Effects of pruning intensity on jujube transpiration and soil moisture of plantation in the Loess Plateau

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Effects of pruning intensity on jujube transpiration and soil moisture of plantation in the Loess Plateau

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Abstract. In order to ease soil desiccation and prevent ecological deterioration in the Loess Plateau, where jujube (Zizyphus jujube Mill) is widely cultivated as a drought tolerant plant, four pruning intensities (PI), from PI-1 (light) to PI-4 (heavy) were set up based on total length of secondary branches to study the effects of pruning on transpiration and soil moisture in jujube plantations. Furthermore, growth indexes were regularly monitored to estimate jujubes biomass. Sap flow, meteorological and soil moisture conditions were monitored using thermal dissipation probes (TDP), weather station (RR-9100) and the combination of time domain transmission (TDT) technology and neutron moisture gauges (CNC503B), respectively. The results showed that daily actual transpiration of jujube was positively correlated with leaf biomass. Compared with PI-1, jujube transpiration during growth period under PI-2, PI-3, and PI-4 dropped by 11.1%, 29.2%, and 47.9%, respectively. On the contrary, annual water storage under PI-2, PI-3, and PI-4 increased by 6.29 mm, 25.78 mm and 34.74 mm while water use efficiency increased by 5.1%, 15.7% and 24.2%, respectively. Overall, increase in pruning intensity could significantly reduce water consumption of jujube and improve soil moisture in jujube plantations.

1. Introduction
Drought and soil erosion are critical limitations for ecological restoration and agricultural development in the Loess Plateau of China [1]. Soil and water loss in the Loess Plateau have significantly improved since the passing of the policy to reconvert farmlands to forests by the Chinese Government in 1999. However, due to the farmland-to-forest conversion policy, increase in vegetation cover has increased demand for soil water. Meanwhile, the increasing vegetation cover has also increased soil water deficit on the Loess Plateau. Large areas of dry soil layers have developed with deregulation of forest soils, a condition that has affected normal vegetation growth and has resulted in degradation and decline in the community and ecosystem [2-4]. Preventing the severe soil desiccation and the deterioration of ecological environment in the semiarid hilly region is a major ecological issue in the study area.

Jujube (Zizyphus jujube Mill) is a major economic forest in the Loess Plateau. The planting area of jujube in Shanxi province exceeds 100 acres, mostly planted in the mountains where dry farming is the
main mode of cultivation due to the severe scarcity of water for irrigation [5]. In the effort to protect the fragile local ecological environment, various water-saving technologies have been proposed, including rainwater harvesting for micro-irrigation, interception ditches and mulching to hold back soil moisture, all of which aim at increasing rainfall infiltration, reducing surface evaporation, increasing water use efficiency and increasing yield of jujube [6-9]. But as water consumption by jujube plant increases with increasing plant age [10], soil desiccation has worsened [4] and traditional water-saving technologies in the region have become ineffective.

Pruning not only regulates fruit tree canopy by increasing light conditions, tree growth and fruit quality [11, 12], but also reduces plant transpiration and improves soil moisture conditions [13-15]. Zhao argued that pruning of jujube plantations can reduce plant water consumption, which can contribute towards water-saving. The study further noted that pruning maintains target yield of plantations under natural rainfall and soil moisture conditions, also prevents soil desiccation and ecological degradation [16]. In recent years, a series of studies have been conducted on jujube water consumption mechanism [5, 10, 17-19], biomass modeling [20] and transpiration response to main branch pruning [21].

Due to limitations in observations and analysis methods, the complete effect of pruning on plant characteristics remain unclear. Issues such as insufficiency and imprecision of pruning index are still not conclusive. Thus in this study, jujube plantations in semiarid hilly region of the Loess Plateau were investigated as total length of secondary branches was used to establish pruning index. The established index was in turn used to determine the correlations between tree size and water consumption of jujube plantation. The study would provide a theoretical basis for soil desiccation prevention and cure, water-saving agriculture and perfect water-saving pruning method for jujube plantations in semiarid hilly regions.

