

# Identification of sap flow driving factors of jujube plantation in semi-arid areas in Northwest China

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**Abstract:** Jujube is widely cultivated in the semi-arid region of the Loess Plateau in Northwest China due to its high water deficit tolerance. In such an ecologically vulnerable area, it is critical to explore the water consumption processes of key tree species and their responses to driving factors. Sap flow data gathered during a two-year field study in a jujube plantation were analyzed as a surrogate for transpiration measurements. The measured sap flows were related to changes in the soil water content, meteorological factors (the vapor pressure deficit and the level of photosynthetically active radiation), and plant physiological factors (the sap wood area, leaf area and leaf area index). The factors that govern sap flow were found to vary depending on the growing season, and on hourly and daily timescales. The plants' drought tolerance could be predicted based on their peak sap flows and the variation in their sap flow rates at different soil water levels. The sap flow was most strongly affected by the water content of the topmost (0-20 cm) soil layer. Of the studied meteorological factors, the photosynthetically active radiation had a greater effect on sap flow than the vapor pressure deficit. The correlation we found could be applied to predict jujube tree water consumption and assist the design of irrigation scheme.

**Keywords:** jujube, sap flow, soil water content, photosynthetically active radiation, the Loess Plateau

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## 1 Introduction

Jujube (*Ziziphus jujuba* Mill.) is a traditional Chinese fruit that has been cultivated continuously for over 7000

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years<sup>[1]</sup>. It is an important cash crop in the hilly regions of the Loess Plateau in Northwest China, which has a typical semi-arid climate. Jujube is well-adapted to growth in this region because of its high resistance to drought stress. However, to increase the efficiency and sustainability of its cultivation, it would be desirable to identify the driving factors that determine its water consumption.

Transpiration represents a critical linkage between water balance and vegetation dynamics<sup>[2]</sup>. Two different approaches are generally used to evaluate the volume of water consumed in plant transpiration processes. The first involves calculating the reference evapotranspiration (ET) using climatic factors in conjunction with a crop coefficient term. In order to eliminate the effect of water stress on ET, the crop coefficient is used to determine whether there is a water deficit or surplus<sup>[3]</sup>. The second approach uses specific instruments to directly

measure the plant canopy, thereby directly determining the level of transpiration<sup>[2]</sup>. Canopy transpiration is traditionally measured using techniques and instruments such as the weighing lysimeter and the field-chamber method. Unfortunately, the second approach usually disturbs the natural environment and microclimatic conditions of plant canopy to a certain extent, causing the measured values to differ somewhat from the actual ET.

Some advanced measurement techniques that minimize the disturbance of the natural ambient conditions have been developed including the Bowen Ratio energy balance technique<sup>[4]</sup>, Eddy Covariance<sup>[5]</sup>, and the aerodynamic method. These approaches preserve the plants' natural environments while providing high temporal resolutions. However, their use is limited in agriculture because they are generally complex and costly to perform. Therefore, sap flow measurements are widely used to monitor crop water consumption. This method has several advantages: it is operationally straightforward, has good precision, minimizes the disturbance of the environment, and enables continuous monitoring over long periods of time<sup>[3,6,7]</sup>.

The sap flow is affected by various aspects of plant physiology as well as soil and meteorological factors. The key soil factor is the soil water content<sup>[8]</sup>, which has been demonstrated to have profound effects on sap flow<sup>[9]</sup>, especially under water deficit conditions<sup>[10,11]</sup>. Three major meteorological factors that affect the sap flow are temperature<sup>[12]</sup>, vapor pressure deficit (VPD), and level of photosynthetically active radiation (PAR)<sup>[13]</sup>. Sap flow has been shown to correlate positively with PAR and VPD in both time and space<sup>[14-17]</sup>. The main aspects of plant physiology and structure that affect sap flow include whether the tree species in question is diffuse or ring porous<sup>[18]</sup>, whether it is deciduous or evergreen, tree height<sup>[19]</sup>, tree diameter<sup>[6,20]</sup>, tree size<sup>[21-23]</sup>, and the leaf area index (LAI)<sup>[8]</sup>.

Partly because of the complex interactions between these factors, there is no general law that can be used to determine which of them will be dominant in any given species or under any given climatic conditions. While the relationships between these factors and sap flow have been studied at length, there is a distinct lack of relevant

data based on long-term studies of jujube trees growing under semi-arid conditions.

To address this issue, we monitored sap flow and relevant environmental, meteorological, and plant physiological factors in jujube trees during successive growth periods in 2012 and 2013. The objectives of this study were to (1) quantify the contributions of biotic and abiotic factors to the trees' transpiration and thereby identify the most influential factors at different growth stages, (2) analyze the dynamics of transpiration to enrich our understanding of its drought-resistance, and (3) establish regression models describing the relationships between transpiration and sap flow as its major drivers.

## 2 Materials and methods

### 2.1 Experimental site

Field experiments were conducted at a commercial pear-jujube orchard in Mengcha Town, Mizhi County, Shaanxi Province of China (37°78'N, 109°47'E, 870 m above mean sea level) in 2012. The site's soil type is loess with a uniform texture, moderate permeability, and a mean bulk density of 1.29 g/cm<sup>3</sup>. The average field capacity (FC) in the upper 1.0 m soil profile is 23%. The average annual rainfall at the site is 409.9 mm, most of which falls during July, August, and September. The site is typical of the arid, hilly and gully terrain of the Loess Plateau. The groundwater level is generally low, and the plants' water requirements are primarily met by natural precipitation. The experimental jujube orchard is nine years old, with 3 m planting rows and 2 m row spacing.

