Effects of water-saving pruning on the growth and water consumption of jujube (*Ziziphus jujuba* Mill.) in a loess hilly region with deep soil desiccation

Jianpeng Ma, Xing Wang, Xining Zhao, Wenfei Zhang and Youke Wang

ABSTRACT

In order to study whether jujube trees can grow normally under rain-fed conditions in loess hilly areas, we planted jujube trees (*Ziziphus jujuba* Mill.) 4 years after felling a 23-year-old apple orchard. The growth process of the jujube trees and the variation in soil water content (SWC) were monitored for three consecutive years following planting in order to study the effects of the water-saving pruning (WSP) technique. Results showed the following. (1) The soil at a depth of 0–1,000 cm had been desiccated when the area was an apple orchard. (2) Under rain-fed conditions, the jujube trees with the WSP technique were always able to maintain normal growth while the jujube trees with conventional pruning method had a normal growth stage of only 4 years. The water use efficiency of the jujube trees with the WSP technique was much higher than that of the jujube trees with conventional pruning. We recommend WSP in jujube orchard management, because the jujube trees with WSP could maintain normal growth in the deep dried soils of the loess hilly region, as WSP can reduce the water consumption of the jujube trees and may have a positive effect on soil moisture restoration.

Key words | jujube plantation, soil moisture, soil water restoration, water use efficiency

Jianpeng Ma
Xining Zhao (corresponding author)
Wenfei Zhang
Youke Wang
Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources,
Yangling 712100, Shaanxi Province,
China
E-mail: *Danuae_17@163.com*

Jianpeng Ma
Wenfei Zhang
University of Chinese Academy of Sciences,
Beijing 100049,
China

Xing Wang
School of Agriculture,
Ningxia University,
Yinchuan 750021, Ningxia Hui Autonomous Region,
China

HIGHLIGHTS

- We proposed water-saving pruning for the growth of jujube trees planted in dry soil.
- Water-saving pruning can significantly improve water use efficiency of jujube trees planted in dry soil.
- Water-saving pruning may have a positive impact on the restoration of soil water in dry soil.

INTRODUCTION

In the loess region of China, groundwater is deeply buried, meaning that the main source soil water is precipitation. Forests in the loess region generally have deep root systems that absorb deep soil moisture in order to meet the requirements of transpiration and metabolic water use. Thus, stores of deep soil water are consumed continually. The appearance of the 'using-type dried layer' currently threaten the deep soil water storage (Wang *et al.* 2000; Da *et al.* 2011; Liu *et al.* 2013b). The depth of infiltration is usually less than 200 cm in loess regions without deep leakage. Once these dried layers appeared, they did not return to normal even after many years, thus they could be called permanently dried layers (Wang *et al.* 2000). Present studies show that the depth of soil moisture depletion in perennial planted vegetation can reach up to 1,000 cm (Wang *et al.* 2002, 2005; Cheng *et al.* 2004; Fan 2004; Chen *et al.* 2005;

doi: 10.2166/ws.2021.117

Li *et al.* 2007). Wang *et al.* (2009) proved that in Suide County of Shaanxi Province the depth of soil moisture depletion in a 7-yr-old artificial alfalfa grassland (*Medicago sativa* L.) could reach up to 1,550 cm, while a 23-yr-old artificial caragana forest (*Caragana microphylla* (Pall) Lam.) was 2,240 cm, and a 23-yr-old artificial Chinese pine forest (*Pinus tabulaeformis* Carr.) was 2,150 cm. Cao *et al.* (2012) found that the depth of soil moisture depletion in a more than 15-yr-old rain-fed apple orchard on the Loess Plateau was no less than 1,180 cm. Many scholars worry that the permanently dried layer would be unfavorable for the growth of existing vegetation, but it also has a great impact on the selection and survival of the vegetation (Wang *et al.* 2002, 2003; Wan *et al.* 2008). Wang *et al.* (2007) studied the SWC restoration of different land-use types in Suide and proved that a land-use change from forest to slope farmland, it would take about 40 years for the SWC to recover to levels observed in continuous cropping areas. In contrast, forest changed to protected grasslands would take at least 150 years to recover, and waste grasslands with grazing may never recover. They found that the SWC within a profile of 3 meters recovered in 5 years. Xie *et al.* (2014) proved corn was the feasible ensuing crop after perennial alfalfa in Loess Plateau. Wang *et al.* (2009) proposed the suitable crop rotation model was 7a alfalfa and 13a crop.

Given the large-scale land-use conversions on the Loess Plateau and the importance of this region to food production and security, it is very important to study the planting and growth rate potential of vegetation grown in dried soils. Most studies have mainly focused on soil moisture restoration and subsequent crop planting (Wang *et al.* 2007, 2009; Xie *et al.* 2014). Studies on the growth of tree plantations are rare, especially for jujube (*Ziziphus jujuba* Mill.). Jujube is a drought-resistant, economically important tree species planted widely in the loess hilly region. The jujube planting area was 100 hm^2 in the year 2,010 (Liu *et al.* 2013a, 2013b). Jujube has played an important role in promoting local economic development. The study of growth rates and water consumption of jujube forests planted after clear cuts or death of the previous plantation is rare, especially with the additional variable testing the effect of WSP of jujube forest.

This study analyzed the growth and water consumption rates of jujube forests that were planted after apple orchards were felled four years previously. The aims of this study were to: (1) provide guidance on the types of vegetation that should be planted in dried soils; and (2) provide a reference for the prevention and cure of permanently dried soil layers caused by plantation forest water consumption.

MATERIALS AND METHODS

Study site

The field study was conducted at Yuanzhi Mountain Demonstration Base of Mizhi Experimental Station of Northwest A&F University (38°11′N, 109°28′E). The base is located at an elevation of 1,049 m in Mizhi County in Shaanxi Province in northwestern China. The study area belongs to the Loess Plateau, where topographic characteristics are typical of loess hills and gullies with semiarid temperate climate. Mean annual precipitation in the study area is 451 mm (most of which falls in July to September). From 2012 to 2015, the precipitation was 404.1 mm, 530.1 mm, 460.4 mm, and 334.8 mm, respectively. The mean annual temperature was 8.5 °C, and frost-free period was 160 days.

