water shortages, but the water consumption was greatly decreased. Thus, we conclude that a limited water supply could reduce jujube water consumption.

### *3.3. Effect of canopy removal (level 6) on soil water restoration*

Fig. 8 shows the average soil water contents in the 0–10 m depth after canopy removal from 2012 to 2015. We examined the effects of canopy removal on soil water restoration. Clearly, transpiration and water consumption decreased after the canopy was removed (Fig. 5). In addition, the average soil water content in the 0–10 m depth increased significantly in the 13-year-old jujube plots (9.92%) compared with the 12-year-old jujube plots (8.91%). We defined the soil water content in 12-year-old jujube plots as the initial soil water restoration value and the soil water content in farmland as the upper limit (Wang et al., 2007). The soil water restoration depth was the depth where the soil water content was more than that in the 12-year-old jujube plots. The water consumption depth in the 12-year-old dwarfing jujube plots (level 1) extended to 5.4 m and by 45 cm per year because more water was consumed than the rainfall received. The soil water restoration depth reached 3 m in 2013, 4 m in 2014, and 4.6 m in 2015 due to the

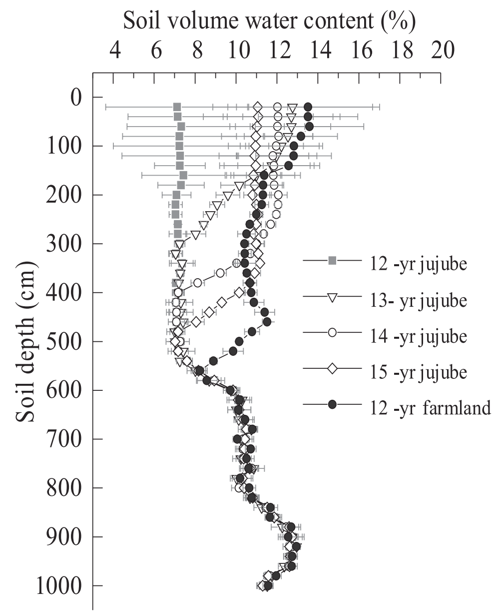


**Fig. 8.** Soil water restoration after jujube canopy removal (level 6) over 3 years. Solid rectangles represent jujube in 2012, empty triangles represent jujube in 2013, empty circles represent jujube pruned in 2014, empty rectangles represent jujube in 2015 and solid circles represent farmland in 2012. Error bars are standard errors (n = 6). Pruning occurred in the fall of 2012.

downward movement of infiltrated water from previous years (Bai, 2015). The annual restoration depth was 153.3 cm from 2013 to 2015, and it was 3.41 times the water consumption. The soil water storage in the 4.6 m profile was 489.07 mm in the jujube plots and 573.38 mm in farmland during 2015. The difference in the soil water storage between jujube and farmland decreased greatly from 2012 to 2015, thereby demonstrating that canopy removal was an effective method for improving soil water infiltration and recovery in old jujube plantations. The soil water restoration depth was deeper than that reported in previous studies (Wan et al., 2008; Wang et al., 2009), possibly because the jujube trees sprouted later and they only retained three branches with clean cultivation, thereby decreasing the water consumption and the well-developed roots might have helped the soil water move down into the soil.

### *3.4. Effect of pruning on the water use efficiency*

The water use efficiencies with different pruning levels are shown in Table 3. The highest water use efficiency was with jujube at level 2 and the lowest with native jujube, where the difference was significant. The maximum water use efficiency was 2.25 times the minimum in 2014 and 3.13 times the minimum in 2015.