### 2.2 Sap flow measurement

Plug-in probe sensors (TDP and Dynamax Co., USA) were used to monitor jujube sap flow during the growth periods of 2012 and 2013 (Figure 1c). The 18 jujube plants selected for measurement were in good condition with straight trunks and no breast bifurcates. All of the probes were installed on the northern side of trunks at a height of 20 cm above the ground surface and packaged in silver membranes to reduce disturbance by radiation and other environmental factors<sup>[2,25]</sup>. A CR1000 data acquisition unit (Campbell, Co., USA) was used to record the sap flow data from the sensors at 10 s intervals. The

collected data were subsequently up-scaled to 10 min averages.

Note that inter-plant variation of transpiration is considerable (Figure 1c). This could attribute to the inter-variability of our samples. Theoretically 18 sampling trees should be selected carefully with canopy structure as similar and representative as possible. However this is limited by the fact that samples could not distribute very far from each other. Firstly increasing the distance between the sensor and data collector can aggravate signal attenuation during the transmission, thereby degrading the measurement accuracy. It is therefore recommended that samples should not locate more than 7 m away from the data collector. More importantly, the terrain varies greatly at the hilly region, thereby inducing the high spatial heterogeneity of meteorological conditions, especially radiation conditions. So the moderate distance was desirable as the tradeoff between the consistency of experimental condition and the similarity of canopy structure.

### 2.3 Measurement of soil water content

The moisture, temperature, and water potential of the topmost layer (0-1.0 m) of the soil profile were continuously monitored. The soil water content was measured using TDT probe sensors and neutron moisture gauges (CNC503B, Hean, Co. CN). The sensors (SDI-12, Acclima, Inc, USA) were installed in close proximity to the trees at depths of 20 cm, 40 cm, 60 cm, 80 cm and 100 cm. The data from these sensors were also collected and recorded with the CR1000 (Campbell, Co., USA) instrument. More attention would pay on the dynamic of soil moisture on daily scale. So the observe frequency was set at 30 min interval. Also this could save the cost of data storage and transmission. Neutron moisture gauges (CNC503B, Hean, Co. CN) were used to measure the water content in the 0-300 cm soil layer at intervals of approximately 10 d. The results obtained using the neutron moisture gauges and TDT probe sensors were calibrated against measurements acquired using the oven drying method.

### 2.4 Measurement of environmental variables

Meteorological variables were monitored continuously using an automatic environment detection system (RR-9100,

RainRoot, Co, CN) that was installed in close proximity to the experimental field. This system simultaneously measures the precipitation ( $P$ ) (Figure 1a), solar radiation ( $R_s$ ), PAR, temperature ( $T$ ), wind speed ( $W_s$ ), wind direction ( $W_d$ ), and relative humidity ( $RH$ ). The vapor pressure deficit ( $VPD$ ) (Figure 1b) can be calculated from  $T$  and  $RH$  using the equations shown below<sup>[26]</sup>:

$$e_s = 0.611 \text{Exp} \left( \frac{17.502 \times T}{T + 240.97} \right) \quad (1)$$

$$VPD = e_s - \frac{e_s \times RH}{100} \quad (2)$$

where,  $e_s$  is the saturated vapor pressure (Pa) at temperature  $T$  (K) and relative humidity  $RH$ .

### 2.5 Measurement of morphological indices

Morphological indices for the jujube plants were measured during the middle of the growth stage (July 10<sup>th</sup>, 2012). The variables measured include plant height, crown breadth, number of main branches ( $M_b$ ), number of secondary shoots ( $S_s$ ), number of mother shoots ( $M_s$ ), number of bearing shoots ( $B_s$ ), breast height diameter ( $BHD$ , cm), and sap wood area (SWA, cm<sup>2</sup>). The SWA value was determined indirectly from the  $BHD$  using the following equation<sup>[27]</sup>:

$$SWA = \alpha \times BHD^\beta \quad (3)$$

where,  $\alpha$  is a constant and  $\beta$  is the allometric scaling exponent. Both of these quantities are species-specific coefficients<sup>[21]</sup>, they take values of 0.175 and 0.201, respectively, for jujube.

The leaf area and LAI were measured every 10 d using a portable leaf area meter (LI-3000A, LI-COR, Co. US). Three bearing shoots from the main branch growing in each cardinal direction were selected for these measurements. The total leaf area (LA) of each jujube tree was determined as follows:

$$LA = M_b \times S_s \times M_s \times B_s \times \frac{1}{12} \sum_{i=1}^m B_{si} \times \sum_{j=1}^n M_{bj} \quad (4)$$

where,  $m$  and  $n$  are the numbers of selected samples for  $B_s$  and  $M_b$ , respectively.

The leaf area index was measured every 10 d using a canopy analyzer (Winscanopy 2005a, Regent Instruments Inc. JP). Canopy images were acquired in the field using the instruments specified above and analyzed with the canopy analyzer in order to determine the LAI.