On average, the water table is more than 50 m below the ground surface and the loess soil is uniform in texture and is moderate permeability. Mean bulk density of the soil is $1.29\ g{\cdot}cm^{-3}$ in the upper 1 m soil profile, field capacity by mass is 17.10% and wilting moisture content is 5.16%. The study area was rain-fed apple orchard in the years 1984 to 2007, and in 2007 the apple trees were cut down, after that, the jujube forest was planted in the year of 2011.

Sample plots

We set up five sample plots in April 2011 after the afforestation of the study site. Plot I, or the ‘test area,’ was an observation plot of jujube trees planted after 23-year-old apple trees were cut down and treated with the WSP technique; there was deep soil desiccation present. Plot II was ‘control jujube forest a,’ where we established an observation plot of jujube trees planted after the 23-yr-old apple trees were cut down and treated with a conventional pruning technique; there was deep soil desiccation. Plot III was the 'control jujube forest b,' where there was an observation plot of jujube trees treated with the conventional pruning technique that were planted on land without deep soil desiccation, as the jujube forest was planted on land immediately converted from cropland. Plot IV was 200 m to the west of plot I and served as an area where we investigated the soil moisture of a 15-year-old jujube forest belonged to 'returning farmland to forest in an earlier stage.' Plot V, or 'farmland,' was 150 m to the east of plot I, which we used to study the soil moisture of farmland; the farmland was divided by crop ownership and crop planted into 'farmland a,' which was planted with beans and 'farmland b,' which was planted with broom corn millet. All of the plots were in terraced fields which were built at the middle of mountain with an area ranging from 520 to 740 m^2. Five observation points were established in every plot and marked with X-shape crosses. The basic information for each plot is shown in Table 1.

All of the jujube plantations were planted with a row-by-stand spacing of 3 m by 2 m. In plots I, II and III, the height of the jujube tree was 120 ± 6 cm, and the diameter of the trunk at about 50 cm above the land surface was 12 ± 2 cm.

Pruning standards

In 2013, we began conventional pruning and WSP according to the plot design. The standard of conventional pruning was a canopy height of about 200 cm and the crown of 200 cm × 200 cm. The standard for WSP was the tree height of 160 cm, a crown breadth of 160 cm × 160 cm, and a sum of the major branch number 1 and lateral branch number 6 equal to a total length of lateral branches of 300 cm.

In this study, we were testing the effectiveness of WSP (Wei *et al.* 2014; Wei 2015) as a means to increase the WUE of the jujube plantation, not simply its effect on the yield. The central idea was to determine the tree size according to the water supply and then the yield would be determined according to tree size. The essence of this central idea is that we control the transpiration rates of jujube by removing branches in order to maintain a relative balance between the annual precipitation and the water consumption of jujube. The WSP is designed to ensure a long-lasting balance of water. Pursuing short-term yields could cause serious soil water deficits and/or reduced yields over time due to excessive transpiration of the tree.

Soil water content

We regularly measured volumetric SWC every 10 days using a neutron moisture instrument (CNC503B, China); the measurement times are shown in Table 1. Neutron tubes (ten meters long with an internal diameter of 40 mm and calibration intervals of 20 cm) were installed at each observation point. The oven-drying method for determining

Table 1 | Experimental plot conditions

Sampling site number	Sampling site label	Jujube pruning type	Dried soil layer condition	Geomorphologic positions	Aspect	Slope (°)	Altitude (m)	Detection period of soil moisture
I	Test area	Water-saving	Deep layer desiccation	Middle	East-facing	32	933	Apr. 21, 2011/Jan. 1, 2013 to Dec. 31, 2015
II	CK1 (jujube forest 1)	Conventional	Deep layer desiccation	Lower middle	East-facing	32	930	Jan. 1, 2013 to Dec. 31, 2015
III	CK2 (jujube forest 2)	Conventional	No desiccation	Upper middle	East-facing	31	947	Jan. 1, 2013 to Dec. 31, 2015
IV	15-year-old jujube plantation	Conventional	None	Upper middle	East-facing	32	938	Jan. 1, 2013 to Dec. 31, 2015
V	Farmland	–	None	Middle	East-facing	28	954	Jan. 1, 2013 to Dec. 31, 2015

gravimetric SWC was used to further calibrate collected data every month.

Growth index

In each sample plot, we randomly selected 10 jujube trees to represent average growth conditions for the growth index monitoring. Around each tree we selected eight shedding shoots in four directions to monitor average shoot length and diameter. Every seven days we measured the shoot length and diameter using a tapeline and a Vernier caliper, respectively. At the end of the fruit ripening period, we took 30 fruits from each tree in order to calculate the average fruit mass. We calculated biomass using the model proposed by She *et al.* (2015). The biomass index included: (a) the whole length and diameter of removed branches; (b) the length, diameter, and quantity of the shedding shoot(s); (c) the horizontal and vertical diameter of leaves, and the number of leaves on each shedding shoot; and (d) the horizontal and vertical diameter of the fruits, and the number of fruits on each tree.

Relative index

The soil dryness evaluation index refers to Chen *et al.* (2004); Liu *et al.* 2004; Yi *et al.* 2009). We calculated soil moisture deficits according to growth retardation SWC (equal to 60% of the field capacity) as follows:

$$K = (\theta_a - \theta)/\theta_a \cdot 100\% \quad (1)$$

where K is the soil moisture deficit in percent (%), θ is the volumetric SWC in %, and θa is the growth retardation volumetric water content in %. A K less than 0 indicates the soil moisture is not deficient. We further subdivided moderate deficits, shown in Table 2.

Soil water storage was calculated according to volumetric SWC as follows:

$$W = 10 \cdot \omega \cdot h \quad (2)$$

where W is the soil water storage in mm, ω is the volumetric SWC in %, and h is the soil layer depth in cm.

