



RESEARCH ARTICLE

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Water use pattern of *Pinus tabulaeformis* in the semiarid region of Loess Plateau, China

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Abstract

Aim of the study: We analyzed the water-use strategy of *P. tabulaeformis* and determine the relationships between environmental factors and transpiration rates in the *P. tabulaeformis* woodlands.

Area of study: Loess Plateau region of Northwest China.

Material and Methods: Sap flow density of the *P. tabulaeformis* trees was measured with Granier-type sensors. Stand transpiration was extrapolated from the sap flow measurements of individual trees using the following Granier equation.

Main results: The mean sap flow rates of individual *P. tabulaeformis* trees ranged from 9 L day⁻¹ to 54 L day⁻¹. Photosynthetically active radiation and vapor pressure deficit were the dominant driving factors of transpiration when soil water content was sufficient (soil water content > 16%), considering that soil water content is the primary factor of influencing transpiration at the driest month of the year. During the entire growing season, the maximum and minimum daily stand transpiration rates were 2.93 and 0.78 mm day⁻¹, respectively. The mean stand transpiration rate was 1.9 mm day⁻¹, and the total stand transpiration from May to September was 294.1 mm.

Research highlights: This study can serve as a basis for detailed analyses of the water physiology and growth of *P. tabulaeformis* plantation trees for the later application of a climate-driven process model.

Keywords: Sap flow; stand transpiration; environmental factor; *Pinus tabulaeformis*; Loess Plateau.

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Introduction

Land degradation is a serious ecological problem in several countries worldwide (Liu *et al.*, 2010; Moran *et al.*, 2009). Desertification is a type of land degradation occurring in arid, semi-arid, and part of semi-humid areas (Liu *et al.*, 2010). Desertification, mainly characterized by water and wind erosion, is induced by the lack of coordination between human population and land (Moran *et al.*, 2009). Vegetation restoration using woody species has been encouraged worldwide because of its multiple benefits (Liu *et al.*, 2010), such as soil erosion control (Liu *et al.*, 2008), sediment reduction (Moran *et al.*, 2009), hydrological regime regulation (Yaseef *et al.*, 2009), and carbon sequestra-

tion (Zhao *et al.*, 2004). However, woody species can consume more water by evapotranspiration than other vegetation types, such as natural grassland (Cao *et al.*, 2011). Some researchers also reported that soils become extremely dry in both deep and shallow layers when vegetation restoration is used (Yaseef *et al.*, 2009; Wang *et al.*, 2010; Cao *et al.*, 2011). Negative impacts of the initially promoted afforestation occur because of soil desiccation; these negative impacts include decreasing restoration effort (Liu *et al.*, 2010; Wang *et al.*, 2010; Rodríguez-Caballero *et al.*, 2012), vegetation deterioration and difficulties in renewal and reforestation (Chen *et al.*, 2008), fluctuating agriculture crop production (Wang *et al.*, 2010), and decreasing ecosystem services (Chazdon, 2008; Liu *et al.*, 2008).

Chen *et al.* (2008) found that high water consumption rates of several forest tree varieties trigger soil drought and ecological degradation in arid and semi-arid regions. To avoid these phenomena, efficient water and soil management are essential because of the prevailing fragile ecological environment. Thus, understanding the mechanism by which water use limits and controls afforestation is particularly important. Exploring the water use pattern of trees is important in investigations of ecosystem function and catchment hydrology (Chazdon, 2008) and in the development of viable water-saving management strategies that support high water use efficiency and economic benefit in regions subjected to water scarcity (Cortina *et al.*, 2011). To encourage proper reforestation practices, studies should focus on understanding the water use strategies of common species under different weather conditions and identifying the suitability of these species in developing stable ecosystems that can improve ecosystem services and reverse degradation (Cortina *et al.*, 2011).

The Loess Plateau in China experiences severe soil erosion, vegetation degradation, and desertification (Jiao *et al.*, 2011). Extensive vegetation reestablishment practices had been implemented by the Chinese government to overcome these problems (Zhang *et al.*, 2009). *Pinus tabulaeformis* is the dominant woody species in the Loess Plateau. This species is widely used for ecological restoration (Xiao *et al.*, 2011). However, the unbalance between water supply and demand is becoming particularly acute because of the initially simple and cultivated vegetation system that has been developed toward a complex, cultivated, and natural ecosystem capable of reversing desertification (Wang *et al.*, 2010). In view of this situation, the water use pattern of *P. tabulaeformis* must be studied, and the effects of *P. tabulaeformis* cultivation on local hydrological resources and on local soil and water conservation must be explored.

This study analyzed the water-use strategy of *P. tabulaeformis* in the Loess Plateau of China. Sap flow was monitored along with meteorological factors and soil water content. This study aimed to (1) evaluate the water use of *P. tabulaeformis* plantation, (2) analyze the hourly and daily transpiration rates of *P. tabulaeformis*, and (3) determine the relationships between environmental factors and transpiration rates in the studied *P. tabulaeformis* woodlands.

Materials and methods

Study site

The experiments were conducted in *P. tabulaeformis* plantations from May 1 to September 30, 2014 in the

Anjiapo catchment, Dingxi County (35°35'N, 104°39'E) of Gansu Province in western Chinese Loess Plateau. The annual mean precipitation (period: 1990–2013) in the study area is 420 mm with great seasonal variations. Over 60% of the precipitation falls between July and September, and over 50% occurs in the form of storm. The average monthly air temperature ranges from −7.4 °C to 27.5 °C, with a mean annual temperature of 6.3 °C. The average annual pan evaporation is 1510 mm. The soil belongs to Chernozem according to the IUSS Working Group WRB (2006). The soil was developed from loess parent material, forming a relatively thick profile (Wang *et al.*, 2010). Vegetation restoration had been widely implemented in the area where *P. tabulaeformis* trees were planted in 1986. The land uses in the study area included croplands, grasslands, artificial shrublands, and woodlands.