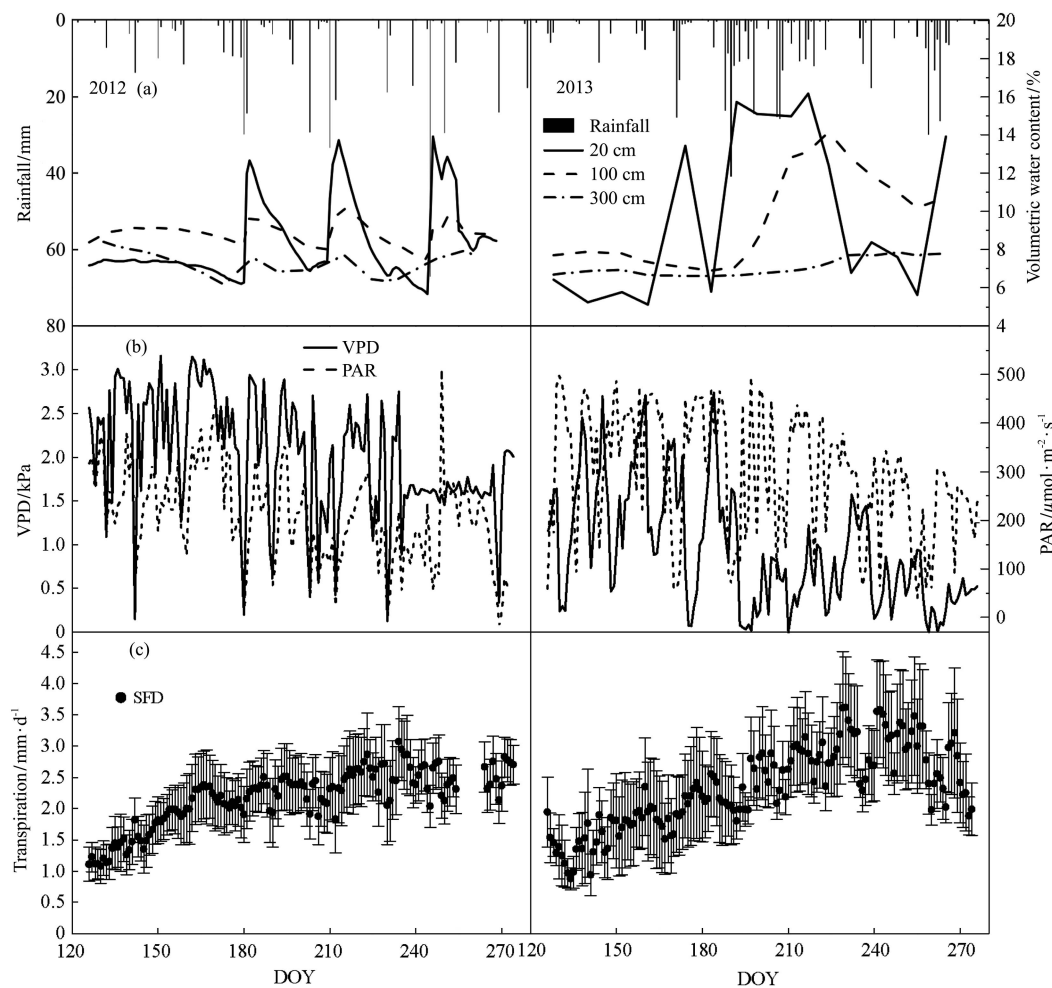


Figure 1 Trends in (a) the precipitation and soil water content (0-300 cm), (b) photosynthetically active radiation (PAR) and vapor pressure deficit (VPD); and (c) transpiration in a jujube plantations in the semi-arid Loess Plateau of Northwestern China during the growing seasons of 2012 and 2013

### 3 Results and discussion

#### 3.1 Influences of physiological factors on sap flow

##### 3.1.1 Sap flow and sap wood area

The sap flow density (SFD or SF, m/s) is a good indicator of plant transpiration and sap flow, which can be determined within a portion of the tree’s cross-section using the method of thermal dissipation<sup>[24]</sup>. The daily sap flow (DSF or transpiration, mm/d) is then obtained by multiplying the sap flow and the SWA. The average SFD and DSF values for a 30-day period in 2012 (DOY150-180) were used to analyze the correlations between SFD, DSF and SWA (Figure 2).

Negative correlation was found between SFD and SWA, while there was a positive correlation between transpiration (DSF) and SWA. The regression equations and curves shown in Figure 2 suggest that variation in the sap wood area explains 37% of the observed SFD

variability and 41% of the observed DSF variability. The SFD decreased as the sap wood area increased. As the sap flow velocity across a unit tree cross-section declined, the total water consumption increased. Xiao et al.<sup>[28]</sup> noted that transpiration in trees with a large breast height diameter is significantly greater than in those with more slender trunks. A tree’s capacity for adaptation to adverse environmental conditions generally decreases with increasingly severe water deficit conditions but increases with the thickness of its trunk, its height, and the width of its crown<sup>[29]</sup>.

##### 3.1.2 Sap flow and leaf area

During the growing season of 2012, which extended from May 1 to October 15 (DOY 120-290), the observed trends in LA and LAI were very similar. Both curves can be described well by quadratic functions (Figure 3), which explain 97.1% and 95.5%, respectively, of the observed variability in the LA and LAI within the study

area. Very similar results were obtained during the growing season of 2013. During the early growth stage, vigorous leaf growth caused both the LA and LAI to increase rapidly. Leaf growth then stopped during the

intermediate growth stage, so neither the LA nor the LAI changed significantly during this period. Finally, defoliation during the late growth stage caused the LA and LAI to decline rapidly.