Table 2 | Evaluation index of dried soil layers in the Loess Plateau

Deficit condition	Volume soil water content (%)	Water deficit degree (%)
Minor water deficit	$>75\theta a$	<25
Moderately light water deficit	$70\theta a$–$75\theta a$	25– < 30
Moderate water deficit	$55\theta a$– $< 70\theta a$	30– < 45
Moderately heavy water deficit	$50\theta a$– $< 55\theta a$	45–50
Severe water deficit	$<50\theta a$	>50

θa is critical moisture for growth and equals 60% of the field water capacity.

The jujube water consumption is calculated by water balance method in test area. While the jujube in our test area was rain-fed with no irrigation, no deep leakage, no groundwater supply and no runoff; thus, the jujube water consumption was calculated as:

$$\mathrm{ET} = Pr + \Delta W \quad (3)$$

where ET is jujube water consumption in mm, *Pr* is precipitation in mm, and ΔW is the difference in soil water storage in mm between the start and end of the calculation period.

Available water volume is the fraction of SWC over the lower limit of available water volume, and thus could be used by jujube. Available water volume was calculated as:

$$W_{TAW} = W_{PO} - 10 \cdot h \cdot \theta_d \quad (4)$$

where W_{TAW} is the available water volume in mm, W_{PO} is soil water storage after the felling in mm, and θ_d is the available water volume limit in %. Previous research (Ma *et al.* 2012; Liu 2013; Liu *et al.* 2014; Ma 2015) by our group has shown that the depth of water consumption in a 4-year-old jujube plantation could reach to 400 cm under normal water conditions. In addition, the increases in the depth of water consumption slow down as the speed of growth slows as the jujube trees age. The depth of water consumption could reach up to 560 cm when the jujube tree was 12 years old, and 600 cm for 15-year-old trees. Liu *et al.* (2014) found that 9-year-old and 12-year-old jujube trees treated with conventional pruning could consume all of the available soil moisture from 200 to 400 cm, while the deep SWC consumption became steady. In this study, we used a value of 6.15% as the lower limit of available effective water according to the jujube actual growth; this value was the average volumetric SWC of the 0–600 cm layer of a 15-year-old jujube plantation. The remaining effective SWC was calculated as:

$$W_{RAW} = W_P - 10 \cdot h \cdot \theta_d \tag{5}$$

where W_{RAW} is the soil remaining effective SWC in mm, and W_P is the current soil water storage in mm.

Consumption of the available effective water ratio can be calculated as:

$$W_{PAWC} = (W_{TAW} - W_{RAW})/W_{TAW} \times 100\% \tag{6}$$

where W_{PAWC} is consumption of available effective water ratio at 100%.

The biomass is the sum of the biomass of each above-ground part of the jujube plant. We employed the equation established by She *et al.* (2015) to calculate the biomass:

$$B = B_1 + B_2 + B_3 + B_4 \tag{7}$$

$$B_1 = 0.002D_1^{1.564} \cdot H_1^{1.016} \tag{8}$$

$$B_2 = 0.005D_2^{1.02} \cdot H_2^{1.078} \tag{9}$$

$$B_3 = 0.00004568Z_1^{1.374} \cdot T_1^{0.901} \tag{10}$$

$$B_4 = 0.631Z_2^{3.601E} - 8 \cdot T_2^{0.999} \tag{11}$$

where B is jujube biomass in g, B_1 is the branch biomass in g, D_1 is the branch diameter in mm, H_1 is the branch length in mm, B_2 is the average biomass of the shedding shoot(s) of in g, D_2 is the average diameter of the shedding shoot(s) in mm, H_2 is the average length of the shedding shoot(s) in mm, B_3 is the average leaf biomass in g, Z_1 is the average horizontal diameter of leaves in mm, T_1 is the average vertical diameter of leaves in mm, B_4 is average fruit biomass in g, Z_2 is the average horizontal diameter of the fruit in mm, and T_2 is the average vertical diameter of the fruit in mm.

The jujube WUE was calculated as:

$$WUE_y = Y/ET \tag{12}$$

$$WUE_b = B/ET \tag{13}$$

where WUE_y is the yield water use efficiency in kg/m^3, WUE_b is the biomass WUE in kg/m^3, Y is jujube yield in kg/hm^2, B is jujube biomass converted to units of kg/hm^2, and ET is crop water consumption in units converted to m^3/hm^2.

Statistical analysis

All of the statistical analyses were performed using Origin (Version 8.0). Significant differences in soil moisture, degree of water deficit, water storage, total available water content, and remaining available water were compared among treatments via multiple comparisons. The results of the multiple comparison tests were compared with an least significant difference (LSD) post-hoc test. For the monitored soil water content data, we calculated the average value of the three replicates under the same treatment, and then used the calculated value for subsequent drawing and related index calculation. The same method was adopted for the measured growth index data of jujube trees.

RESULTS

Soil dryness

There were rain-fed apple orchards planted in 1984 in our study area, which were felled in 2007 with all parts dug out, after which the land lay idle. The SWC was monitored on the land starting 4 years after the felling (October 11–14 in 2011, DOY 273–276) and in the control farmland (the average volumetric SWC of farmland A and B) presented in Figure 1 and Table 3. We employed a value of 6.6% (volumetric SWC) as a dry layer indicator in this study, and using equation (1) we determined that our sites had a severe water deficit. We saw that the SWC of the orchard after felling and that of the farmland were nearly consistent with each other within the 0–250 cm soil layer. The average SWC in this