P. tabulaeformis plantations were installed about 40 years ago to reforest abandoned farmlands. The understory was few grasses, and the contribution of water use by understory vegetation and bare soil surface was not calculated in this study. An experimental plot of 20 m×20 m was set in a plantation located at the southeast-facing slope with a declination of 26°. Up to 64 *P. tabulaeformis* were planted in the plot during 2009 when this study was carried out. The tree density and basal area were 1600 trees ha^{−1} and 25.6 m² ha^{−1}, respectively. The tree canopy height (*H*) and diameter at breast height (DBH, 1.3 m above the ground) were recorded for all trees >1 cm in DBH in the plot. The average tree *H* and DBH in the plot were 9.4 m and 10.5 cm, respectively. The distribution of trees DBH in the plot is presented in Table 1. The leaf area index (LAI) in the plot was measured once a month through the study period with a plant canopy analyzer (LAI-2000, Li-Cor, Lincoln, NE, USA). The averaged LAI from April to October was 2.96.

Meteorological variables and soil moisture

We installed a meteorological tower approximately 100 m from the study site. The recorded meteorological variables were wind speed, air temperature, relative humidity, net and photosynthetically active radiation, rainfall, and atmospheric pressure. These parameters were measured using an AG1000 automatic weather station (Onset Computer Corporation, Pocasset, MA, USA). Rainfall was measured with a tipping-bucket rain gauge (model TE525, metric; Texas Electronics, Dallas, TX).

Volumetric soil moisture was measured by using probes (Em 50, Decagon Devices, Pullman, WA, USA) installed at five depths below the soil surface (10, 20,

Table 1. Number of trees and proportion of sapwood area for each DBH class in the experimental plot

DBH class	Number of trees	Average DBH (cm)	Total sapwood area in the class (A_{si} , cm ²)	Percentage of sapwood area in the plot (A_{si}/A_{st} , %)
4 (3.0–4.9)	3	4.4	13.4	1.21
6 (5.0–6.9)	12	6.2	153.1	13.88
8 (7.0–8.9)	10	8.1	211.3	19.16
10 (9.0–10.9)	17	9.7	187.6	17.01
12 (11.0–12.9)	12	11.9	300.0	27.20
14 (13.0–14.9)	7	14.2	148.5	13.46
16 (15.0–16.9)	3	15.8	89.2	8.08
Total	64		1103.1	100

30, and 40 cm) in the *P. tabulaeformis* woodlands. The monitoring sites were located in the upper, middle, and lower portions of the selected study plot, with one sensor per soil depth and slope position. Soil water content was measured every 2 days by means of oven drying to validate the soil moisture data provided by the probes during the study period.

We used the data from the weather station to estimate evapotranspiration with the Penman–Monteith equation, which had been strongly recommended for estimating evapotranspiration:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma(900/T + 273)u_2(e_s - e_a)}{\Delta + \lambda(1 + 0.34u_2)}, \quad (1)$$

where R_n is the net radiation at the plant surface (MJ m⁻² day⁻¹), G is the soil heat flux (MJ m⁻² day⁻¹), Δ is the vapor pressure curve slope (kPa °C⁻¹), γ is the psychrometric constant (kPa °C⁻¹), T is the mean air temperature (°C), u_2 is the wind speed at 2 m height (m s⁻¹), and $e_s - e_a$ is the saturation vapor pressure deficit (kPa).

Sap flow and sapwood area measurement

Sap flow density (F_d) of the *P. tabulaeformis* trees was measured with Granier-type sensors (Granier, 1987) from May to September 2014. Sapwood thickness was measured with a tree core drill. The sapwood thickness of *P. tabulaeformis* trees in the study site ranged from 0.5 cm to 1.0 cm (mean±SD=0.73±0.10, $n=27$). Thus, 10 mm-long sensors were used in this study. Each sensor consisted of two cylindrical probes, a continuously heated upper probe, and an unheated lower probe. Both probes were 10 mm in length and 2 mm in diameter, covered by an aluminum tube to homogenize temperature along their length. When installing the probes, two pieces of bark of 2 cm×2 cm approximately 15 cm vertically apart on the north side of the sampled trees at breast height were peeled until the cambium was exposed. Two holes 10 mm in depth and 2 mm in diameter

were drilled radially at the center of the exposed cambium with a portable drill. The probes were then inserted into the two holes of each sample tree. The upper heated probe included a heater that was continuously supplied with 0.15 W (James *et al.*, 2002) constant power. The lower unheated probe served as a temperature reference. Both probes contained a copper–constantan thermocouple in the middle. These thermocouples were joined at the constantan side. The copper leads were connected to a data logger (CR1000, Campbell Scientific) with a multiplexer (AM16/32, Campbell Scientific) programmed to measure the temperature difference between the two probes directly. Temperature differences between the two probes were scanned every 30 s, and 30 min averages were recorded. After installation, the exposed cambium and the probe were covered with silicone gel to prevent water from contacting the probe. The portion of the stem equipped with the probes was covered with an aluminum mantle and then wrapped with several layers of aluminum foil. The purpose of this procedure is to prevent solar radiation from heating the area being measured and to avoid the effect of natural temperature gradients in the stem. The edges of each aluminum mantle were also sealed with silicone gel to prevent water entry. The temperature difference between the two probes was affected by the sap flow close to the upper heated probe. The mean sap flow density (F_d , m³ m⁻² min⁻¹) along the length of the heated probe was calculated on the basis of the temperature difference between the two probes using the empirical equation of Granier (1987):

$$F_d = 119 \times 10^{-6} \left(\frac{\Delta T_M - \Delta T}{\Delta T} \right)^{1.231}, \quad (2)$$

where ΔT is the temperature differences between the two probes and ΔT_M is the value of ΔT when the sap flow density is zero ($F_d=0$, generally taken as the peak nighttime value of ΔT during several days).