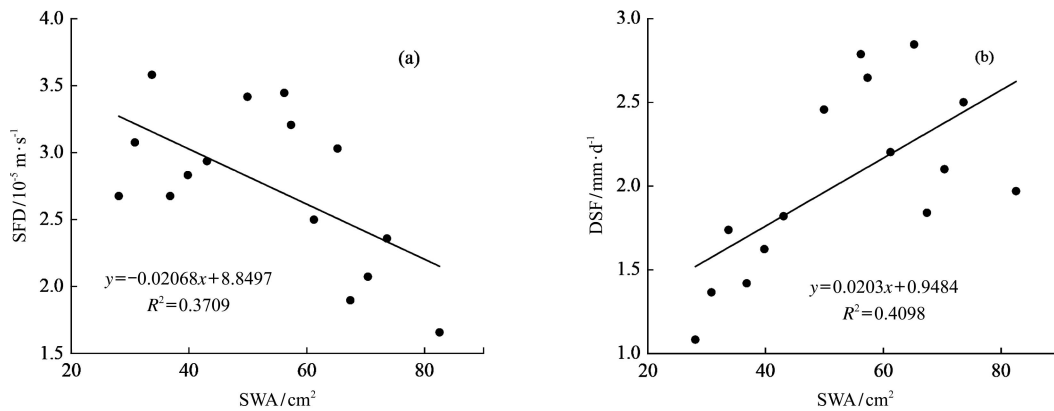


Figure 2 Correlations between sap wood area (SWA) and (a) sap flow density (SFD); and (b) daily sap flow (DSF) in jujube trees

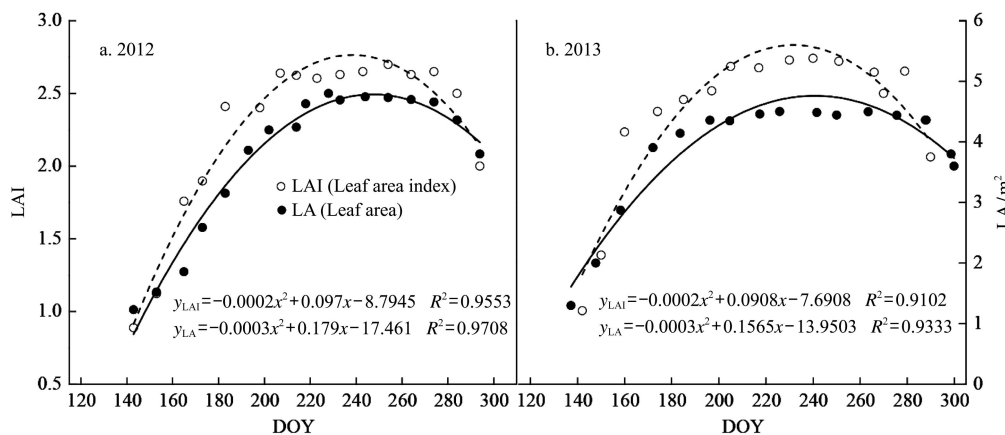


Figure 3 Trends in leaf area (LA) and the leaf area index (LAI) of jujube trees during the growing seasons of (a) 2012 and (b) 2013

There were two distinct relationships between LA and sap flow (transpiration) during the growth period as a whole, one during the initial growth stage (Stage I) and the other during the intermediate-to-late growth stage (Stage II) (Figure 4).

During stage I (the early growth stage) the LA was less than 2.1 m<sup>2</sup>; during the intermediate-to-late growth stage (Stage II) the LA was greater than 2.1 m<sup>2</sup>. In Stage I, the LA was below 2.1 m<sup>2</sup> and increased in parallel with transpiration ( $R^2=0.90$ ). This implies that transpiration was heavily influenced by LA during this stage<sup>[30]</sup>. The LA during Stage II was greater than 2.1 m<sup>2</sup> but there was no significant correlation between SF and LA during this period, and the sap flow was primarily driven by environmental factors. Similar results have previously been reported for apple trees<sup>[11]</sup> and grapes<sup>[31]</sup>.

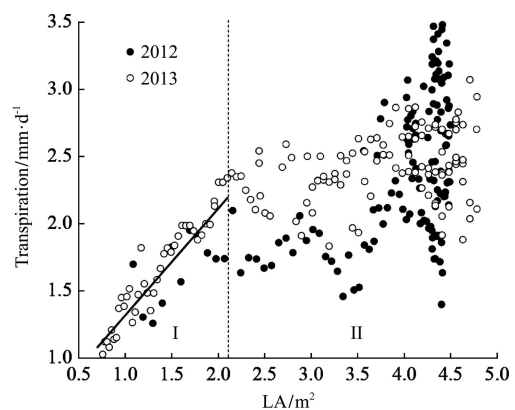


Figure 4 Relationships between leaf area (LA) and daily transpiration during different growth stages in 2012 and 2013

### 3.2 Effects of meteorological factors on sap flow

Sap flow is influenced by solar radiation, relative humidity, temperature, wind speed, and precipitation, especially during the intermediate-to-late growth stage (Stage II). Although there are strong correlations among these factors, the main driving forces of sap flow may

vary with the crop type, time, and geographical location. Sap flow characteristics are normally explained in terms of the variables PAR and VPD. To determine the influence of leaf area on sap flow, we analyzed the relationship between meteorological factors and sap flow during this stage of jujube plant growth. Further as these variables do not follow the same distribution, their correlation on different scales may results in different conclusions due to the statistical effect. Therefore their correlation was inspected carefully on hourly and daily scales to eliminate the scale effect and reveal their true correlation.

### 3.2.1 Daytime dynamics

To determine how PAR, VPD, and sap flow are

interrelated, response curves were plotted for four typical days during stage II: days 182 and 277 in 2012 and days 193 and 256 in 2013 (see Figures 5a-5c for results obtained on sunny days and Figure 5d for cloudy day results). In general, the relationships between these variables depend on the climatic conditions and the season. However, they do not change greatly on the diurnal scale. There are four key points or phases in plots of sap flow over the course of a day: the period of increasing flow, the peak flow, the period of declining flow, and the stable flow level. The times at which these phases occur change with the seasons and are sensitive to various physiological and environmental factors.