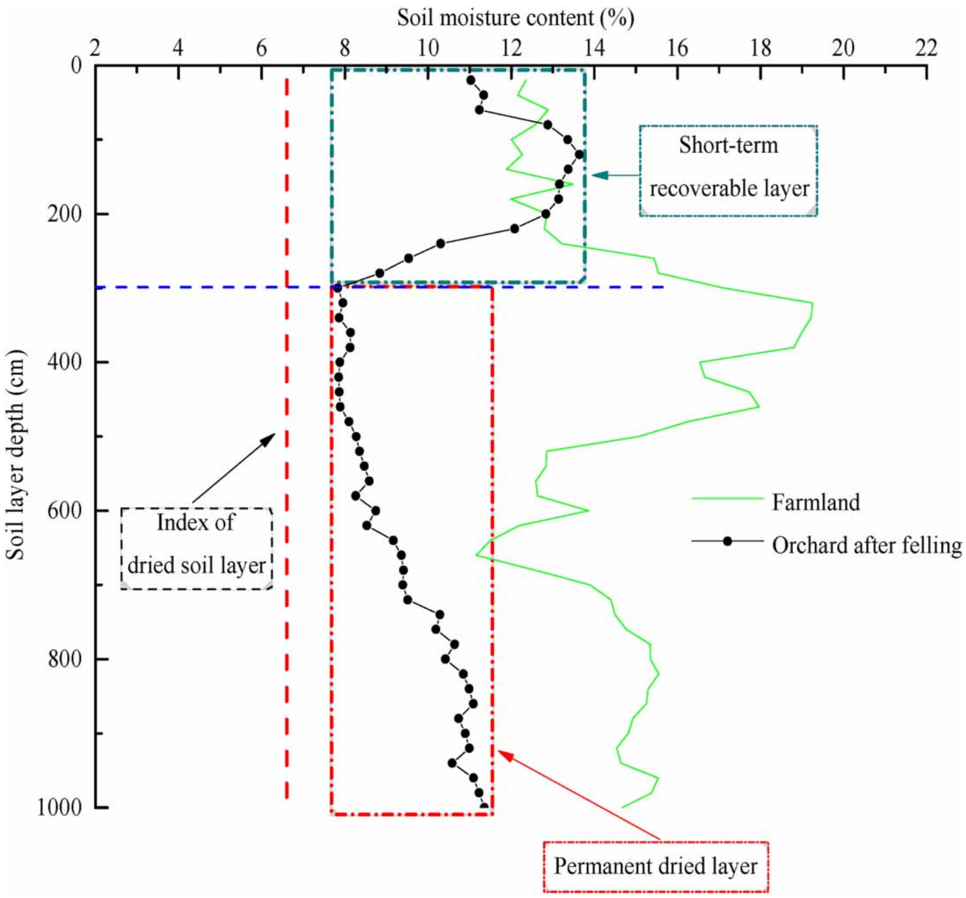

Figure 1 | Soil moisture in the 0–1,000 cm soil layer of orchards after felling and farmland.

Table 3 | Soil moisture deficit at 300–1,000 cm profile of soil in orchard after felling and control farmland

	Orchard after felling					**Farmland**			
Soil depth/cm	**Average volumetric soil moisture content (%)**	**Water deficit degree (%)**	**Deficit condition**	**Water storage (mm)**	**Proportion in farmland water storage (%)**	**Average volumetric soil moisture content (%)**	**Water deficit degree (%)**	**Deficit condition**	**Water storage (mm)**
>300–400	7.99a	45.93a	Moderate heavy	99.08a	46.91	18.55a	−27.82a	No	207.52a
>400–500	7.99a	45.90a	Moderate heavy	99.08a	46.94	16.74b	−15.26b	No	187.10b
>500–600	8.49b	41.56b	Moderate	105.28b	62.51	12.96c	6.50c	Minor	160.69c
>600–700	9.17c	36.82c	Moderate	113.74c	71.38	12.26c	11.49c	Minor	152.12c
>700–800	10.21d	24.32d	Minor	126.57d	68.66	14.87b	−7.32b	No	184.44b
>800–900	10.91e	21.26e	Minor	135.59e	71.94	15.17b	−9.46b	No	188.12b
>900–1,000	11.05e	20.26e	Minor	136.99e	73.92	14.95b	−7.88b	No	185.41b

For each column, values followed by the same letter are not significantly different according to the LSD multiple testing ($P < 0.05$).

layer differed by only 1.3% (Table 3). This layer self-restored in the 4 years post-felling without any human interference. SWC was gradually closer to the dry layer indicator as depth increased within the 250–300 cm layer, but within the 0–300 cm layer the SWC gradually migrated from top to bottom via the infiltration of rainwater. So, we named this layer the short-term recoverable layer. SWC was the closest to the dry layer indicator in the 300–500 cm layer, indicating a severe water deficit, and rainwater infiltration cannot reach this layer; thus, this layer was named the difficult recoverable layer. Although SWC was improved within the 500–1,000 cm layer compared to that within the 300–500 cm layer, it was still obviously lower than that of the same depths in the farmland. That means apple forests consumed the soil moisture to depths reaching 1,000 cm before felling, and we called the dried layer of more than 300 cm a permanently dry layer (Wang *et al.* 2000). At 300–1,000 cm, the average volumetric SWC of the orchard after felling was 9.40% and water storage was 816.03 mm, while at the same layer in farmland the SWC and water storage was 15.07% and 1,308.25 mm, respectively. The amount of water storage of the orchard after felling was 37.62% lower than that of the farmland, which can be regarded as the water storage consumed by the apple forest over the course of the 23 years of past cultivation. The depth of water consumption by the 23-year-old apple forest reached up to 1,000 cm, which was consistent with the results of research on a number of dry farming apple orchards in semiarid loess hilly areas noted by Cao *et al.* (2012).