The ultimate aims of economic plantation management are decreasing the water consumption and increasing the water use efficiency. In our study, the native jujube consumed more water than the dwarfing jujube (level 1), and the water use efficiency exhibited the opposite trend. The water use efficiency by the native jujube was only 2.1 kg/$m^3$ in 2014 and 1.8 kg/$m^3$ in 2015, but the water use efficiency with dwarfing jujube was 62% higher in 2014 and 72% higher in 2015. We found that the yield and water use efficiency were highest at level 2 in both the wet year (2014) and dry year (2015). Thus, an appropriate pruning level decreased the water consumption but increased the yield and water use efficiency under certain water supply conditions. More rainfall could obviously improve the yield and water use efficiency. Our findings demonstrate that dwarfing jujube in this region can potentially improve the yield and the decrease water consumption, thereby increasing the water use efficiency.

**Table 3**
Jujube yield (Y), water consumption (ET), transpiration (T), evaporation (E) and water use efficiency (WUE) under different pruning levels during the whole growth period comprising 2014 and 2015.

| | 2014 | | | | | | 2015 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | H (m) | Y (kg·ha$^{-1}$) | ET (m$^3$·ha$^{-1}$) | T (m$^3$·ha$^{-1}$) | T/ET (%) | WUE (kg·m$^{-3}$) | H (m) | Y (kg· ha$^{-1}$) | ET (m$^3$· ha$^{-1}$) | T (m$^3$·ha$^{-1}$) | T/ET (%) | WUE (kg·m$^{-3}$) |
| no pruning | 4.6 ± 0.2a | 9642.2 ± 208.2e | 4591.5 ± 26.5a | 3305.9 ± 63.8a | 72% | 2.10 ± 0.08c | 5.1 ± 0.2 a | 7937.9 ± 180e | 4491.1 ± 18.30a | 3358.3 ± 53.2a | 74.8% | 1.77 ± 0.33c |
| Level 1 | 2.2 ± 0.2b | 17394.0 ± 215.0d | 4366.3 ± 66.0b | 2273.9 ± 53.8b | 52.1% | 3.98 ± 0.01b | 2.2 ± 0.2b | 12076.6 ± 215d | 2748.5 ± 66.0b | 1750.4 ± 43.1b | 63.7% | 4.39 ± 0.32b |
| Level 2 | 2.0 ± 0.18 bc | 20307.8 ± 133.2a | 4296.5 ± 10.0b | 2027.5 ± 41.2c | 47.2% | 4.73 ± 0.04a | 2.0 ± 0.18bc | 14842.8 ± 190a | 2678.1 ± 114.0b | 1621.1 ± 31.2c | 60.5% | 5.54 ± 0.18a |
| Level 3 | 1.8 ± 0.18c | 19181.9 ± 156.0b | 4149.0 ± 108.0c | 1772.2 ± 60.8d | 42.7% | 4.62 ± 0.08a | 1.8 ± 0.18c | 13884.2 ± 145b | 2531.8 ± 6.0c | 1523.4 ± 37.8d | 60.2% | 5.48 ± 0.74a |
| Level 4 | 1.6 ± 0.14c | 17695.8 ± 164.0c | 3904.1 ± 108.0d | 1483.6 ± 32.7e | 38% | 4.53 ± 0.08a | 1.6 ± 0.14c | 12846.1 ± 124c | 2450.3 ± 6.0c | 1342.6 ± 21.7e | 54.8% | 5.24 ± 0.39a |
| Level 5 | 1.1 ± 0.1d | 5361.8 ± 86.0f | 1166.1 ± 25.4e | 492.0 ± 25.4f | 42.2% | 4.6 ± 0.02a | 1.1 ± 0.1d | 3618.5 ± 58f | 785.9 ± 4.0d | 395.6 ± 27.2f | 50.3% | 4.6 ± 0.27b |

The canopy removal treatment (level 6) is not shown in the table because it had no yield.
Figures are means ± SD.
[a,b,c,d,e,f] Different letters indicate significant differences between means for different treatments ($P < 0.05$, Duncan's test, n = 6).