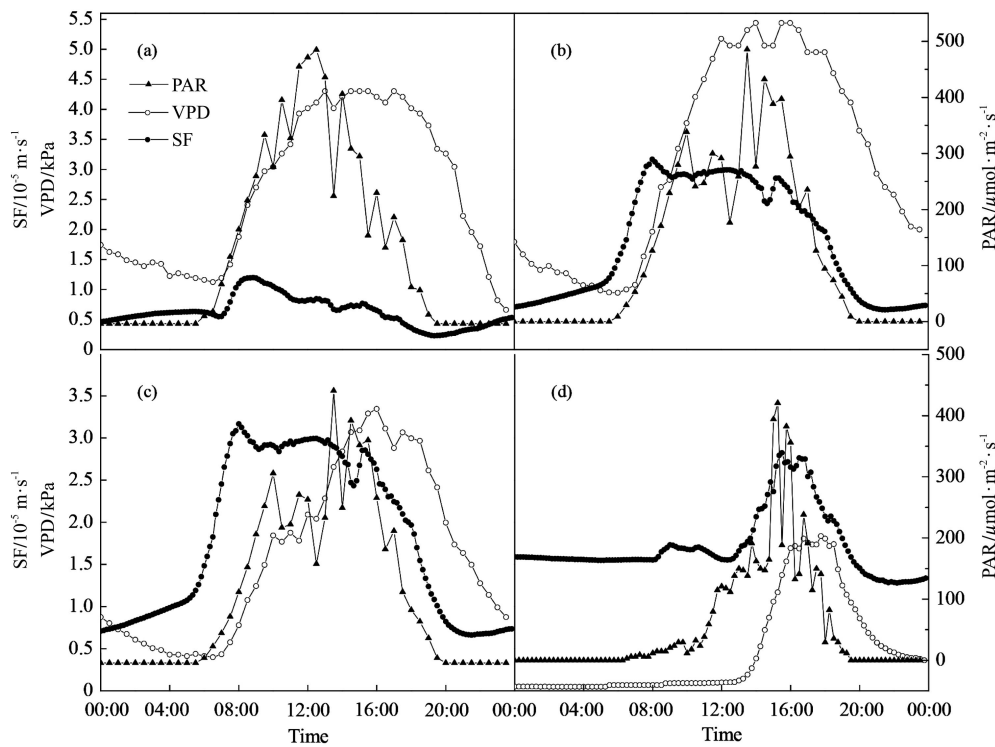


Figure 5 Daily trends in the photosynthetically active radiation (PAR), vapor pressure deficit (VPD) and transpiration (SF) measured on four representative days, days 182(a) and 277(b) in 2012 and days 193(c) and 256(d) in 2013 (a-c for results obtained on sunny days and d for cloudy day) during the intermediate-to-late growth stage of the studied jujube plantation

On sunny days (Figures 5a-5c), the sap flow generally increased between 05:30 and 07:00, peaked at about 08:30-09:00 (corresponding to the rapid transpiration stage), declined until about 16:00, and then finally stabilized after 20:00. The rapid transpiration stage was thus very short (Figure 5a). The sap flow declined very shortly after peaking because the measurements were conducted during the dry season, when the soil water content was low. The VPD and PAR both started to

increase at around the same time as the sap flow but peaked rather later, at around 12:00-13:00. They both then declined, with the PAR falling much more rapidly than the VPD. Similar patterns were observed on the cloudy day, but all of the key events happened later in the day than they did on the sunny days.

Depending on the circumstances and time, the sap flow may be increased, reduced, or unaffected by increases in the VPD and/or PAR. The PAR and VPD

varied in parallel with the sap flow when the latter was increasing or decreasing. There were no correlations between these variables at other times, so they were only weakly correlated on a daily basis. However, they were relatively strongly correlated during the periods when the sap flow was either increasing (Figures 6a and 6c) or decreasing (Figures 6b and 6d). The relationships between the sap flow, VPD, and PAR during the period when the sap flow was increasing are best described with quadratic curves. The sap flow increased almost linearly with the PAR and VPD while these variables were below 1200  $\mu\text{mol}/\text{s}$  and 3.5 kPa, respectively.

Once these threshold values were exceeded, the sap flow stabilized. The coefficients of determination ( $R^2$ ) for the exponential SF-PAR and SF-VPD curves were 0.81 and 0.42, respectively. During the declining flow stage, the sap flow began to decrease linearly with the PAR and VPD once these quantities fell below the threshold values of 1000  $\mu\text{mol}/\text{s}$  and 3.0 kPa, respectively. The coefficients of determination for the exponential SF-PAR and SF-VPD curves were 0.80 and 0.76, respectively. Similar trends have previously been reported for sap flows in apples<sup>[11]</sup>, grapevines<sup>[30]</sup>, and lemons<sup>[32]</sup>.