SWC within the 0–300 cm layer was greatly affected by precipitation and surface plants and, due to the influence of precipitation, this layer had been restored to a certain extent during the 4-year fallow period. Given this recovery, we analyzed the degree of soil drying below 300 cm (Table 3). The degree of soil moisture deficit decreased with increased soil depth in the orchard after felling. Within the 300–500 cm layer, the soil moisture was classified as a moderately heavy deficit. The classifications of the >500–700 cm and >700–1,000 cm layers were moderate deficit and minor deficit, respectively. The soil water storage in the 300–500, >500–700, and >700–1,000 cm layers was 46.93%, 66.82%, and 71.51% of the same layer in farmland, respectively. In farmland, the soil moisture of the 300–500 cm and >700–1,000 cm layers showed no deficit, and only a minor deficit in the >500–700 cm layer. It is generally believed that crops only consume rainfall from the current year in dry farming, and so they tend to consume only shallow soil moisture without forming a permanently dry layer (Wang *et al.* 2000; Liu *et al.* 2004). The minor deficit within the >500–700 cm layer of farmland may be caused by the differences in soil particle composition that are not affected by crop water consumption (Wang *et al.* 2009). Table 3 shows the inconsistency of the soil moisture deficit and SWC differences of the different layers. These results indicate that the traditional classification of the soil moisture deficit is not as accurate as the statistical analysis. For example, in the orchard after felling, soil moisture of the >500–600 cm and >600–700 cm layers were both consistent with a moderate deficit, but there was a significant difference ($P < 0.05$) in the soil moisture content of these two layers. In farmland, soil moisture in the >300–400 cm and >400–500 cm layers showed no deficit, but there was a significant difference ($P < 0.05$) in the soil moisture content of these two layers.

Changes in soil moisture after planting jujube trees

Figure 2 and Table 4 show the soil moisture of the jujube forest in our study area from 2013–2015 and the available soil moisture on April 21, 2011 of the jujube forest converted from the measured SWC of the orchard after the felling. As shown in Table 4, the total available water was 387.77 mm in the 0–1,000 cm layer, and 149.71 mm in the 0–300 cm layer. The remaining available water decreased year by year with the growth of jujube forest: 334.22 mm (3 years old), 262.05 mm (4 years old), and 252.21 mm (5 years old). The proportion of available water consumption was 13.59% (3 years old), 21.59% (4 years old), and 3.64% (5 years old). Figure 2 and Table 4 show that during the years of jujube forest growth, the trees mainly consumed water in the 0–300 cm soil layer, and the overall available water consumption was 131.20 mm. The amount of available water consumed by the 3-year-old jujube forest was 34.97% of the total available water, and that of the 4-year-old jujube forest was 48.07%. The 5-year-old jujube forest only consumed 4.59% of the total available water due to the lack of available water. The jujube forest basically lost the effective supply of soil moisture after the age of 4 years old.

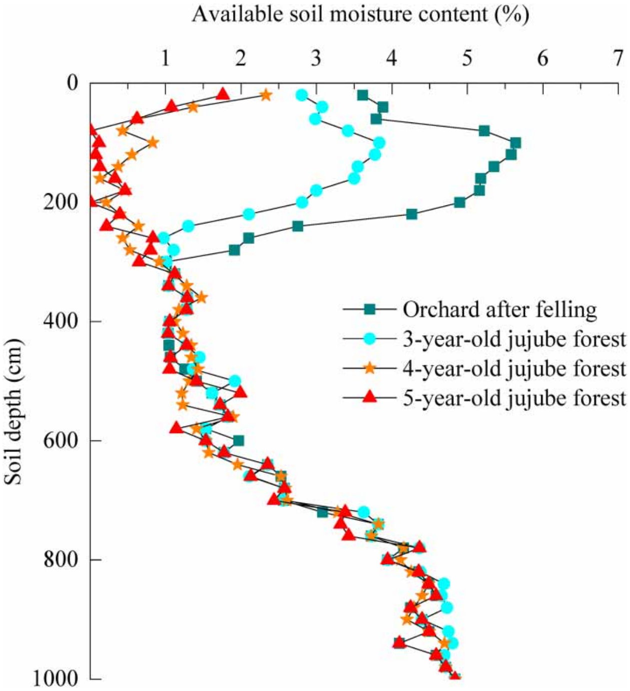

Figure 2 | Available soil moisture content of orchard after felling and 3-, 4-, and 5-year-old jujube forests.

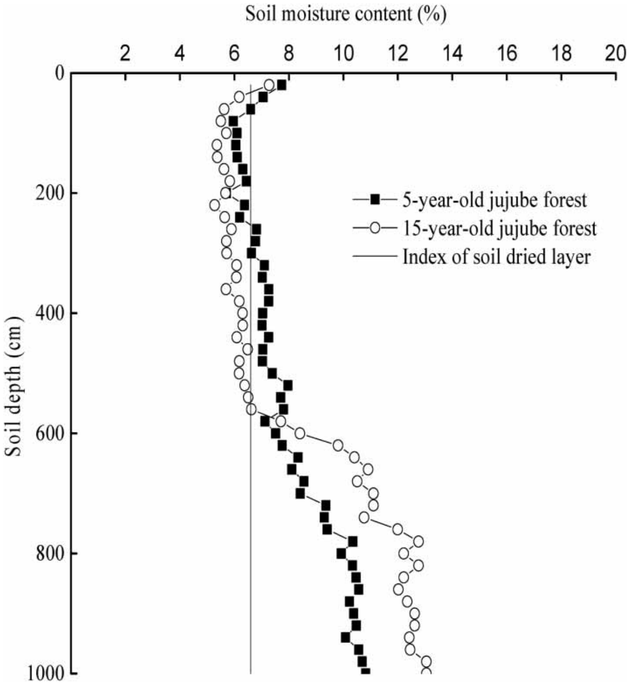

Figure 3 | Soil moisture content of 5-year-old jujube forests in the test area and 15-year-old jujube forests.