2. Materials and Methods

2.1 Study site
This study was conducted for the period from 1st January to 31st December 2015 at the Mizhi Experimental Station (38°11’N, 109°28’E) of Northwest Agriculture and Forestry University. The study area belongs to the Loess Plateau region, where topographical characteristics are typically loess/gullies with semi-arid temperate climate. Mean annual rainfall in the station is 451.6 mm (which mostly occurs in July through September), with mean annual temperature, sunshine duration, percent sunshine, total radiation and mean elevation of 8.4 °C, 2761 h, 62%, 580.5 kJ/cm², 1049 m, respectively. The average depth to water table is over 50 m with loess soil of uniform texture and moderate permeability. The mean bulk density of soil (depth of 1.0 m) is 1.29 g/cm³, with field capacity of 23% and wilting moisture content of 5.16% (percent mass).

2.2 Pruning design
Jujube trees of 9-year-old tested (Lizao jujube variety) were planted in row and stand spacing of 3 m × 2 m on horizontal bed sloping eastwards at 25° and bed width of 2 m. A total of 16 jujube trees were observed on 4 horizontal beds (Figure 1), each treated as an independent test plot with 4 trees measured and others in a plot pruned at the same intensity.
Shoots with fruits and leaves were mainly secondary branches of the jujube trees and therefore the main fruit bearing parts. Besides, Wei proved that number of main branches of jujube affect its transpiration mainly due to size of trees after pruning, to regulate size of trees more accurately and study effects of tree size on transpiration, total length of secondary branches was used as pruning intensity (PI) index and four PIs (from PI-1 to PI-4) were set for four plots (Table 1). The control treatment was the jujube tree of PI-1, was the traditional PI with maximum yield. Pruning was taken every 5 days from 1st May (before sprouting) to 15th October to maintain the tree size. For jujube under each pruning intensity (PI), if the number or length of secondary branches on a main branch was not enough for the design, the number or length of secondary branches on other main branches was increased to make up for the deficiency. Thus, PI was decided by total length of secondary branches.

Table 1. A table detailing the pruning design of each pruning intensity (PI) used in the study.

<table>
<thead>
<tr>
<th>PI</th>
<th>Number. of main branches</th>
<th>Number. of secondary branches</th>
<th>Length of secondary branches (cm)</th>
<th>Total length of secondary branches (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI-1</td>
<td>3</td>
<td>27</td>
<td>33.3</td>
<td>800±20</td>
</tr>
<tr>
<td>PI-2</td>
<td>3</td>
<td>24</td>
<td>28.6</td>
<td>600±15</td>
</tr>
<tr>
<td>PI-3</td>
<td>2</td>
<td>14</td>
<td>28.6</td>
<td>400±12</td>
</tr>
<tr>
<td>PI-4</td>
<td>1</td>
<td>6</td>
<td>33.3</td>
<td>200±10</td>
</tr>
</tbody>
</table>

2.3 Measured and calculated indices

2.3.1 Jujube growth indices. Using measuring tools such as the vernier caliper and measuring tape, the growth index of jujube was measured every 7 days. The indices measured included the number of main and secondary branches, the length and diameter of main and secondary branches, the number, length and diameter of jujube branches, the number of fruits and leaves, and the transverse and longitudinal diameter of fruits and leaves. Jujube plant biomass of each part was calculated using the specialized jujube biomass model [20] as follows:

\[
W_{\text{branch}} = 0.002 \times D_1^{1.564} \times H^{1.016} \quad (1)
\]

\[
W_{\text{fruit shoot}} = 0.005 \times D_1^{1.02} \times H^{1.078} \quad (2)
\]

\[
W_{\text{leaf}} = 4.568 \times 10^{-5} \times Z^{1.374} \times T^{0.901} \quad (3)
\]

\[
W_{\text{fruit}} = 0.631 \times D_1^{2.601 \times 10^{-8}} \times D_2^{0.999} \quad (4)
\]

where \(W\) is biomass of each jujube part (g); \(D\) is diameter of jujube branch and shoot (mm); \(H\) is length of jujube branch and shoot (mm); \(Z\) is longitudinal length of leaf (mm); \(T\) is transverse length of leaf (mm); \(D_1\) is longitudinal diameter of fruit (mm); and \(D_2\) is transverse diameter of fruit (mm).
2.3.2 *Jujube sap flow and transpiration.* Thermal diffusion method was used to monitor jujube sap flow and the data recorded from April 30 through October 15 of 2015. To eliminate detection errors due to position and height, thermal diffuse probes (TDP, Dynamax Co., USA) were installed to the north of jujube trunks at about 20 cm above the land surface. Silver membranes of 30 cm width were used to package the probes in order to reduce the impact of external environment [22]. The CR1000 data logger (Campbell, Co., USA) was used to record sap flow every 10 min. Sap flow density was calculated [23] as follows:

$$J_s = 119 \left( \frac{\Delta T_m - \Delta T}{\Delta T} \right)^{1.231}$$

(5)

where $J_s$ is sap flow density (g/m$^2$s); $\Delta T$ is the temperature difference between heated and unheated probe (°C); and $\Delta T_m$ is the temperature difference at zero sap flow (°C).