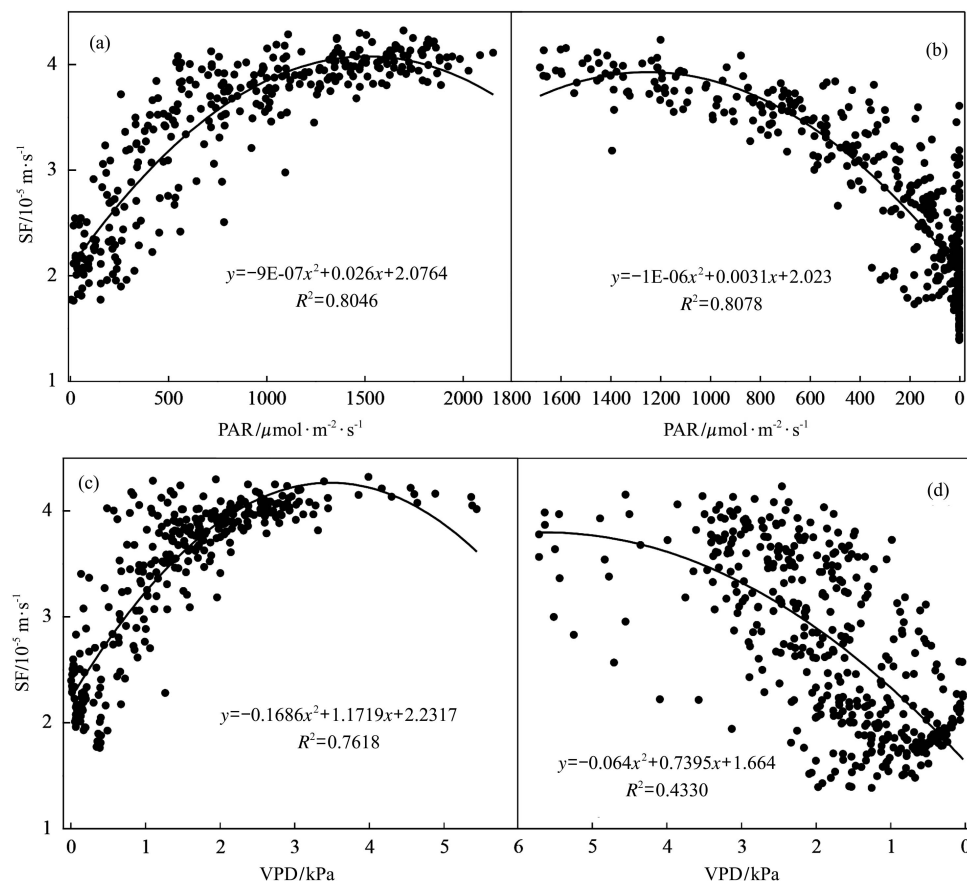


Figure 6 Correlations of the sap flow (SF) with the vapor pressure deficit (VPD) and photosynthetically active radiation (PAR) during the rising (a and c) and falling (b and d) flow stages in jujube trees

The VPD thresholds are effectively identical for both the rising and falling flow periods. However, the PAR threshold for the increasing flow period was slightly higher than that for the falling flow period. The threshold temperature was higher for the falling period than for the rising one. High temperatures have previously been reported to reduce the PAR threshold<sup>[33]</sup>. When the VPD fell below 4.0 kPa, there was a corresponding linear increase in sap flow. However, the

sap flow stabilized when the VPD exceeded the threshold in apples<sup>[11]</sup>. Other studies have shown that sap flow stabilizes at a VPD threshold of only 1.0 kPa in trembling aspen<sup>[34]</sup> and in riparian buffer trees<sup>[35]</sup>.

The PAR threshold was found to be 900  $\mu\text{mol}/\text{m}^2 \cdot \text{s}$  in mature beech<sup>[14]</sup> and 55  $\text{mol}/(\text{m}^2 \cdot \text{d})$  in Asian temperate mixed-deciduous forests<sup>[36]</sup>. However, other studies were not able to identify any VPD threshold that responded linearly to the PAR<sup>[11,37,38]</sup>. The thresholds

for both PAR and VPD depended on the prevailing conditions. Cultivated jujube in the Loss Plateau of Northwest China is highly drought-tolerant, which makes its PAR and VPD thresholds lower than those observed in humid regions.

On the hourly scale, VPD and PAR both correlated significantly with sap flow during both the rising and falling flow periods (Figure 6).

However, the coefficient of determination ( $R^2$ ) for PAR was higher than that for VPD. This suggests that the sap flow was primarily driven by PAR. In addition,

the coefficient of determination for VPD was significantly lower for the falling than for the rising flow period. This may be due to the time lag, which is especially pronounced during the falling flow period<sup>[39]</sup>.

### 3.2.2 Daily dynamics

The daily VPD and PAR had similar seasonal ranges of 0.01-3.0 kPa and 21.7-542.2  $\mu\text{mol}/\text{m}^2\cdot\text{s}$ , respectively. The daily sap flow (or transpiration) ranged from 1.1-3.1 mm/d, with an average of 2.2 mm/d. The daily sap flow (or transpiration) exhibited significant exponential correlations with both the VPD and PAR (Figure 7).

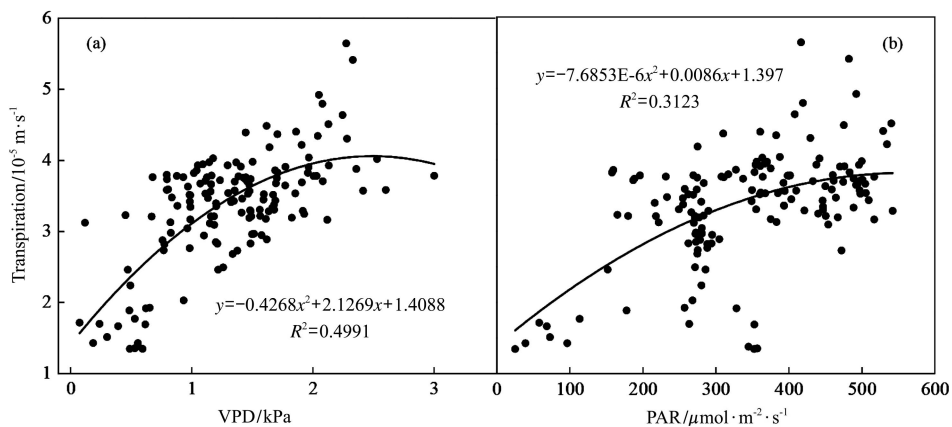


Figure 7 Correlations between the vapor pressure deficit (VPD), photosynthetically active radiation (PAR) and transpiration in jujube trees during the growing seasons of (a) 2012 and (b) 2013