Figure 3 shows the SWC of the 5-year-old and the 15-year-old jujube forest. The average SWC of the 0–600 cm soil profile in the 15-year-old jujube forest can be used as the lower limit of available water for the growth of jujube trees, as the SWC in this layer was lower than the dry layer index, which indicates the jujube tree has a stronger water absorption capacity than apple trees. The average SWC in the 0–600 cm soil layer of the 15-year-old jujube forest was 6.15% while that of 5-year-old jujube forest in test area was 6.88%. The difference between them was only 0.73%, which is very small. That means the soil moisture condition of the 0–600 cm layer in our test area was close to that of the 15-year-old jujube forest, thus, the roots of the jujube tree would not extend to the soil layer lacking water, and jujube trees replanted in the test area lacked deep soil water storage. Based on this analysis, we concluded that

Table 4 | Variation of available water content during growth of the jujube forest in the 0–1,000 cm soil layer

	Orchard after felling	3-year-old jujube forest		4-year-old jujube forest		5-year-old jujube forest	
Soil depth (cm)	Available moisture content (mm)	Remaining available moisture (mm)	Proportion of available moisture consumption (%)	Remaining available moisture (mm)	Proportion of available moisture consumption (%)	Remaining available moisture (mm)	Proportion of available moisture consumption (%)
0–100	54.94a	39.98a	27.23	13.87a	47.52	8.87a	9.10
>100–200	64.90a	41.25a	36.44	4.29b	56.95	2.46b	2.82
>200–300	29.87b	16.12b	46.03	7.22c	29.79	7.18a	0.13
>300–1,000	237.06c	236.87c	0.08	236.67d	0.08	234.00c	1.13
Whole soil profile (0–1,000 cm)	386.77	334.22	13.59	262.05	21.59	252.51	3.64

For each column, values followed by the same letter are not significantly different according to the LSD multiple testing ($P < 0.05$).

the lack of deep soil moisture may inhibit the growth of jujube roots in the test area. Since the depth of water consumption of the 5-year-old jujube forest was only about 300 cm, the tree growth only relied on the current year of precipitation and the infiltration of precipitation into the shallow soil layers, and the function of soil reservoir basically disappeared.

The growth and WUE of jujube trees planted in dry soil

We compared the changes of the jujube trees of the 4-year-old and 5-year-old jujube forests in CK1 and the test area, including the average length of the shedding shoot of the jujube tree (L_1), the accumulated length of removed branches (L_2), and the biomass of a single tree (B_1) (Figure 4). As shown in Figure 4, L_1, L_2, and B_1 all increased with time and tended to stabilize after reaching a certain value. The precipitation in 2015 was less than that in 2014, thus, the growth rate and final value of all indicators were lower in 2015 compared to 2014, indicating that the growth of the jujube tree is significantly affected by the precipitation in the loess hilly area. The final value of L_1 in 2015 decreased by 34.26% in the test area, and by 32.46% in CK1 when compared to 2014. In 2014 the final value of L_1 in the test area was 1.08 times that in CK1, and that was 1.05 times the value in 2015. Jujube trees in the test area were pruned with a water-saving technique, or WSP, and the pruning intensity was higher than that in the control area. Under these circumstances, L_1 was still slightly higher than that in CK1, indicating that WSP was beneficial to the reproductive growth of the jujube trees, which was also the basis of yield. The effect of the intensity of pruning was embodied by L_2. The pruning amount in the test area of two years was both greater than that in CK1, and the pruning amount of the test area and CK1 both decreased in 2015. In 2015, B_1 decreased by 22.31% compared to the test area in 2014, while that of CK1 was 52.33%. Meanwhile, B_1 in the test area decreased by 56.77% compared to that of CK_1 in 2014, and by 81.89% in 2015. This indicated that the decrease of precipitation had a greater impact on the biomass of the jujube trees in CK1 than in the test area. The influence of precipitation on the growth of jujube trees in the test area can be reduced to some extent by using WSP to reduce transpiration-related consumption (Wang *et al.* 2009; Xie *et al.* 2014).

Table 5 shows the fruit growth status, biomass, yield, water consumption, and WUE of jujube trees at the ages of 4 and 5 in the test area, CK1 and CK2 sites. A higher WUE is key to the sustainable and stable development of agriculture under the condition of water shortage (Wang *et al.* 2000). In this study, we analyzed WUE_b (the yield WUE) and WUE_y (the biomass WUE).

As can be seen from Table 5, the fruit number of 4- and 5-year-old jujube trees in the test area was larger than in CK1 and CK2, but the single fruit mass had very little difference. The water consumption of jujube trees in the test area was lower than that of jujube trees in CK1 and CK2 during the

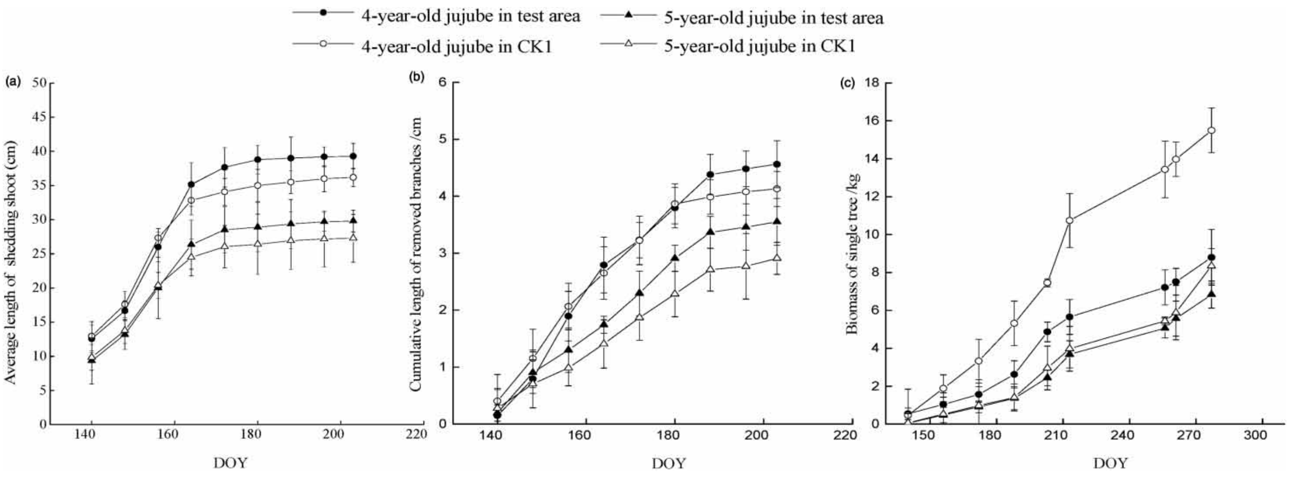

Figure 4 | Average length of shedding shoot (a), cumulative length of removed branches (b), and biomass of single trees in the test area and CK1 (c).