Therefore, daily actual transpiration of jujube was calculated as follows:

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

(6)

where $AT$ is daily actual transpiration (mm/d); $A_s$ is area of sap wood (cm$^2$); and $J_{si}$ is sap flow density at 10*i min. To determine sapwood area of tested jujube, a regression equation between $A_s$ and the diameter at breast height (DBH) was obtained through the investigation of jujubes as: $A_s = 0.8249 \times \text{DBH} + 1.5634$, $R^2 = 0.8901$, where $A_s$ is sapwood area (cm$^2$) and DBH is breast-height diameter of jujube (cm). Transpiration water use efficiency of Jujube was calculated as follows:

$$WUE = \frac{Y}{AT'}$$

(7)

where $WUE$ is transpiration water efficiency of jujube (kg/m$^3$); $Y$ is yield of jujube (kg/hm$^2$); and $AT'$ is total transpiration during jujube growth (m$^3$/hm$^2$).

2.3.3 *Soil moisture.* Roots of the jujube trees older than 10 years can reach the depth of 10 m [24]. Based on preliminary investigations, roots jujube trees can reach the depth of 7 m in the study area. Thus the soil moisture monitoring neutron tubes were set to the depth of 10 m. In the study area, however, it has been noted that change in soil moisture mainly occurs in the 0‒2.6 m depth soil layer, and inter-annual variations in soil moisture are low [19]. In order to determine the effects of pruning intensity on soil moisture of jujube plantation, 3 neutron probes were set 3 m apart in each plot. The neutron probes (CNC503B, China) were used to collect soil moisture data at every 20 cm depth of 0-300cm soil layer every 10 days. Tree plant water demand is generally affected by available moisture in the soil layer with fine root network [25]. In this study, fine roots (mainly water-absorbing tissues) of jujube trees were mainly concentrated in the 0–1 m depth soil layer [24]. To get detailed soil moisture data for the 0–100 cm depth soil layer to analyze the effects of soil moisture on transpiration, TDT soil moisture probes (Acclima, USA) were set at 20 cm, 40 cm, 60 cm, 80 cm and 100 cm depths, respectively at about 50 cm north of the jujube branches. The probes were connected with the CR1000 data logger and data collected every 1 h. Soil moisture condition was classified based on relative effective water (REW) as follows[23]:

$$REW = \frac{SWC - SWC_{min}}{SWC_{max} - SWC_{min}}$$

(8)

where $SWC$ is soil moisture (%); and $SWC_{max}$ and $SWC_{min}$ are the maximum and minimum soil moisture (%) for the period of study.

The soil water storage was calculated as follows:

$$W = \theta_v \times h$$

(9)

where $W$ is soil water storage (mm); $\theta_v$ is percent soil moisture by volume (%); and $h$ is soil depth (cm).

2.3.4 *Meteorological factors.* Weather station (RR-9100, UK) was in the study area and the weather station data collected every 10 min. Meteorological indices monitored included rainfall (mm), total radiation (W/m$^2$), net radiation (W/m$^2$), photosynthetically active radiation (μmol/m$^2$s), wind speed (m/s), temperature (°C) and relative humidity (%). Vapor pressure difference (VPD) was calculated from temperature and relative humidity [26] as follows:
\[ VPD = 0.6108 \times (1 - RH) \times e^{12.27T/(T+273.3)} \]  \hspace{1cm} (10)

where \( VPD \) is vapor pressure difference (kPa); \( RH \) is relative air humidity (%); and \( T \) is temperature of air (°C).