To avoid injuring the sample trees used for sap flow measurements, the sapwood thickness of the sample trees was determined as the mean sapwood thickness

of the corresponding DBH class in the trees used for measuring the sapwood area (described below in this section). Whole-tree sap flow (F , $\text{m}^3 \text{min}^{-1}$) was calculated as the product of F_d and the sapwood cross-sectional area (Granier, 1987):

$$F = F_d A_s, \quad (3)$$

where A_s is the cross-sectional area of sapwood at the upper heated probe level. Sap flow was measured on 18 *P. tabulaeformis* trees that were selected to represent the distribution of all DBH classes in the plot. The DBH of these trees ranged from 4.9 cm to 16.6 cm (Table 1). Thirty trees around the plot were randomly selected and radially cored with an increment borer in the four compass directions of the stems at breast height. For each selected tree, DBH was measured with a diameter tape. The bark and sapwood thicknesses were measured with a ruler in the extracted cores, and an average of the four orientation measurements was used for regression analysis. The sapwood area (A_s) was computed as the difference between the stem cross-sectional area beneath the bark and heartwood area. The computation was based on the measured DBH and mean bark and sapwood thicknesses of each tree, assuming that the stem cross sections were circular. The relationship between A_s and DBH was developed according to the allometric equation (Vertessy *et al.*, 1995):

$$A_s = B_0 \times \text{DBH}^{B_1} \quad (4)$$

where B_0 and B_1 are the species-specific coefficients determined by the nonlinear regression techniques. The equation was used to estimate A_s from the DBH of trees in the plot.

Stand transpiration

Stand transpiration (E_c) was extrapolated from the sap flow measurements of individual trees using the following equation (Granier *et al.*, 1996):

$$E_c = J_s \times \frac{A_{st}}{A_g}, \quad (5)$$

where A_{st} (m^2) is the total cross-sectional sapwood area of the plot, A_g is the ground area of the plot (m^2), and J_s is the stand average sap flow density. J_s was calculated as:

$$J_s = \sum_{i=1}^n (F_{di} A_{si}) / A_{st}, \quad (6)$$

where F_{di} is the average sap flow density of trees in DBH class i , A_{si} is the total cross sectional sapwood

area of trees in DBH class i , and n is the number of DBH classes in the plot.

Water balance model

Precipitation (P) is the only source of water (i.e., input) in the Anjiapo catchment. The change in soil water content (ΔSW) is controlled by (1) canopy interception (I), (2) soil evaporation (E), (3) plant transpiration (T), (4) runoff (R), and (5) drainage at the bottom layer of the soil profile (D). Data of E and I were from our previous study (Jian *et al.*, 2015). D is nil in the study area according to *in situ* observations. R was ignored. The soil water balance in the root zone (1 m) is given as follows:

$$\Delta SW = P - I - E - T. \quad (7)$$

Data analyses

Stepwise multiple regression analyses were performed to determine the relationships between daily changes in stand transpiration and environmental factors (soil water content, photosynthetically active radiation, vapor pressure deficit, and potential evapotranspiration). All statistical analyses were conducted using the SPSS software package version 18.0 (IBM, USA). The regression equations were performed in SigmaPlot version 11.0 (Systat Software, Chicago, Illinois, USA). For all tests, we used a significance level of $P < 0.05$.

Results

Soil moisture characteristics

Soil water content from 0 cm to 10 cm was the highest and fluctuated significantly with increasing rainfall, with 46.5% of the variation coefficient for *P. tabulaeformis*. Rainfall affected the soil water content at 10 cm depth more frequently than the other three soil depths. The soil water content and variation coefficient in deep soil layers were relatively low (Fig. 1). The soil water content at 10 cm depth responded to rain events if the cumulative rainfall over a 3–5 day period exceeded 10–12 mm. Single rain events of less than 10 mm slightly affected the soil water content at 20, 30 or 40 cm depth (Fig. 1). Soil water content generally increased during the rainy season (nearly 70% of annual precipitation occurs during May to September in this region).