Table 5 | Average fruit weight (AFW), number of fruits (NF), biomass, yield, water consumption (WC), and water use efficiency (WUE) of jujube trees under different treatments

	4-year-old jujube tree							**5-year-old jujube tree**						
Treatment	**AFW (g)**	**NF**	**Biomass ($kg\ m^{-2}$)**	**Yield ($kg\ hm^{-2}$)**	**WC ($m^3\ hm^{-2}$)**	**WUE ($kg\ m^{-3}$)**		**AFW (g)**	**NF**	**Biomass ($kg\ m^{-2}$)**	**Yield ($kg\ hm^{-2}$)**	**WC ($m^3\ hm^{-2}$)**	**WUE ($kg\ m^{-3}$)**	
						WUEY	**WUEB**						**WUEY**	**WUEB**
Test area	14.5	328	8.8	7,930.81	1,191.68	6.7	4.9	11.3	220	6.8	4,156.12	851.6	4.9	5.3
CK1	14.1	98	9.1	2,300.70	1,200.50	1.9	5.1	11.1	76	7.3	1,404.60	881.3	1.6	5.5
CK2	14.9	229	15.5	5,693.55	1,303.80	4.4	7.9	11.1	157	8.3	2,910.84	980.5	3.0	5.6

WUEY is yield water use efficiency, kg/m^3; WUEB is biomass water use efficiency, kg/m^3.

two years. The biomass of 4-year-old jujube trees in the test area was 97 and 57% of that in CK1 and CK2, respectively; WUE_b was 96 and 62% of that in CK1 and CK2, respectively. The biomass of 5-year-old jujube trees in the test area was 93 and 82% of that in CK1 and CK2, respectively; WUE_b was 96 and 95% of that in CK1 and CK2, respectively. The main reason was water-saving pruning that limit vegetative growth of the jujube trees in the test area. The yield of 4-year-old jujube trees in the test area was 3.45 times and 1.39 times that in CK1 and CK2, respectively; the test area WUE_y was 3.53 times and 1.52 times that in CK1 and CK2. In 2015 the jujube trees were 5 years old, due to the decrease of precipitation in 2015, the yields of the test area, CK1 and CK2 were both lower than in 2014. But the yields of 5-year-old jujube trees in the test area was still 2.96 times and 1.43 times that in CK1 and CK2, respectively; the test area WUE_y was 3.06 times and 1.63 times of that in CK1 and CK2, respectively. The yield and WUE of jujube trees in the test area were much higher than those in CK1, which had the same dry deep soil condition. The deep soil moisture regulation capacity in both areas was poor, and precipitation became the dominant factor influencing jujube tree yield. That indicates that water-saving pruning can keep the size of jujube trees to a small range in order to maintain a higher WUE despite different precipitation conditions.

DISCUSSION

Soil dried layers of jujube forests in loess hilly regions

On the Loess Plateau, evaporation is greater than precipitation, and groundwater is buried deeply, which are the main reasons why the soil is often water deficient. In addition, water consumption of plantation forests intensifies the process of soil water consumption, and soil water deficits significantly increase (Zhang 2017). Precipitation in the Loess Plateau can only reach the lower boundary of the alternating layers of wet and dry soil during the processes of surface infiltration and evapotranspiration, and the plantation forests consume a lot of water. As a result, the soil that used to be desiccated and short of water has become dried layers (Zhang *et al.* 2012, 2017). The dried layer becomes the isolation layer of water transfer, which interrupts the path of precipitation and vertical infiltration needed to recharge groundwater (Li 2005). The exchange of soil moisture between the upper and lower layers is cut off or slowed down (Chen *et al.* 2005), which led to the weakened function of the 'soil reservoir' (Li & Shao 2006), reduced survival rates of vegetation, slowed growth of vegetation, and led to even large areas of vegetation death (Hou *et al.* 1999). Soil moisture deficiency has become the main limiting factor of vegetation restoration and environmental reconstruction on the Loess Plateau (Chen *et al.* 2007, 2008). There is plenty of evidence that soil desiccation in the Loess Plateau is due to the dual effects of natural and man-made factors (Zhao *et al.* 2012), and the natural factors mainly refer to the arid climate of the region, which can hardly be directly changed by human beings. In the process of vegetation reconstruction on the Loess Plateau, people have unilaterally pursued fast growth, high yield, and high WUE (Guo & Shao 2003; Chen *et al.* 2008), and they have failed to follow the rules of vegetation succession. As a result, plantation density is too high, the natural vegetation is damaged, and the climate in this region is drying up (Li *et al.* 2005), leading to the development of soil desiccation

(Yang *et al.* 1998; Shi & Shao 2000; Zhong *et al.* 2004; Li & Shao 2006).

The desiccation and restoration of the Loess Plateau are mutually restricted with the environment, and is the synergy result of internal and external conditions (Yang *et al.* 1999; Wu *et al.* 2004; Li 2005; Ma *et al.* 2005). In recent years, the focus of research has gradually shifted to whether human activities can regulate the causes of the formation of dried layers in the Loess Plateau (Wang *et al.* 2007), thereby slowing down or reducing soil desiccation. Zhang *et al.* (2003) believed that the problem of dried layers could be solved if precipitation can be fully used via methods like retaining precipitation and increasing infiltration rates. Hou *et al.* (1999) believed that small topography, ground composition, tree species and afforestation technologies, and other factors will have an impact on the soil dried layers, and may significantly improve the soil moisture status; this is in line with the research conducted by our group. As a kind of afforestation technology to ensure the survival of jujube trees, we found WSP has achieved a positive impact on jujube survival and growth. Previous mulching measures have changed the underlying surface of jujube forest, reduced evaporation and increased precipitation infiltration, and improved the soil moisture status in jujube forest (Yang *et al.* 2010; Li *et al.* 2015; Feng *et al.* 2016; Hu *et al.* 2017). However, due to the ecology of the formation of dried layers (Wang *et al.* 2003), vegetation growth in deep dried soil is mainly restricted by the arid climate (Chen *et al.* 2005). In addition, for the young age of the jujube trees, these two studies are still conducted independently. In the future, both measures can be combined to increase precipitation infiltration and reduce transpiration water consumption of the jujube forest. After the survival of jujube forests in our study area, it will slow down the drying process of the regional climate and have an impact on the regional microclimate to some extent. A wetter microclimate will provide favorable conditions for the reconstruction and survival of vegetation in the larger area and play a positive role in the restoration of dried soil layers.