The hourly and daily sap flows were closely related to the VPD and PAR during the intermediate-to-late growth stage (Figures 6 and 7). The coefficient of determination on the daily scale was significantly lower than that for the hourly scale. Jujube sap flow (or transpiration) was thus mainly driven by PAR and VPD, so an increase in either of these two variables would increase the sap flow. Higher sap flows generally reduce a tree's water potential<sup>[40]</sup>. However, when transpiration exceeds root water uptake, the resulting water loss leads to tree deficit<sup>[41,42]</sup>. Severe water deficits can lead to tree withering and even death<sup>[43,44]</sup>.

The sap flow generally peaked at an earlier point than PAR and VPD, suggesting that there was some stomatal regulation of transpiration<sup>[45]</sup>. The “time lag”<sup>[46]</sup> between the peak in sap flow and those of PAR/VPD is a critical index of drought tolerance in jujube. The sap flow can sometimes be estimated from the PAR and VPD. However, when these driving forces cause the sap flow to exceed a certain threshold, the stomata of the jujube

leaves close partially. This limits the increase in sap flow and may even cause it to decline, thereby preventing excessive water losses. This is probably the water conservation mechanism responsible for the efficient water use of jujube plants growing in semi-arid regions such as the Loess Plateau of Northwest China. High time lag values are common among trees in especially arid regions<sup>[39,47,48]</sup>.

### 3.3 Sap flow and soil water content

The uneven distribution of jujube tree roots<sup>[49]</sup> caused variation in the soil water content at different soil depths. The soil water content was measured at different intervals in the 0-300 cm soil profile. Regression analyses were then used to relate the measured values to sap flow (Table 1 and Figure 1a).

Soil water contents in the 0-20 cm, 0-100 cm, and 0-300 cm soil layers all correlated significantly with sap flow, with  $R^2$  values of 0.54, 0.48, and 0.26, respectively. Soil water contents at other soil depths were not correlated with sap flow. The water content in



the 0-20 cm soil layer correlated with both sap flow (reflecting soil water consumption) and also with precipitation (soil water refilling). We therefore studied the soil water content in the 0-20 cm layer (or the upper soil water content, USWC) to determine the effect of soil water on sap flow.

**Table 1 Data on the regression analysis of the relationship between daily sap flow and the soil water content at different depths in jujube trees growing in a semi-arid region**

Depth/cm	a	b	c	R <sup>2</sup>	N
0-20	-0.0318	0.6634	-0.678	0.5443	87
20-40	-0.0647	1.3618	-4.4419	0.4765	87
40-60	0.1726	-2.9409	14.945	0.1723	87
60-80	-0.1306	2.2453	-7.0674	0.0778	87
80-100	-0.0791	1.1043	-1.1756	0.1036	87
0-100	-0.1812	3.4496	-13.747	0.4464	87
0-300	0.0138	-0.0653	0.1472	0.2639	15

Note: A TDR probe was used to measure soil water content. The variables a, b, and c are empirical parameters; R<sup>2</sup> is the coefficient of determination; and N is the number of samples.

The USWC can significantly influence daytime sap flow. To minimize the effect of meteorological factors, data for eight days with similar meteorological conditions (all typical sunny days) were used to analyze sap flow in jujube plants (Figure 8).

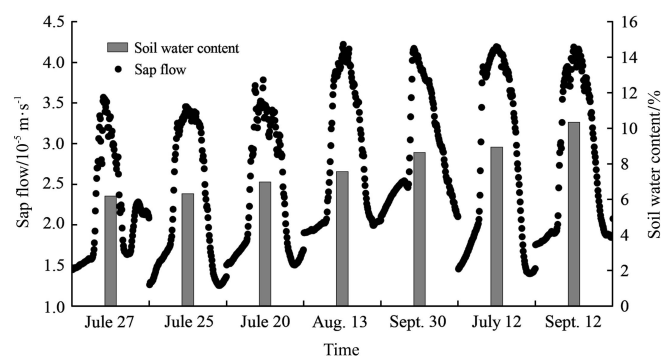


Figure 8 Trends in sap flow in jujube trees during eight sunny days with different upper soil water contents

The trends in sap flow on each of these days were very similar. Low USWC values significantly inhibited sap flow; as the USWC increased, the high and low amplitudes of sap flow increased linearly, stabilizing when the USWC exceeded 7%. As the USWC increased further from 7% to 15%, the peak sap flow stabilized at  $4.1 \times 10^{-5}$  m/s.

The relationships between daily sap flow and USWC were best expressed by piece-wise regression with a turning-point of 7% USWC (Figure 9).