Generally, vapor pressure difference accounts for over two-thirds and solar radiation accounts for most of the remained one-third of total transpiration [5, 27-29]. Thus variable transpiration [5, 27-29], which is an integrated index, was used to classify meteorological condition and \( VPD \) and radition (\( Rs \)) calculated as follows:

\[ VT = VPD \times Rs^{1/2} \]  \hspace{1cm} (11)

where \( VT \) is variable transpiration [kPa(W/m^2)^{1/2}]; \( VPD \) is deficit saturated vapor pressure (kpa); and \( Rs \) is total radiation (W/m^2).

2.4 Data analysis
Excel 2012, PASW Statistics 18.0 and SigmaPlot 12.5 were used to analyze the data and draw relevant figures. The variables measured with their equipments, time interval and start & finish date could be seen in Table 2.

<table>
<thead>
<tr>
<th>Measured variable</th>
<th>Equipment</th>
<th>Time interval</th>
<th>Start &amp; Finish date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jujube growth index</td>
<td>Vernier caliper, etc</td>
<td>7 days</td>
<td>2015/4/30-2015/10/15</td>
</tr>
<tr>
<td>Jujube sap flow</td>
<td>TDP probes</td>
<td>10 minutes</td>
<td>2015/4/30-2015/10/15</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>TDT probes</td>
<td>1 hour</td>
<td>2015/1/1-2015/12/31</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>Neutron probes</td>
<td>10 days</td>
<td>2015/1/1-2015/12/31</td>
</tr>
<tr>
<td>Meteorological factors</td>
<td>Weather station</td>
<td>10 minutes</td>
<td>2015/1/1-2015/12/31</td>
</tr>
</tbody>
</table>

3. Results
3.1 Pruning intensity and transpiration
3.1.1 Pruning and sap flow. Following different PIs, jujube sap flow was monitored under different meteorological conditions (sunny, cloudy and rainy days) in September 2015 to determine the effect of pruning on sap flow. Vegetative growth of jujube trees basically ended before September and therefore the amount of branches and leaves was stable. The measured sap flow in jujube trees is plotted under different PIs in Figure 2. Note that plate (a, d) is for sunny day on September 6, 2015; plate (b, e) is for cloudy day on September 8, 2015; and plate (c, f) is for rainy day on September 9, 2015.

Overall, sap flow in jujube trees increased in the morning with increasing VT, reached peak amount in the afternoon and then dropped before finally stopping at about 20:00 hours local time. Also sap flow was significantly correlated with VT and was highest on sunny days, followed by cloudy days and then lowest on rainy days under the same PI. Although sap flow under different PIs had similar trends under the same meteorological condition, it decreased with increasing PI. The sap flow curve had a double peak on September 6 (Figure 2d) might due to the "noon break" phenomenon of plant transpiration. Irrespective of the effect of meteorological factors on peak sap flow, pruning limited sap flow in jujube partly due to pruning-driven physiological changes in the plants.
3.1.2 Pruning intensity and daily transpiration. Figure 3 depicts daily actual transpiration for the whole growth period under different PIs. Although the trends were similar, value of the transpiration varied (within a small range) with weather conditions, soil moisture and other environmental factors. With dormancy break in May, the range and difference variations in daily actual transpiration gradually increased. The range of daily actual transpiration was driven by PI, generally decreasing with increasing PI. Peak daily actual transpiration under PI-1, PI-2, PI-3 and PI-4 was 2.64 mm, 2.51 mm, 2.10 mm and 1.65 mm, respectively. There was no obvious difference between daily actual transpiration under PI-1 and PI-2 in August. This was attributed to the arrival of the rainy season during which time mild pruning has no significant effect on water use of jujube. By the end of September, daily actual transpiration under different PIs started declining and become the same. With continuous defoliation in October, leaf transpiration deduced and the difference in daily actual transpiration among the different PIs gradually weakened during the period, jujube trees went dormant.
3.1.3 Pruning intensity, transpiration and growth stage. The growth period of jujube trees lasted for 164 days in 2015. Based on observed germination, flowering and other physiological processes during the growth period of jujube, growth period was divided into four stages. The period from May 5 to June 12 was germination-frondescence stage, June 13 to July 15 was flowering-fruit-bearing stage, July 16 to September 16 was fruit-enlargement stage and September 17 to October 15 was deciduous stage. Figure 4a shows that pruning affected each of the growth stages above, although the degree of the effects were not the same across the growth stages. Transpiration significantly decreased with increasing PI from germination-frondescence stage to flowering-fruit-bearing stage. From fruit-enlargement stage to deciduous stage, increase in PI beyond PI-2 did not significantly reduce transpiration. For the whole growth period, transpiration decreased with increasing PI (Figure 4b). Compared with transpiration under PI-1, jujube transpiration for the whole growth period under PI-2, PI-3 and PI-4 dropped by 11.1%, 29.2% and 47.9%, respectively.