Conventional versus water-saving pruning

The horticultural pruning used in the daily management of orchards is what we call conventional pruning. Fruit trees are pruned to cultivate the appropriate size, structure, and characteristics of the canopy through the construction and management of a reasonable shape of the fruit trees (Kato *et al.* 2004). Pruning can regulate the growth and fruit yield to achieve the goal of high yields and high-quality fruits under certain conditions (Ma 2011). The common pruning techniques for fruit trees are cutting branches and tips, removing buds and leaves, pinching, bending or binding branches, bending or shorting roots, girdling, and so on. There have been many studies on the management of fruit tree canopies by pruning. The growth and development of fruits are based on the changes of environment and ecological factors in the canopy, and the propagation and distribution of natural light radiation in the canopy is the most influential factor of plant photosynthesis (Palmer 1989; Robinson & Seeley 1991; Sonohat *et al.* 2002). Optimizing the illumination intensity and distribution within the canopy in order to improve the utilization rate of light energy is helpful to improving the yield, fruit quality, and economic benefit of fruit trees (Widmer & Krebs 2001; Hampson *et al.* 2002; Gao *et al.* 2003; Bellow & John 2004). Previous studies on pruning that focus on increasing yield and quality (Asrey *et al.* 2013) are concerned with the comprehensive evaluation and qualitative optimization of different pruning methods in order to qualitatively recommend better pruning methods. However, few studies have been conducted on the quantitative relationships between the amount of pruning, transpiration water consumption, and yield.

WSP is designed to solve this issue. Different from the existing jujube pruning methods, WSP regulates the growth of jujube trees through the construction of a reasonable tree shape and canopy structure and the cultivation and management of branches at all of the levels, but its ultimate purpose is to improve the WUE of the jujube trees. As a jujube garden management technology, WSP can be used to determine the reasonable jujube tree yield based on local precipitation and different soil moisture conditions, the reasonable jujube tree size based on jujube tree yield, and thus to realize the reasonable control of jujube tree size through pruning (Zhao *et al.* 2012). Wei (2015) and Wang *et al.* (2017) have shown that WSP can regulate the transpiration of jujube trees by controlling the tree size, resulting in significantly reduced water consumption, improved WUE, and an effective method to influence the formation and restoration of soil dried layers in jujube forests.

There are two sides to everything, and the same is true of pruning. It is necessary to determine the appropriate pruning time and intensity for water-saving pruning to achieve the desired results. As for the timing of pruning, previous research in our group has yielded exact results. The pruning stage of jujube is divided into a dormant pruning (from February to April every year) and a growing period pruning (from May to August every year). Jujube can be pruned in winter and summer, but it should be based on the temperature in different areas. This is consistent with the research of Wu & Zhang (2013). We considered the effect of temperature when pruning in this study, but due to time constraints, we were unable to confirm the ideal pruning intensities in this study. Using the previous findings of our group (Nie 2017) in combination with the soil moisture condition of the test area, we chose a single intensity level. In this study, there are only 5-year-old jujube plantations, which are saplings of fruit trees. In order to determine whether they can reach an age with normal growth in the deep dried soil, if they can achieve stable yields for a long time, and whether the deep dry soil environment and pruning measures affect the roots of jujube trees, we would need longer experimental observations. With regard to this issue, we will supplement gradient tests of pruning intensities in later experiments to determine the appropriate intensity of water-saving pruning in dried soil. Pruning intensity should also be combined with the jujube tree age, because as the jujube tree ages it enters different growth stages, and the proportion of vegetative growth and reproductive growth will change (Xia 2004). We know that the responses of jujube trees to pruning at different growth stages vary from tolerance to the production of compensatory growth (Bassi *et al.* 1994; Balandier *et al.* 2000). Theoretically, soil water storage plays a critical role in regulating the growth of jujube trees. Although the regulating function of deep dried soil is greatly reduced, the appropriate pruning intensity could potentially maintain the continuous growth and appropriate yield of the jujube trees. Meanwhile, pruning could reduce the transpiration-related water consumption of the jujube trees to compensate for reduced soil moisture to some extent.

CONCLUSIONS

In the semiarid loess hilly region, excessive pursuit of economic benefits will result in the soil desiccation in the area, the future development will stagnate due to water shortages in the long run. We should take ecological benefits into account while pursuing economic benefits, and ensure sustainable development by controlling reasonable output and making full use of precipitation. Through this study, we believe that water-saving pruning is a reasonable measure suitable for the management of jujube forests in the study area, and can play a positive role in the restoration of moisture in the desiccated soil in the study area to a certain extent.

ACKNOWLEDGEMENTS

We acknowledge the support of the staff from the Northwest A&F University Experiment Station and the valuable suggestions of the anonymous reviewers. We thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript.

AUTHOR CONTRIBUTIONS

J. P. Ma and W. F. Zhang contributed to the yield experiment maintenance and data collection. X. N. Zhao and Y. K. Wang contributed to the study design. X. Wang and J. P. Ma performed the Origin (Vision 8.0) for data analyses and graphs. Data interpretation was performed by all authors. J. P. Ma actively participated in the writing of the manuscript. All authors provided significant input to the final manuscript.

FUNDING

This research was funded by the China National Support Program (No. 2015BAC01B03) and the China National Forestry Charity Project (No. 201404709).

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 3 December 2020; accepted in revised form 8 April 2021. Available online 29 April 2021