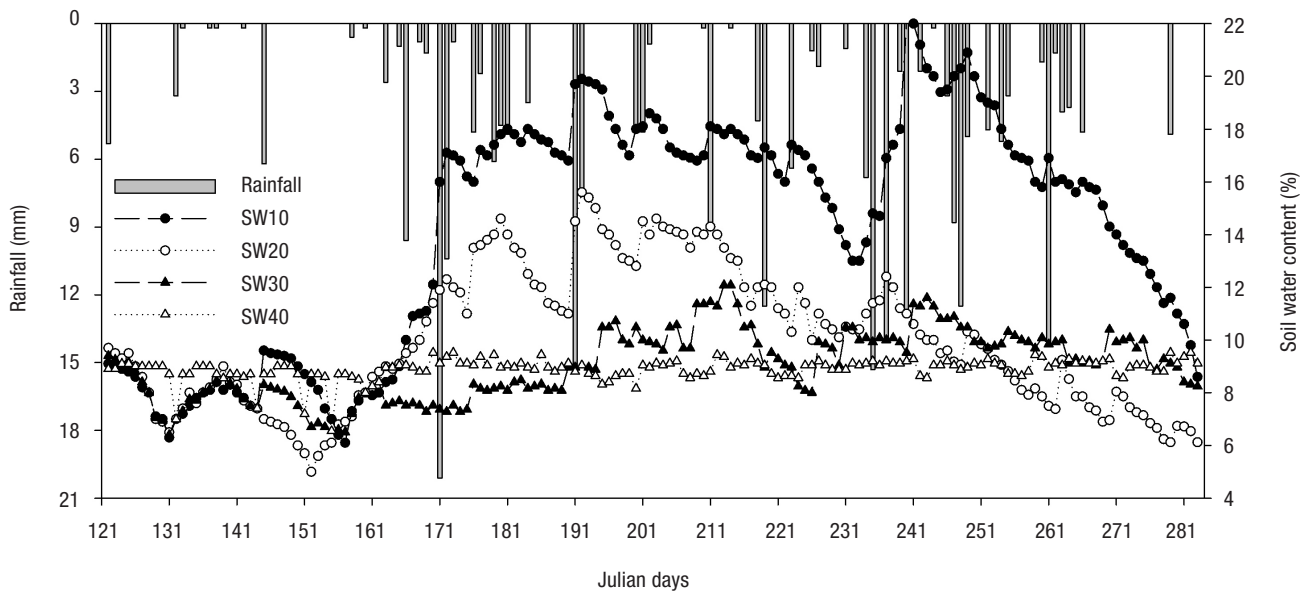


Figure 1. The dynamic variation of rainfall pulses and soil water content (%). SW10, SW20, SW30, and SW40 are soil water content (%) at 10, 20, 30, and 40 cm below the soil surface, respectively.

Stand-level estimates of sapwood area

A regression equation between A_s and DBH ranging from 3.3 cm to 24.4 cm was derived from the measurements of 30 sampled trees, covering the range of tree DBH in the whole plot. The A_s of *P. tabulaeformis* trees was reliably described as a power function of DBH ($A_s = 0.541 \text{ DBH}^{1.403}$, $R^2 = 0.924$, $P < 0.001$). The cumulative sapwood area of each DBH class (A_{si}) and the ratio of A_{si} to the A_s are shown in Table 1.

Diurnal variation of sap flow density

The sap flow density in *P. tabulaeformis* exhibited distinct diurnal variation throughout the growing season. Three diurnal variation examples of sap flow density in *P. tabulaeformis* in sunny, cloudy, and rainy days are shown in Fig. 2. Sap flow density was low and relatively steady at night and before dawn under the three weather conditions. During sunny days, the sap flow density gradually increased after 06:30 h, reached the peak value of $0.184 \text{ cm}^{-3} \text{ cm}^{-2} \text{ cm}^{-1}$ after 13:00 h, gradually decreased after 14:30 h, sharply decreased after 18:00 h, and then stabilized after 20:30 h. Meanwhile, the sap flow density during cloudy and rainy days increased approximately 1 h later than that during sunny days. In addition, the variation of sap flow density was not significant. During sunny days, Q and D exhibited the same trend as the daily course of sap flow density. This phenomenon is clearly shown by the coincident high and low values in Fig. 2A. Up to 1–2 h time lag existed between the sap flow and D . Moreover,

no significant time lag was observed with Q . Determinant coefficients (R^2) of sap flow with Q and D under the three weather conditions are presented in Table 2.

Daily variations of stand transpiration

The experimental period was hot, relatively rainy, and humid (Figs. 3B and C). The stand transpiration (E_c) of *P. tabulaeformis* during the study period showed a mean value of 1.91 mm day^{-1} , ranging from 0.78 mm day^{-1} to 2.93 mm day^{-1} . The mean daily transpiration rates in May, June, July, August, and September were 1.84 ± 0.21 , 1.63 ± 0.29 , 2.19 ± 0.19 , 2.06 ± 0.23 , and $1.27 \pm 0.25 \text{ mm day}^{-1}$, respectively. Cumulative transpiration was 291.4 mm, equivalent to 89.1% of the total rainfall during this period.

In most cases, increased stand transpiration (E_c) coincided with the increased values of daily photosynthetically active radiation (Q_o) and mean daily vapor pressure deficit (D_z) normalized by daylight hours (Fig. 3). For instance, E_c values were 2.21 and 2.45 mm day^{-1} on May 11th and June 17th, respectively. On September 6th and 8th, when water demand was low because of cloudy day, E_c values were 1.39 and 0.79 mm day^{-1} , respectively. On days when rain occurred, E_c was greatly reduced (Fig. 3). On September 16th, when sudden rainfall occurred with associated humid and cloudy weather conditions, E_c was 0.89 mm day^{-1} . Similarly, the succession of rainy days on September 1st and 15th suppressed E_c . However, on some rainy days followed by sunshine, such as June 30th, July 29th, and August 24th, E_c was rela-