3.2 Jujube growth index and transpiration

3.2.1 Tree size and transpiration. To determine the relationship between transpiration and jujube tree size under different PIs, total length of secondary branches, average leaf biomass and average tree biomass for the growth period were analyzed. Figure 5 shows that transpiration during growth period increased with increasing tree size. After the total length of secondary branches exceeded 600 cm, the rate of increase in transpiration decreased. Compared with average tree biomass, the relationship between transpiration and average leaf biomass was much closer to that between transpiration and total length of secondary branches. This was because jujube tree transpiration mainly depended on the proportions of leaves, fruits and branches in the average tree biomass. Figure 5 also shows that total length of secondary branches can be used as a proxy (pruning index) for leaf biomass and transpiration in jujube trees.

![Figure 4. Plots of transpiration at different growth stages (a) and growth periods (b) of jujube. Note that means with the same letter at the same stage or period are not significantly different at the 0.05 level (Duncan’s test).](image)

3.2.2 Leaf biomass and daily actual transpiration. To further explore the relationship between transpiration and leaf biomass, the plant growth model \( BL = \frac{a}{1 + e^{b \times DOY + c}} \) was used to fit leaf biomass (BL) under different PIs and days of year (DOY) during growth period, where \( a, b \) and \( c \) were the model constants. For DOY 140–273 (i.e., May 20 to September 30), jujube growth indices measured every 7 days were used to calculate jujube leaf biomass (see Table 3 for the fitted results). Taking into account the high error in TDP probes for vapor pressure differences (VPD) less than 0.6 kPa [27, 28], sap flow data for VPD was less than 0.6 kPa was removed. Then the fitted leaf biomass...
(BL) and daily actual transpiration (AT, mm) under different PIs was expressed as \( AT = 2.1710 \times BL + 1.0602 \) (\( R^2 = 0.6918 \), \( n = 468 \)). This indicated that a significant positive correlation existed between daily actual transpiration and jujube leaf biomass.

**Figure 5.** Relationships between size of jujube tree and transpiration during growth period.

**Table 3.** A table detailing the results of statistical fitting between leaf biomass (BL) and day of year (DOY) under different pruning intensities (PIs) in the study area.

<table>
<thead>
<tr>
<th>PI</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>( R^2 )</th>
<th>n</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI-1</td>
<td>2.584</td>
<td>-0.083</td>
<td>14.117</td>
<td>0.995</td>
<td>17</td>
<td>0.001**</td>
</tr>
<tr>
<td>PI-2</td>
<td>2.468</td>
<td>-0.080</td>
<td>14.002</td>
<td>0.991</td>
<td>17</td>
<td>0.018*</td>
</tr>
<tr>
<td>PI-3</td>
<td>1.484</td>
<td>-0.071</td>
<td>12.547</td>
<td>0.994</td>
<td>17</td>
<td>0.004**</td>
</tr>
<tr>
<td>PI-4</td>
<td>0.762</td>
<td>-0.063</td>
<td>10.868</td>
<td>0.975</td>
<td>17</td>
<td>0.004**</td>
</tr>
</tbody>
</table>

Note that a, b and c were parameters in the growth model \( BL = \frac{a}{1 + e^{b \times DOY} + c} \), taken to fit leaf biomass (BL) and day of year (DOY); \( R^2 \) is coefficient of determination; \( n \) is sample number; and \( p \) is significant difference. The superscript of \( p \) "**" expresses that \( p < 0.01 \) and the difference is highly significant; then the superscript of \( p \) "*" expresses that \( 0.01 < p < 0.05 \) and the difference is significant.

Transpiration was not only closely related to tree size, but it was also affected by soil moisture, weather conditions and other environmental factors. For higher correlations between BL and AT, soil moisture and meteorological conditions were classified into two groups. During the whole jujube growing period, average daily relative effective water (REW) of 0-100 cm soil layer was 0–0.98 and that of VT was 5.78–40.90 kPa (W/m\(^2\))\(^{1/2}\). Thus the soil moisture was classified into REW < 0.5 and REW > 0.5 and then meteorological conditions classified into VT < 20 kPa (W/m\(^2\))\(^{1/2}\) and VT > 20 kPa (W/m\(^2\))\(^{1/2}\) — see Figure 6 for the fitted results.