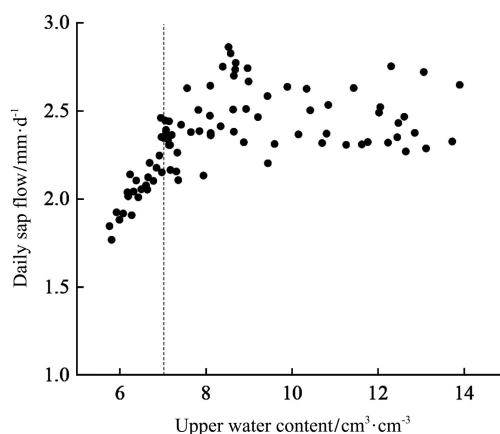


Figure 9 Correlations between the upper soil water content (UWC) and sap flow (SF) in jujube plantations

When the USWC fell below 7%, sap flow decreased linearly. Above this point, however, the sap flow fluctuated rather than increasing linearly. The measured daily sap flow depended on both the soil water content and the meteorological conditions. When the USWC exceeded 7%, the daily sap flow ranged from 2.1-2.9 mm/d. Under such conditions, the sap flow was no longer limited by the soil water but by meteorological factors. The sap flow also stabilized under stable meteorological conditions (i.e. on typical sunny days). Similar observations have previously been reported by Wang et al.<sup>[49]</sup>, although a different turning point was identified in that case. Lagergren and Lindroth<sup>[50]</sup> subsequently showed that the sap flow in pines and spruce stabilized when the soil water content exceeded 9% and 10%, respectively. This suggests that sap flow in spruce is more sensitive to drought than that in pines. A wide range of different threshold values have been identified in other environments and species: 11% in a monsoon forest<sup>[51]</sup>, 16% for *Quercus ilex*<sup>[52]</sup>, 17% for wine grapes<sup>[31]</sup>, and 21% for apples<sup>[53]</sup>.

On the other hand, lower peak sap flows and levels of variation in sap flow were observed on days with different soil water contents (2.9 mm/d and 1.05 mm/d). In keeping with these findings, Du et al.<sup>[54]</sup> reported that although sap flow in drought-sensitive plants increases markedly, it generally varies from species to species.

The sap flow in the studied jujube plants was very low when the upper soil water content was 7%, which is close to the wilting point for this species<sup>[55]</sup>. Jujube can absorb deep soil water to sustain growth, making it less

sensitive to the soil water content than some other plant species. However, low soil water levels still limited the magnitude of the peak flow and the observed variation in sap flow. This demonstrates that changes in the soil water content can have varied effects on the properties and growth of jujube plants in the semi-arid region of the Loess Plateau.

### 3.4 Regression analysis

The sap flow in jujube plants is sensitive to changes in plant physiology, the soil water content, and the meteorological conditions. In addition, the major driving factors of sap flow often differ between growth stages. During the early growth stage (Stage I), the jujube exhibited vigorous vegetative growth and their leaf area increased rapidly. The variation in sap flow during

Stage I was best described by a linear function of the leaf area:  $SF = 0.8635LA + 0.4787$ . The  $R^2$  value for this function during this stage was 0.93, suggesting that the leaf area was the main driving factor of the observed growth.

During the intermediate-to-late growth stage (Stage II), the sap flow was primarily driven by the soil water content and the meteorological conditions. Because there were no clear trends in the soil water content during the daytime, multiple correlation analysis was used to determine how the VPD, PAR, and USWC affected sap flow on the hourly and daily time scales. Sap flow correlated significantly with all three of these factors on both of the studied timescales, with  $R^2$  values of 0.61 and 0.98, respectively (Table 2).

**Table 2 Data on the multiple correlation function relating the daily sap flow, upper soil water content, and meteorological variables for jujube plants during the intermediate-to-late growth stage (Stage II)**

Scale	USWC	PAR	VPD	$R^2$	Linear function
Hourly		0.75**	0.21**	0.61**	$SF = (0.03691PAR - 0.6471VPD + 18.1853)^6$
Daily	0.77**	0.73**	-0.44**	0.98**	$DSF = (-5.9547 + 0.7826VWC + 0.2739PAR - 0.002164VPD)^5$ $(-5.9547 + 0.7826VWC + 0.2739PAR - 0.002164VPD)^5$

Note: <sup>a</sup>Asterisks (\*\*) denote values that are significant at  $p < 0.01$ ; USWC is the upper soil water content, PAR is photosynthetically active radiation, and VPD is the vapor pressure deficit.

On the daily time scale, the partial correlation coefficients for PAR and VPD were 0.75 and 0.21, respectively. This suggested that PAR was the primary driver of sap flow during the daytime. The partial correlation coefficients for USWC, PAR and VPD were 0.77, 0.73 and -0.44, respectively. This also suggested that VPD and PAR were the main drivers of sap flow. On the hourly timescale, the relative order of influence of the three studied factors on sap flow from the greatest to the least was USWC, PAR, VPD.

## 4 Conclusions

This work demonstrated that the sap wood area was inversely proportional to the sap flow density but proportional to the daily sap flow (transpiration) and that the primary drivers of sap flow differ between growth stages. During the early growth stage, sap flow was mainly driven by increases in leaf area. Conversely, during the intermediate-to-late growth stage, sap flow was mainly driven by meteorological factors (VPD and PAR) and the soil water content. Lower soil water

contents were associated with greater time lags. The degree of drought resistance in jujube plants was thus determined by the time lag as well as the peak sap flow and the level of sap flow variation. On the hourly timescale, sap flow was driven more strongly by PAR than by VPD during both the rising and falling flow stages. On the daily scale, the sap flow was more sensitive to the soil water content than meteorological factors. Multiple correlation analysis using the VPD, PAR, and soil water content as the predictor variables yielded an  $R^2$  value of 0.98, identifying these variables as the main factors governing sap flow in jujube plants in the semi-arid Loess Plateau of Northwestern China. The results demonstrate that integrated with soil moisture and weather information, the proposed empirical model could be used to predict the water consumption of jujube tree and thereby guide the design of irrigation scheme.

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