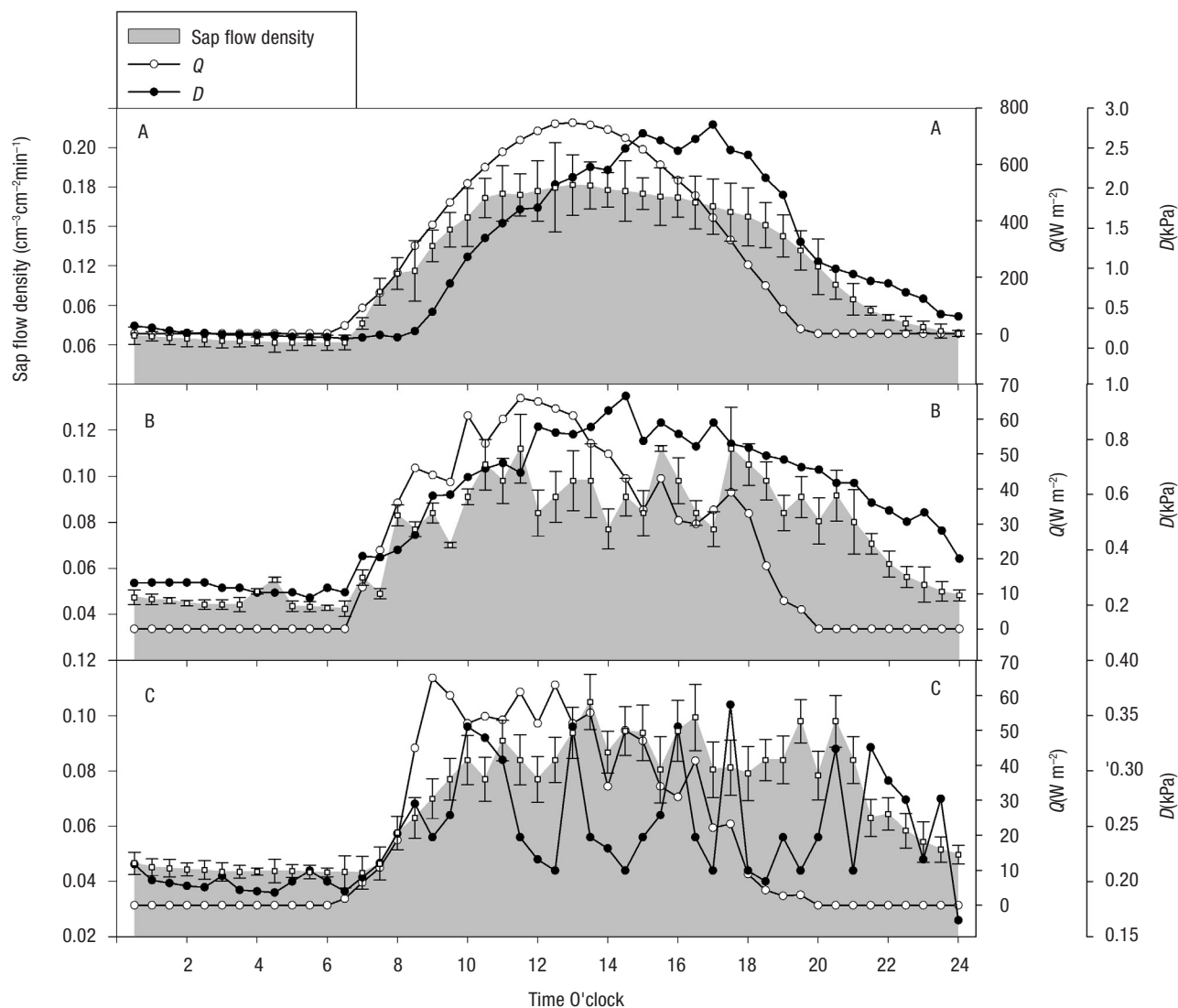


Figure 2. Half-hourly patterns of photosynthetically active radiation (Q), vapour pressure deficit (D) and half-hourly patterns of sap flow density under different weather conditions for *P. tabulaeformis*. A, sunny days (we selected 3 sunny days in each month (from May to September)); B, cloudy days (we selected 3 cloudy days in each month (from May to September)); C, rainy days (we selected 3 cloudy days in each month (from May to September)). Data of sap flow density = mean $\pm$ SD, Data of D and Q = mean.

tively high. Daily E_c patterns of *P. tabulaeformis* showed relatively low values under sunny weather conditions from May 24th to June 8th, although Q_o remained high (Fig. 3).

Correlation between *P. tabulaeformis* stand transpiration and environmental factors

Determinant coefficients (R^2) of daily vapor pressure deficit (D_z), daily photosynthetically active radiation (Q_o), air temperature (T_a), soil water content (SW), and potential evapotranspiration (ET_0) with stand transpiration (E_c) in each month are presented in Table 3. During the experimental period, daily changes in transpiration

correlated with Q_o ($R^2=0.305-0.802$), D_z ($R^2=0.311-0.824$), T_a ($R^2=0.465-0.672$), SW ($R^2=0.306-0.802$), and ET_0 ($R^2=0.206-0.403$).

The multiple linear regression equations of E_c with SW , D_z , Q_o , T_a , and ET_0 are shown in Table 4. SW only significantly affected E_c in May. E_c was the result of D_z and Q_o in June, July, and September. In August, E_c mainly depended on D_z , Q_o , and T_a .

Total transpiration sharply increased with D_z at low levels ($D_z < 0.9$ kPa) but leveled off at increased D_z values (Fig. 4a). Despite considerable data scattering, increases in Q_o up to values of 0–500 $W m^{-2}$ induced a reasonably linear increase in transpiration, after which transpiration leveled off for increased values of Q_o (Fig. 4b).