Little difference existed between the correlations under the two soil moisture conditions, suggesting that soil moisture in the study area was as much driven by leaf biomass and daily actual transpiration. Conversely, significant difference existed in terms of the correlation between the two meteorological conditions. The coefficients of the correlations increased to up to 0.8, suggesting a significant impact of daily actual transpiration on meteorological factors. The correlation between leaf biomass and daily actual transpiration was even more significant under the classified meteorological conditions.

As REW < 0.5, soil moisture of 0-100 cm soil layer was between 5.27%–6.37%; while REW > 0.5, soil moisture of 0-100 cm soil layer was between 5.63%–7.99%. Jujube trees with the same leaf biomass consume more water in higher soil moisture condition. However, the correlations under the two soil moisture conditions were not affected much while the range of soil moisture was only 2.73% in growth period. Besides, as VT < 20 kPa(W/m\(^2\))\(^{1/2}\), daily mean temperature was 8.06–28.46 °C, relative humidity was 28.77%–72.89%, total radiation was 87.16–286.20 W/m\(^2\) and vapor pressure difference was 0.60–1.63 kPa; while VT > 20 kPa(W/m\(^2\))\(^{1/2}\), daily mean temperature was 15.39-
31.19 °C, relative humidity was 18.38%-57.08%, total radiation was 182.05-314.0 W/m² and vapor pressure difference was 1.23-2.44 kPa.

Figure 6. Correlation plots for biomass of leaves (BL) and daily actual transpirations (AT) under two soil moisture (a) and two meteorological (b) conditions.

The coefficient of determination, intercept and slope for VT > 20 kPa(W/m²)¹/² and REW > 0.5 were much higher than those for VT < 20 kPa (W/m²)¹/² and REW < 0.5, respectively. This implied that better correlation existed between leaf biomass and daily actual transpiration for VT > 20 kPa(W/m²)¹/² and REW > 0.5, in other words, transpiration of jujube was more sensitive to leaf biomass under higher soil moisture and higher temperature, radiation, vapor pressure difference, and low relative humidity. Presumably, jujube transpiration consume more water in good environment, but the correlation between transpiration and tree size would became more reliable because bad environment obstructed transpiration to some extent.

3.2.3 Yield and transpiration. Table 4 shows reductions in jujube yield under PI-2, PI-3 and PI-4, compared with that under PI-1. No significant difference existed between yield under PI-1 and PI-2, possibly due to the lack of significant difference between transpiration under PI-1 and PI-2 in the late growth stage of jujube (Figure 4a). Although yield and transpiration under PI-3 and PI-4 were significantly smaller than under PI-1, water use efficiency significantly increased with increasing PI. Compared with PI-1, water use efficiency under PI-2, PI-3 and PI-4 increased by 5.1%, 15.7% and 24.2%, respectively.

Table 4. A table listing yield, transpiration and water use efficiency of jujube tree under different pruning intensities (PIs) in the study area.

<table>
<thead>
<tr>
<th>PI</th>
<th>Yield (kg/hm²)</th>
<th>Transpiration (m³/hm²)</th>
<th>Water use efficiency (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI-1</td>
<td>11908.94a</td>
<td>3200.70a</td>
<td>3.70a</td>
</tr>
<tr>
<td>PI-2</td>
<td>11534.66b</td>
<td>2836.44b</td>
<td>3.89ab</td>
</tr>
<tr>
<td>PI-3</td>
<td>9701.04c</td>
<td>2265.81c</td>
<td>4.28c</td>
</tr>
<tr>
<td>PI-4</td>
<td>7662.98c</td>
<td>1667.15d</td>
<td>4.60c</td>
</tr>
</tbody>
</table>

Note that means with the same letter in the same column are not significantly different at the 0.05 level (Duncan’s test). Also, water use efficiency was calculated from transpiration and yield of jujube.