## 4. Discussion

The consumption of water by jujube is affected by interactions among the atmosphere, plant, and soil. In general, we cannot change the atmosphere under field conditions, but the jujube canopy size and soil environment can be regulated. Few studies have considered the relationship between the canopy size and water consumption in jujube. In general, transpiration is regarded as controlling water consumption by plants to maintain regular growth (Nie et al., 2017). Thus, we propose that the canopy should be pruned to reduce transpiration by jujube according to the average annual rainfall in order to maintain sustainable jujube plantation development and prevent deep soil drying, as well as obtaining a high stable yield and improved water use efficiency. The availability of abundant water leads to excessive transpiration, which produces larger tree with more transpiration but a lower yield. We found that the native jujube plots with larger trees and higher water consumption had lower yields than the dwarfing jujube. Thus, pruning could reduce excessive water consumption in jujube. Further studies should investigate how to convert greater transpiration to increase the yield.

The soil water content increased as the canopy size decreased. Thus, we showed that canopy regulation can be an effective method for preventing soil drying. Chen et al. (2016) reached the same conclusion and showed that branch removal in jujube plantations could improve the soil water content. Richardson et al. (2010) also found that canopy trimming led to greater throughfall and higher soil moisture contents. The soil water content increased gradually after pruning in the jujube level 6 plots, thereby reducing the drying of the soil. The water consumption in the jujube level 4 plots were 3904.1 m$^3$ ha$^{-1}$ (equal to 390.4 mm) in 2014 and 2450.3 m$^3$ ha$^{-1}$ (equal to 245 mm) in 2015 over the whole growth period, which was lower than the rainfall received (402 mm in 2014 and 251.4 mm in 2015). Thus, pruning at level 4 could prevent the occurrence of permanent deep soil drying. Further studies should investigate how to relieve soil drying based on rainfall prediction.

A soil dry layer below 2 m is usually regarded as a permanent dry layer that is unlikely to be restored (Wang et al., 2007). The soil water restoration depth in our jujube level 6 plots with canopy removal was greater than that found in previous studies where it took many years to restore the deep soil dry layer (Wang et al., 2007). We found that the water consumption was low in the jujube plots with canopy removal and the soil was favorable for rainfall infiltration, thereby demonstrating that canopy removal is suitable for restoring the soil moisture.

The local dwarfing jujube occupied an area of 6 m$^2$ with a distance of 3 m between the trees and 2 m between the rows of trees, and the roots extended several meters. In the level 5 treatment, the area was only one-third of that for the usual dwarfing jujube with an area of 2 m$^2$ and a root depth of 1 m. The level 5 jujube plots survived and produced a yield in this extremely limited space, where the trees exhibited strong drought resistance. Thus, we conclude that jujube can survive and produce a yield when the local rainfall received is decreased to one-third by appropriate pruning, i.e., appropriate pruning can ensure that the jujube yield is obtained in low water consumption conditions.

We found that pruning could reduce the water consumption in jujube. Compared with the 15-year-old native jujube plots and dwarfing jujube plots, the difference in the water consumption depth was more than 2 m, and thus dwarfing plantations can help to reduce the soil water consumption. Similarly, Liu et al. (2013) showed that the root distribution depth in native jujube was 2 m deeper than that in dwarfing plantations. Zhang et al. (2016) also found that decreasing the height of grass can reduce the root depth and soil water consumption. In addition, Ma et al. (2013) showed that dwarfing jujube trees can reduce the root depth. Comas et al. (2005) demonstrated that root production by Concord grapevines was greater under minimal canopy pruning than heavy pruning. Zhao (2013) found that pruning could clog grape ducts and reduce the water consumption. The results obtained in these studies are consistent with our findings. All of these studies showed that pruning can save water, so we suggest that pruning can save water by regulating water consumption according to the available water supply, thereby maximizing the conversion of limited water into the fruit yield and improving the water use efficiency. Jujube has been cultivated for 1000 years because of its drought tolerance (Chen et al., 1990), and we showed that effective pruning can improve the soil ecological environment and maintain good plantation growth. Maffei et al. (2016) also concluded that pruning has a positive effect on longevity. Thus, future studies should determine whether canopy pruning might affect the long-term longevity of plantations.

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