Table 2. Partially adjusted coefficients of determination between sap flow density and significant environmental factors under three weather conditions (sunny, cloudy and rainy days). Half-hourly patterns of photosynthetically active radiation (Q), vapour pressure deficit (D)

Environment factors	Partial coefficient and significance	Weather conditions		
		Sunny day	Cloudy day	Rainy day
Q	R^2	0.847	0.381	0.115
	P	<0.0001	<0.05	0.16
D	R^2	0.816	0.324	0.109
	P	<0.0001	<0.05	0.09

Soil water balance in *P. tabulaeformis* woodlands

The daily soil water content in the *P. tabulaeformis* plots from May to September 2013 was calculated using the water balance equation. The results are presented in Table 5. The net soil water storage (ΔSW) was negative in each month throughout the experimental period.

Discussion

Variation of sap flow and transpiration

Throughout the growing season, the sap flow density of *P. tabulaeformis* varied regularly, especially during sunny days (Fig. 2). Giorio & Giorio (2003) also reported that the variation in sap flow for olive tree during sunny days was greater than that during cloudy days. Yue *et al.* (2008) pointed out that the sap flow of *Larix principis-rupprechtii*, an important principal species for afforestation in North–West China, changes regularly from day to night in later growing season in both typical sunny and cloudy days. However, the sap flow rate during sunny days was greater than that during cloudy days. We found that *P. tabulaeformis* trees at night presented remained sap flow values different than zero, which cannot be night transpiration. The most probable process is because the trunk, as an important source of water storage and capacitance, replenishes water (Goldstein *et al.*, 1998). Yaseef *et al.* (2009) reported that *Juglans mandshurica* demonstrates several peaks of sap flow rate. In specific, the sap flow still occurs at night, but the sap flow rate at this period is much lower than that during day time and is constant. Ma *et al.* (2001) also indicated that the sap flow rate of *Betula platyphylla* at night is 11.47%–39.93% of that during the whole day and that the variation in sap flow rate is greater during sunny days than during cloudy days. Moran *et al.* (2009) reported that the seasonal variation of the hourly sap flow rate of two eucalyptus plantations is similar between the two sites. However, their values were rela-

tively higher during the wet season than during the dry season. Moreover, the variation of the sap flow rate was large during the dry season. In this experiment, the diurnal and seasonal variations of E_c in *P. tabulaeformis* under different weather conditions were in agreement with previous studies. In addition, the results (Fig. 2) indicated that the sap flow density in *P. tabulaeformis* exhibited no significant “noon depression” phenomenon. At noon, the stomata of *P. tabulaeformis* are not completely closed; thus, tree transpiration continues during this time of the day. Alternatively, sap flow measured in the trunk shows liquid water movement within this organ, with a time lag compared with the vapor phase at the stomatal level. Independent measurements of leaf transpiration and stomatal conductance at noon can allow us to elucidate this phenomenon.

The daily transpiration of *P. tabulaeformis* ranged from 0.78 mm to 2.93 mm in 2014, with a mean value of 1.91 mm day⁻¹. These values were lower or similar than those reported for some coniferous forests of cold climates (Alsheimer *et al.*, 1998; Bosch *et al.*, 2014). In this regard, Alsheimer *et al.* (1998) found that canopy transpiration varies from 1.4 mm day⁻¹ to 2.8 mm day⁻¹ for 140-year-old Norway spruce (*Picea abies*) stands in the Lehstenbach catchment, Germany. Lagergren & Lindroth (2002) reported that transpiration ranges from 0.95 mm day⁻¹ to 2.65 mm day⁻¹ in the wet, cool season in Norway spruce stands in a boreal forest in central Sweden. Differences between forests in canopy transpiration are expected because of the significant influences of tree physiology (Lagergren & Lindroth, 2002), stand density (Alsheimer *et al.*, 1998), the stand age (Alsheimer *et al.*, 1998), and soil moisture availability.

Response of sap flow to environmental factors

The sap flow rate in tree species is related to meteorological factors. Chazdon (2008) indicated that D_z and Q_o considerably affect the stand transpiration of apple trees (*Malus domestica*) and that the sap flow rate increases with D_z and Q_o during sunny days. An