3.3 Pruning intensity and soil moisture
Figure 7 depicts rainfall and dynamic changes in soil moisture at the 3 m depth soil layer under different PIs. Rainfall was only 46.2 mm before jujube growth period, soil moisture mainly driven by rainfall and evaporation and the differences in soil moisture between different PIs not obvious.
Rainfall increased to 246.4 mm during jujube growth period and the difference in soil moisture under different PIs increased with tree pruning. After August, soil moisture under different PIs had obvious differences, with higher PI resulting in higher soil moisture. Compared with PI-1, volumetric soil moisture under PI-2, PI-3 and PI-4 increased by 3.2%, 8.5% and 14.2%, respectively. During this period, even increase in rainfall could not significantly improve soil moisture content because of high water demand of jujube under PI-1 and PI-2. As rainfall was only 88.2 mm after jujube growth period in 2015 and soil moisture no longer affected by vegetative water consumption, rainfall, as much as pruning, greatly improved soil moisture. For the investigated period, water storage of 0-300cm soil layer increased significantly with increasing PI. Compared with 1st January 2015, water storage under PI-1, PI-2, PI-3 and PI-4 increased by 0.76 mm, 7.05 mm, 26.54 mm and 35.50 mm, respectively on 31st December 2015.

![Figure 7. Dynamics of rainfall and soil moisture (percent volume) of jujube plantation under different pruning intensities in 2015.](image)

4. Discussions

4.1 Transpiration and pruning intensity

In addition to the effect of environmental factors, transpiration of a tree plant is generally correlated with leaf area index [29, 30]. This could be the reason why transpiration of jujube trees decreased with increasing PI. Namirembe noted that pruning of *Cassia spectabilis* narrowed trunk xylem vessel diameter and decreased water conductivity in environmental conditions with limited water resources, which suppressed canopy transpiration rate and reduced soil moisture consumption [31]. Also Zhao observed that tylosis originated from catheter of grape branches after pruning, which reduced branch water transportation and sap flow rate maximally by 21.10% [32]. This study showed that sap flow in jujube trees decreased with increasing PI (Figure 2), partly due to physiological changes induced by pruning. There was no significant difference between daily actual transpiration of jujube under PI-1 and PI-2 in August (Figure 3). Also there was no significant difference between jujube transpiration under PI-1 and PI-2 at fruit enlargement and deciduous stages (Figure 4). This was attributed to mild pruning which effectively regulated canopy water demand in jujube plantations. It suggested then that it was only at certain PIs that pruning effectively regulated tree water demand. This observation was in agreement with previous reports on the effects of pruning on *Grevillea robusta* agroforestry system on hill slopes [33].

4.2 Total secondary branch length and pruning

As leaf stomata are the main transpiration organs of plants, plenty research has been conducted on the relationship between transpiration and leaf area. Generally, transpiration has positive significant correlation with leaf area. The rate of transpiration increases with increasing leaf area or it even stops completely unless leaf area reaches a certain value [18, 30, 34]. Tree leaf area is usually calculated by
multiplying leaf area index with projected area. However, as crown volume of dwarf jujube under close planting is small and irregular in shape, high errors persist in measuring leaf area index and projected area. The correlation between transpiration and biomass was similar to that between transpiration and leaf area. This implied that total length of secondary branches can be used as a proxy (index) to estimate the range of pruning more accurately for the efficient regulation of transpiration. Furthermore, jujube biomass can be calculated using the high correlation biomass model [20] after monitoring specific growth indices. This facilitates ready analysis of water use efficiency and biomass-transpiration correlations. Theoretically, PI is the factor used to control tree structure and volume and thereby control water consumption. As the practical definition of pruning remains largely unclear, total length of secondary branches could be a reliable pruning index to improve water-saving pruning method. Although further studies are required in this direction, this study has successfully demonstrated the use of this index in precision pruning.

4.3 Soil moisture, meteorological factors and transpiration

Significant difference were noted in the correlations between the two meteorological conditions for Jujube trees, reflecting that sap flow was deeply affected by meteorological factors, which was in agreement with other studies [5, 35]. However, only a little difference were found in the correlations between the two soil moisture conditions, possibly due to the severe soil water deficit during jujube growth period. In 2015, rainfall was 292.6 mm before October 15, which made the soil dry with average soil moisture of the 0‒1 m depth soil layer of only 5.27–7.99%. The classification standards of soil water deficit shows water deficit for relative soil moisture (θ_e) of less than 0.4 [5, 36]. Relative soil moisture for the 0‒1 m depth soil layer was 0.01–0.14 during the growth period. This indicated severe water deficit under different PIs, lack of available soil moisture and narrow soil moisture range, which weakened the difference between the correlations of the two soil moisture conditions. The severe water deficit also affected the correlation between daily actual transpiration and leaf biomass. Daily actual transpiration for similar jujube treatments exceeded 3.5 mm [21], with the highest value (2.64 mm) under the different PIs. Under this soil moisture condition, simple linear correlation was found between daily actual transpiration and leaf biomass. Daily actual transpiration might be limited due to severe water deficit.

4.4 Pruning effect on soil moisture

In recent years, a series of research has been done on the effects of pruning on soil moisture under fruit plantations. Li observed that compared with traditional pruning method, soil moisture in the 2.4 m depth soil layer greatly improved under repeated pruning at higher PI [15]. Wei also found that maximum PI (of one main branch per plant) increased soil water storage by 40.5 mm after 2 years [21]. The results of this study agreed with the findings of the above reports. With annual rainfall of 380.8 mm, 2015 was, far less than the average local annual rainfall (451.6 mm), even slight pruning could increase the soil storage water under tree plantations. This suggested that pruning can effectively improve soil moisture in 0-300 cm soil layer in jujube plantations. The long-term effects of pruning on deep soil moisture (of over 3 m deep) remains unclear, and therefore require further research.

5. Conclusions

(1) Pruning can significantly reduce transpiration water demand of jujube plant at different periods of growth. Compared with PI-1 (the control treatment) jujube plant transpiration for the whole growing season under PI-2, PI-3 and PI-4 dropped by 11.1%, 29.2%, 47.9%, respectively. At daily scales, the range of daily actual transpiration decreased with increasing pruning intensity (PI). Peak daily actual transpiration under PI-1, PI-2, PI-3 and PI-4 were 2.64 mm, 2.51 mm, 2.10 mm and 1.65 mm, respectively. Sap flow in jujube trees was similar in trend under different PIs, while sap flow rate decreased with increasing pruning intensity (PI). Jujube transpiration was easily influenced by meteorological factors at small time scale (day and hour).
(2) Jujube transpiration during the growing season increased with increasing plant size. The rate of increase in transpiration slowed after the tree attained a certain size (when the total length of secondary branches exceeded 600 cm). Otherwise while increase of pruning intensity (PI) reduced yield of tree, it reduced water consumption that in turn significantly increased water use efficiency of fruits.

(3) The correlation between daily actual transpiration and leaf biomass of jujube tree was positive and significant, but with a significant difference between the correlations for the two sets of meteorological conditions. When VT < 20 kPa (W/m²)¹/², AT = 0.7908 x BL + 0.7912, R² = 0.8112, n = 220. Then when VT > 20 kPa (W/m²)¹/², AT = 1.3379 x BL + 1.0843, R² = 0.8254, n = 248.

(4) Increased pruning intensity (PI) could effectively prevent soil desiccation and improve soil moisture under jujube plantations. During dormancy period, the difference in soil moisture due to pruning was significant after rainfall. Annual change in water storage in jujube plantations under PI-1, PI-2, PI-3 and PI-4 increased by 0.76 mm, 7.05 mm, 26.54 mm and 35.50 mm, respectively.

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References
[8] Pute W, Youke W, Xiaogui X and Delan Z 2008 Integration and demonstration of the date micro-irrigation technology in the hilly of Shanbei Agricultural Research in the Arid Areas 26(4) pp 1-6+12


[26] Norman J M 1998 An Introduction to Environmental Biophysics (Springer-Verlag, New York New York Springer-Verlag)

[27] Ewers B E and Oren R 2000 Analyses of assumptions and errors in the calculation of stomatal conductance from sap flux measurements Tree Physiology 20(9) pp 579-589


[32] Xianhua Z 2013 Pruning Effects on Sap Flow and Transporation Assignment of Photosynthates in Grapevine Shanxi Place Northwest Agriculture and Forestry University


[34] Zhaoquan G, Xianchuan Z and Xiaowei W 2006 Mathematical simulation of canopy transpiration rate of peach tree canopy Acta Ecologica Sinica 26(2) pp 489-495


[36] Black T A 1979 Evapotranspiration from Douglas fir stands exposed to soil water deficits Water Resources Research 15(15) pp 164-170