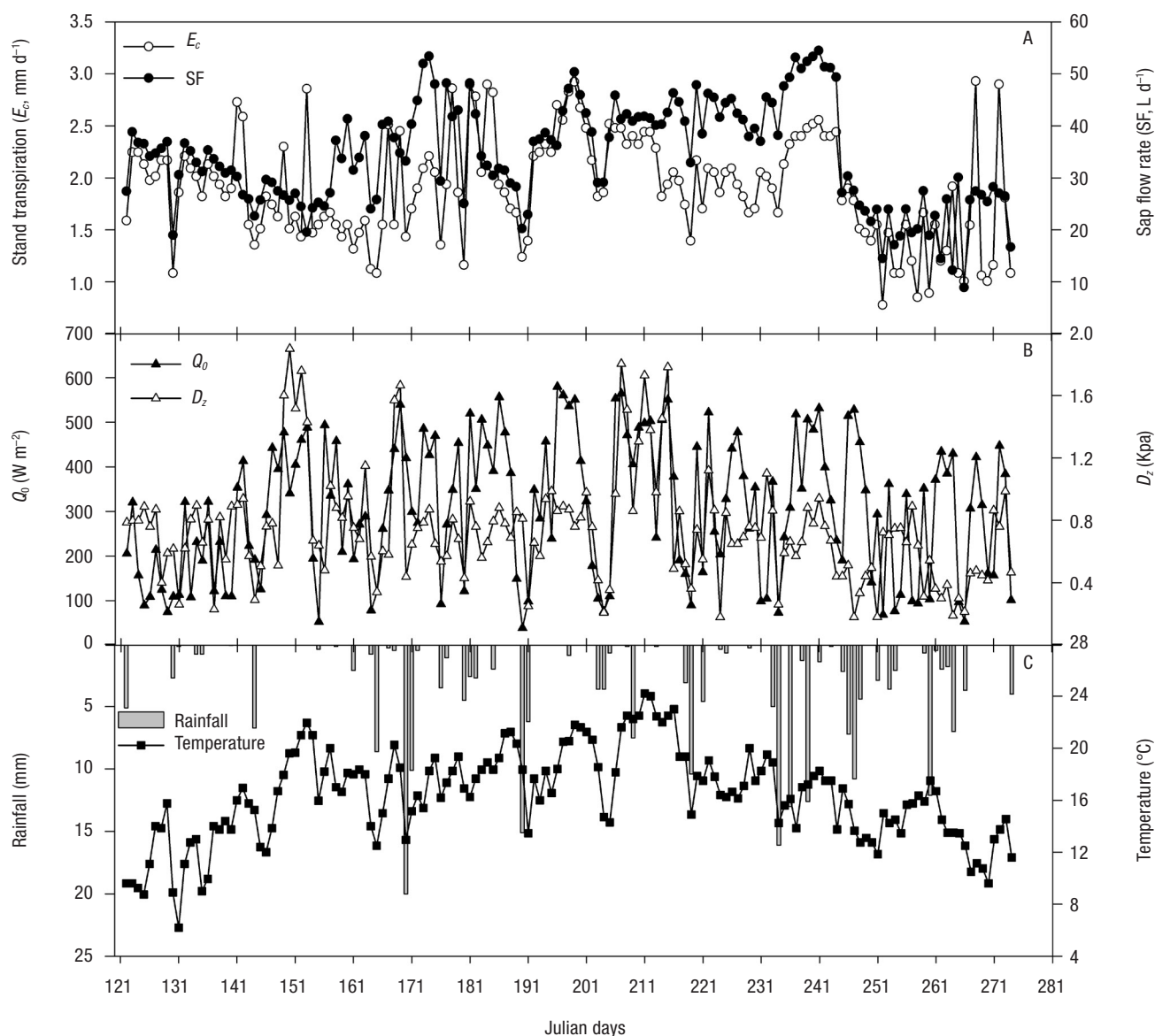


Figure 3. Daily values for (A) sap flow rate (SF) and stand transpiration (E_c) during whole experiment period (1st May to 30th September), data represented the mean values of the three plots for *P. tabulaeformis*. (B) Daily vapor pressure deficit (D_z) and daily photosynthetically active radiation (Q_o). (C) Temperature and precipitation.

experimental result in the southern Ningxia hilly area of northern China showed that Q_o , T_a , and relative humidity are the three significant environmental factors determining the daily transpiration of *Larix principirupprechtii* (Moran *et al.*, 2009). In another study, the average daily stand transpiration of two eucalyptus (*Eucalyptus urophylla*) plantations is significantly related to available SW and daily D_z (Chen *et al.*, 2008). In the present experiment, the trunk sap flow rate in *P. tabulaeformis* was influenced by D_z and Q_o . However, the magnitude of the influence of these two environmental factors on the sap flow rate varied in each month. Similarly, another study in north-east China showed that T_a , relative humidity, and Q_o are the major three factors affecting the sap flow rate of *B. platy-*

phylla during sunny days, but the role of the three factors varies at the different growth stages (Chazdon *et al.*, 2008).

The imbalance between water supply and demand was particularly acute under the poor growing conditions of May in the study area (Table 5). The soil surface is often considered as an important source of water for plant transpiration (Rodríguez-Caballero *et al.*, 2012). Considering the low rainfall of 16.4 mm in May (Table 5), SW was expected to be a key factor limiting stand transpiration in this month. For this reason, we can conclude that different environmental factors drive stand transpiration at different time periods. SW was more important than Q_o and D_z in influencing stand transpiration in May.

Table 3. Partially adjusted coefficients of determination between transpiration and significant environmental factors in May, June, July, August, and September 2014

Environment factors	Partial coefficient and significance	Month				
		May	June	July	August	September
Q_o	R^2	0.305	0.765	0.783	0.802	0.711
	P	<0.05	<0.0001	<0.0001	<0.0001	<0.0001
D_z	R^2	0.311	0.824	0.694	0.733	0.795
	P	<0.05	<0.0001	<0.0001	<0.0001	<0.0001
T_a	R^2	0.502	0.514	0.465	0.672	0.582
	P	<0.01	<0.01	<0.01	<0.01	<0.01
SW	R^2	0.802	0.505	0.306	0.415	0.426
	P	<0.0001	<0.01	<0.01	<0.01	<0.01
ET_0	R^2	0.311	0.206	0.453	0.336	0.240
	P	<0.05	<0.05	<0.05	<0.05	<0.05

* Daily photosynthetically active radiation (Q_o), daily vapor pressure deficit (D_z), air temperature (T_a), soil water content (0–100 cm) (SW) and Potential evapotranspiration (ET_0), the number of samples is 153.

Table 4. Multiple linear regression equations between daily stand transpiration and environmental factors in each month (1st May–30th October 2014) for *P. tabulaeformis*

Month	Regression equations	R^2	F	Sampled number (n)
May	$E_c=0.986+0.197SW$	0.756	49.866	31
June	$E_c=2.034+0.502 D_z+1.345 \times 10^{-3} Q_o$	0.806	60.234	30
July	$E_c=2.037+0.366 D_z+1.215 \times 10^{-3} Q_o$	0.824	55.122	31
August	$E_c=3.345+0.157 D_z+1.005 \times 10^{-3} Q_o-8.64 \times 10^{-2} T_a$	0.836	50.475	31
September	$E_c=1.976+0.119 D_z+2.034 \times 10^{-3} Q_o$	0.791	63.120	30

*The dependent variable is stand transpiration (E_c), the independent variables are daily vapor pressure deficit (D_z), daily photosynthetically active radiation (Q_o), air temperature (T_a), soil water content (SW) and potential evapotranspiration (ET_0). Significant difference ($P < 0.05$).

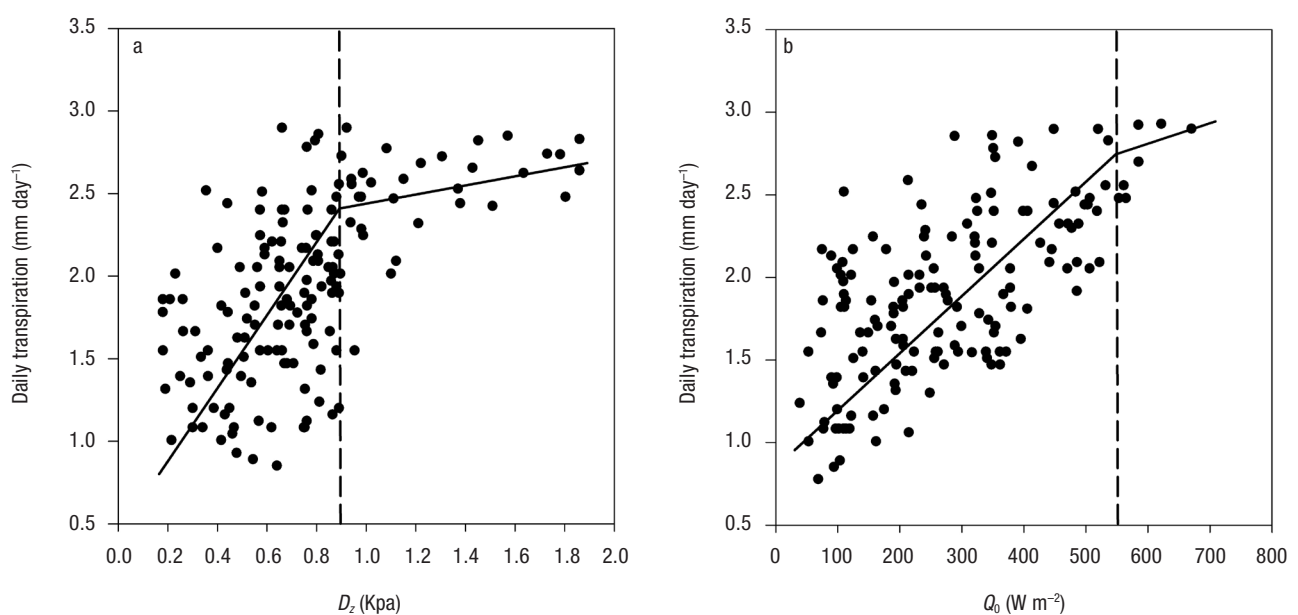
**Figure 4.** The relationships between transpiration and daily vapor pressure deficit (D_z) and daily photosynthetically active radiation (Q_o).

Table 5. Monthly values (mm) of water balance components estimated in the *P. tabulaeformis* studied plots in 2014

Month	<i>P</i>	<i>T</i>	<i>E</i>	<i>I</i>	ΔSW
May	16.4	59.8	11.2	5.3	-59.9
June	55.9	53.0	15.6	11.7	-24.4
July	52.0	61.3	18.9	9.4	-34.6
August	64.1	67.8	18.8	12.5	-35.0
September	60.0	43.5	12.2	10.3	-6.0

Note: *P*, rainfall; *T*, transpiration; *E*, soil evaporation; *I*, canopy interception; ΔSW , net soil water storage. Runoff was ignored. $\Delta SW = P - T - E - I$. Data of *E* and *I* were estimated from a previous study (Jian *et al.*, 2015).

The *P. tabulaeformis* trees in the study site can still meet their water demand even though transpiration is frequently restricted by the soil water availability in the upper soil profile as shown by the influence of *SW* in May. The transpiration rates remained high despite the high temperature and intense radiation on representative clear days for *P. tabulaeformis* (Fig. 3). This condition was due to the deep and developed rooting systems. Our previous studies in the same area reported that the roots of *P. tabulaeformis* show a distribution pattern that can reach 2.8 m in depth (Jian *et al.*, 2014). However, the majority of absorbing roots were concentrated in the upper 1.0 m of the soil.

Conclusions

This study showed the stand transpiration of *P. tabulaeformis* in the semiarid region of northwest China. The total stand transpiration was 294.1 mm during the 2014 growing period. The maximum and minimum daily stand transpiration rates was 2.93 and 0.78 mm day⁻¹, respectively, with a mean stand transpiration of 1.9 mm day⁻¹.

Future studies should consider variations in tree physiology to research its relationship with water use. Ecological and physiological research on *P. tabulaeformis* is also important to understand the *P. tabulaeformis* forest hydrologic process and to provide further theoretical support for forest management in semiarid regions. Long-term transpiration measurements for *P. tabulaeformis* forests must be conducted to quantify the interseasonal and interannual variations in transpiration for the construction of long-term water balance estimates and the development of predictive hydrological modeling techniques in semiarid regions.

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